Appendix A

Completed Green Stormwater Infrastructure Projects

Table 1: Completed Public Green Stormwater Infrastructure Projects

Project Name	Greened Acres
West Mill Creek Farm Swales	0.1
Ogden St and Ramsey St (West Mill Creek Recreation Center)	0.2
47th & Grays Ferry	0.3
Cliveden Park	1.3
Clark Park Basketball Court	0.8
Jefferson Square Raingarden	0.1
McMahon St (Waterview Recreation Center)	0.5
Liberty Lands	0.2
Lancaster Ave from N 58th St to N 63rd St	1.6
16th St between Passyunk Ave and Jackson St	0.2
Palmer St from Frankford Ave to Blair St (Shissler Playground)	0.3
7th St, 8th St, and Cumberland St (Hartranft School)	1.0
Benjamin Franklin Parkway from 21st St to 23rd St	1.0
Bus Shelter Green Roof	0.0

Project Name	Greened Acres
Reese St	0.2
Diamond St	0.4
9th St	0.3
Front St	0.3
8th St	0.3
Earl St (Hetzell Playground)	0.2
Madison Memorial Park	0.1
Eadom Parking Lot	2.9
Bureau of Laboratory Services	0.4
Herron Playground	0.5
Philadelphia Military Academy	0.7
Berks, Mascher (Towey Recreation Center)	1.0
22nd St, Cecil B Moore Ave (Martin Luther King Recreation Center)	1.7
Norris St, Van Pelt St, and Berks St (Frederick Douglass Elementary School)	1.4
58th St Connector(Bartram's Garden, Francis Myers Rec, Cobbs Creek Park)	1.4

Project Name	Greened Acres
Montgomery Ave, Shissler Playground	0.9
Morris Leeds Middle School	9.0
Woolston Ave, Walnut Ln, Rodney St (Simons Recreation Center)	2.6
60th St, 61st St, Cedar Ave, and Hazel Ave (Bryant Elementary School)	1.8
William Harrity School	0.8
Christian St, Webster St, 56th St (Christy Recreation Center)	1.5
52nd St, 53rd St, Pine St, and Osage St (Samuel B. Huey Elementary School)	1.4
Baltimore Ave Island from S 60th St to Wharton St	0.9
21st St from Venango to Pacific	0.4
58th St, 59th St, and Walnut St (Sayre High School)	2.3
Haverford Ave, 57th St and Vine St (Shepard Recreation Center)	2.6
56th St, 57th St, Race St, and Vine St (Daroff School)	2.9
Pine St, Frazier St, and 57th St (Andrew Hamilton School)	1.3
White Hall Commons/Carmella Playground/Gambrell Recreation Center/Warren G Harding School	3.4
Magnolia Cemetary	0.5

Project Name	Greened Acres
Hellerman St, Cottage St, and Levick St (Roosevelt Playground)	2.2
Hegerman St, Magee Ave, and Hellerman St (Dorsey Playground)	1.6
Bridesburg Recreation Center/Bridesburg School	2.0
Wakefield Park	1.3
Harper's Hollow Park	1.1
St Thomas Aquinas School	1.3
13th St, Porter St, and Moyamensing Ave (A.S. Jenks School)	0.9
Smith Elementary School	0.8
4th St, 5th St, Federal St, and Washington Ave (Sacks Playground)	1.8
Womrath Park	1.2
Philadelphia Zoo	2.0
Belfield Ave from Chew Ave to Walnut Ln	1.6
Shissler Playground	0.8
24th St and Wolf St (Smith Playground)	2.5
23rd St, 24th St, and Jackson (E.H. Vare Middle School)	1.2

Project Name	Greened Acres
Stephen Girard School	0.4
Southwark School	0.6
Oakford, 30th (Donald Finnegan Playground)	1.0
22nd, Carpenter, Montrose (Julian Abele Park)	1.0
Columbus Square	0.3
William Cramp School	1.3
Rosehill St (Barton School)	1.3
27th St from Indiana to Toronto	0.3
Chalmers (29th and Chalmers Playground)	0.9
Passyunk Ave	1.0
33rd & Dauphin SEPTA Bus Stop Loop	0.1
William Dick Elementary	2.4
Stenton Avenue and Washington Lane, NE Intersection	0.6
Blue Bell Inn Triangle Park	0.6
Alder St from Norris St to Diamond St	0.5

Project Name	Greened Acres
William Gray Youth Center	1.2
Parking Lot - 12th St, Marvine St, and Diamond St	2.0
24th St and Diamond St (Dick Elementary School)	1.2
Trenton Ave and Norris St	1.1
Thompson St and Columbia Ave	1.1
Old Cathedral Cemetary	0.8
Preston St, 41st St, Brown St, and Aspen St (Belmont School)	1.8
49th St, Parrish St, and Ogden St (James Rhoads School)	1.0
53rd St and Peach St (Mastery Charter School)	0.9
47th St, 48th St, Wyalusing Ave (Muhammed Square)	1.9
62nd St and Lebanon (Overbrook Elementary)	0.9
Kenmore Rd, Haddington St, and Atwood Rd (Cassidy Elementary School)	1.6
Sister Clara Muhammad School	0.8
Springfield Ave and Cobbs Creek Island	0.9
McCreesh Playground / Catharine Elementary School	2.4

Project Name	Greened Acres
57th St and Pentridge St (Longstreth School)	1.2
Little Sisters of the Poor	2.7
Passyunk Ave from Dickinson St To Reed St	0.4
10th St from Wilder St to Reed St	0.3
12th St from Dickinson St to Tasker St	0.8
12th St and Reed St (Columbus Square)	0.5
18th St, 19th St, Ellsworth St, and Washington Ave (Chew Playground)	1.4
4th St and Cambridge St (Bodine High School)	0.8
3rd St and Fairmount Ave Intersection	0.4
Penn Street Trail	0.5
Wister Woods Park	9.5
Kemble Park	10.2
10th St and Jefferson St (Dendy Recreation Center)	0.6
Poplar St from 8th St to Franklin St	0.3
Welsh School	0.5

Project Name	Greened Acres
Diamond St from 25th St to Stillman St	0.3
Wakisha Charter School	0.8
George W. Nebinger School	2.0
Elmwood, 64th, Grays, 65th (Connell Park)	2.5
Buist, 63rd, Chelwynde, 64th (Mother Mary of Peace School)	1.6
St. James Episcopal Church of Kingesessing	4.3
Buist Ave, 70th, Elmwood, Holbrook (Patterson School)	1.5
72nd, Buist, 71st, Dicks (Elmwood Park)	4.9
73rd and Grays	2.6
18th St, 19th St, and Bigler St (Barry Playground)	4.2
Panati Playground	0.8
Ralph Brooks Park	0.4
Benson Park	0.5
Woodland Ave (Tiger III)	1.9
Callowhill Stormwater Trees	0.1

Project Name	Greened Acres
Bustleton Ave (Tiger III)	0.7
Jackson St, Tree St, 13th St (Epiphany of Our Lord School)	0.2
Duval St, Crittenden St, and Johnson St (Anna B. Day School)	2.7
8th St, Wolf St, and Mildred St (Francis Scott Key School)	0.8
Stinger Square	0.8
Heston Lot	1.0
Baker Playground	0.4
Mill Creek Playground Basketball Court	0.4
Sepviva St from Susquehanna Ave to Dauphin St	0.4
Percy St from Catharine St to Christian St	0.2
Belgrade St and Marlborough St	0.3
Sepviva	0.3
Franklin St from Diamond St to Norris St	2.0
Rockland St	1.9
Dauphin from Frankford to Tulip	1.3

Project Name	Greened Acres
56th from Greenway to Paschall	0.7
Hope St from Master to Jefferson	0.4
Hope St from Berks to Norris	0.4
Total	**179.7**

Table 2: Completed Incentivized Green Stormwater Infrastructure Projects

Project Name	Greened Acres
Cardone Whitaker Ave Facility - Stormwater Retrofit- Phase 1	53.0
GSFS, Green Street Friends School Retrofit	1.0
1148 Wharton Street	0.7
Methodist Home Rain Gardens	2.0
Cardone Whitaker Ave Facility- Stormwater Retrofit- Phase 2	15.8
Site 10 Phase 1 Stormwater Credit Retrofit Design	5.2
Site 10 Phase 2 Stormwater Credit Retrofit Design	3.4
Globe Dye Works Rainwater Detention System	0.6
Site 10 Phase 3 Stormwater Credit Retrofit Design	35.5
MINK1143, LLC	0.7
La Salle University SMIP Grant	8.3
Lea Elementary School Greening Phase 1	2.3
Site 031	5.4
Wolf Pack Stormwater Project	11.7

Project Name	Greened Acres
Northeast Tower Center Retrofit	17.7
Philadelphia Montessori School	0.2
Philadelphian Green Roof	0.1
Site 32 Stormwater Credit Retrofit Design	3.3
Site 16 Stormwater Retrofit - Quaker City Flea Market	1.7
Site 26 - Phase 1 Stormwater Retrofit Design	9.1
Site 26 - Phase 2 Stormwater Retrofit Design	2.7
Site 38, Stormwater Credit Retrofit Design	7.0
Site 26, Phase 3 Stormwater Credit Retrofit Design	9.9
Site 5, PWD Stormwater Credit Retrofit Design	21.9
Site 32, Phase 2 Stormwater Credit Retrofit Design	7.3
Community Legal Services	0.1
1518 Cambridge Street to 1521 Poplar Street	0.2
2150 E. Westmoreland St.	1.4
St. James Episcopal Church Retrofit	0.3

Project Name	Greened Acres
The Enterprise Center Green Roof	0.1
Newman and Company Rainwater Harvesting System	1.0
Vernon Park Rain Garden	0.1
6225 State Road	0.3
Roof Leader Disconnection Retrofit	0.9
6225 State Road	2.5
US GSA Green Roof	0.3
PECO Green Roof	0.7
Friends Center	0.2
Total	**234.6**

Table 3: Completed (Re)Development Green Stormwater Infrastructure Projects

Project Name	Greened Acres
Philadelphia Youth Center	2.5
Parkwest Town Center	37.4
Inglis Apartments at Elmwood	1.2
Liberties Station	0.0
Temple U. Parking Lot #10	1.9
Greater Gray's Ferry Estates Town Hall	0.7
G.W. Carver High School Addition	2.5
Multi Purpose Health Services Center	0.7
Wexford Science Center	0.5
Maria de los Santos	0.2
30th Street Switching Station	0.6
777 Lofts	2.0
934 - 950 North Third Street	0.1
South Philadelphia Athletic Super Site Sitework and Support Facilities	2.3

Project Name	Greened Acres
Family Dollar Store #117104	0.1
Angela Court II - St. Ignatius Nursing Home	0.8
Annenberg Public Policy Center	0.1
BCRC Asssociates	0.2
Beazer Homes - Proposed Residential Development	1.6
Booth Manor 2 Addition	0.7
BridgeView Court	0.7
C&C Poultry	4.5
Cintas Distribution Center	8.6
Commodore John Barry Elementary School	0.9
Edwin Forrest Primary Education Center	0.8
Fairmount Substation	1.2
Federal Reserve Bank of Phila. Receiving Annex	0.3
Front & Erie - Ronald McDonald House	0.5
General Kearny School Addition	0.3

Project Name	Greened Acres
Hess Gray's Ferry Avenue	0.6
Hope VI Ludlow Area Homeownership	0.5
Hunter School Homeownership	1.4
Lawton Elementary School Addition	1.2
LE 22 Condominiums	0.7
Shackamaxon Real Estate Development	0.4
National Museum of American Jewish History	0.5
New Foundations Charter School	2.5
Overbrook School for the Blind	1.8
Pasqualino Basilico (Proposed Garages)	0.3
Pennsylvania Convention Center Expansion	2.3
Philadelphia Residential Development Co.	0.1
Pilgrim Gardens	1.1
Pizza Hut/KFC	0.2
Preferred Freezer	1.6

Project Name	Greened Acres
Progress Plaza	3.7
Proposed Development	1.0
Reba Brown Senior Residence	2.1
Safeguard Storage, Inc.	0.6
Solis-Cohen Elementary School	2.0
24th and Brown St Townhomes	0.4
St. Joseph's University 54th Street Garage	1.1
Kentucky Fried Chicen/Taco Bell	0.2
Imhotep Charter School	0.2
Temple Fox School of Business	0.6
Temple Mini Arts Campus	1.1
Union Hill Home Ownership Project	1.1
Vaux School	1.3
Walnut Street Mixed Use	0.7
#1615 North 23rd Street	0.6

Project Name	Greened Acres
4839-4859 Lancaster Avenue	1.0
Around the Clock Home Health Care	0.5
Cecil B. Moore Homeownership Zone- Phase III-2	1.1
Cecil B. Moore Homeownership Zone- Phase III-3	0.8
Drexel University Recreation Center	0.8
Eye Institute	0.4
Gambrel Field at Whitehall Commons	0.1
Gambrel Park	1.5
Germantown Friends School Upper School Science Center Building	0.8
Guion S. Bluford Elementary School	1.4
HACE Life Center	0.5
Herron Playground	0.6
Howie's House	0.3
Lasalle College Site	10.6
McDonald's Restaurant Rebuild	0.5

Project Name	Greened Acres
McDonald's Rebuild	0.1
Mt. Tabor Senior Cyber Village	0.3
Powelton Green	0.4
Pradera 3/ Ludlow 5	1.5
Saint Joseph's University Fieldhouse Expansion	3.6
Simons Recreation Center	0.5
South Broad and Wolf Street	0.1
The Church of Christian Compassion	0.6
The Lutheran Seminary at Philadelphia	0.5
The Mansions at Bala	6.4
University of Pennsylvania Music Building	0.4
Warnock Phase I	2.1
Warnock Phase II	2.7
Washington Avenue, LP	1.0
West Philadelphia YMCA	0.0

Project Name	Greened Acres
Willard Elementary School	5.0
1600-24 North American Street	0.5
2.0 University Place	0.4
2116 Chestnut Street - Hillman Project	0.5
CVS - 401 Spring Garden St.	0.5
Barnes Foundation Art Center	3.5
Castor Avenue	0.0
Class of '62 Walkway	0.3
Community College of Philadelphia - Pavilion and Bonnell Buildings	2.3
Drexel University - Integrated Sciences Building	1.5
Drexel Dorms - Phase II	0.2
Weiss Pavilion at Franklin Field	0.3
Francisville East	0.7
Martin Luther King - IIC	0.6
Naval Square Phase II	5.8

Project Name	Greened Acres
New Kensington Capa High School	5.2
New Life Affordable Housing	0.5
New Life Affordable Housing, II	0.5
Clark Park - 'A' Park Improvement Plan	0.4
Proposed West Philadelphia High School	5.4
Roland Holroyd Science Center Addition and Renovation	0.2
Rotem USA Railcar Assembly and Test Facility	1.6
Schmidt's Brewery Redevelopment	4.4
Sheridan Street Housing	0.2
Strawberry Mansion Home Ownership Project - NE Corner of Cecil B. Moore & 32nd Street	0.4
Strawberry Mansion Home Ownership Project - SE Corner of Cecil B. Moore & 32nd Street	0.3
The Curtis Institute of Music	0.2
Walgreens	0.5
Woodland Walk 3700 Block Renovations	0.5
Global Charter School	1.8

Project Name	Greened Acres
Penn Park	3.9
IATSE Swanson Street	0.8
Presbytery Headquarters of Philadelphia	1.9
Dorazio Construction	0.4
Strawberry Mansion Home Ownership Dev. Parcel C+D	0.2
Strawberry Mansion Home Ownership Dev. Parcel H	0.3
Mantua Revitalization	3.6
Lawrence Court Homeownership Development	3.0
Sister Cities Park-Phase 1	0.2
New Haddington Health Center	0.3
Temple University International Apartments	0.9
TD Bank	1.1
2007 Freezer, Cooler, Dry Expansion	17.7
Philadelphia Family Court	0.3
Temple University- Geasy Field Resurfacing	1.5

Project Name	Greened Acres
Franklin Towne Charter Elementary School	4.1
PECO Energy Peltz Street 230-13kV Substation	2.8
Sister Cities Park-Phase 2	0.4
HELP Philadelphia Tract #1 and #2	3.7
Nicetown Court	0.4
Jannies Place	0.3
Prince of Peace Baptist Church	0.5
Cancer Treatment Center Parking Expansion	6.1
Hawthorne Park	0.3
Schuylkill Parks Connector Bridge	0.7
The Modules	0.4
WOLCS Building Addition	1.7
Penn Law School	0.4
Rodin Museum Garden & Landscape Rejuvenation	0.2
New Fire Engine 38	0.5

Project Name	Greened Acres
The Plymouth Hall Apartments	0.1
7149-51 Frankford Avenue	0.4
Parkside Bus Loop	0.1
Philly RORO (Savage Yard)	14.6
Congreso Education and Training Center	2.8
Paschall Village Phase 1C	3.3
Bridesburg Elementary School	1.1
PSDC - Broad & Federal	1.1
Paschall Village Phase 2C	2.2
St. Josephs University Learning Commons Project	1.0
Esperanza Health Center	1.1
1800 Lombard St	0.8
4109 Walnut St.	0.2
411 West Girard Ave	0.2
University of Pennsylvania Krishna P. Singh Center of Nanotechnology	0.7

Project Name	Greened Acres
Temple University Student High Rise	2.9
8828-8832 Frankford Avenue	1.2
3737 Science Center	0.3
Waterfront Square Parking Lot	3.1
Broad Street Food Market	0.9
PNK Warehouse	2.3
Hunting Park	0.1
Philly Live! - Phase B	2.2
CHOP ACC	2.6
Gest Lawn Residence Hall	1.1
Proposed Wawa- Roosevelt Blvd.	2.4
Architectural Building - Temple University	0.2
Drexel University Lebow College of Business	1.5
Dickinson Square Park	0.7
1940 Allegheny Ave	0.6

Project Name	Greened Acres
5526-48 Vine Street	0.5
Crease Townhomes	0.3
Northwood Academy Charter School	0.9
Early Childhood Center	0.5
Pleasant Playground	0.2
Dilworth Plaza Renovation	0.7
Philly Live - Phase C	3.4
Norris Apartments - Design Phase	2.1
AJILE Properties - Proposed Shopping Center	1.4
University of Pennsylvania - Shoemaker Green	1.4
Proposed Social Security Building & Parking Lot	1.6
Cancer Treatment Center - ICU Expansion	0.2
Locust Walk 3800 & 3900 Block Pavement Replacement Project	0.2
Convention Center Parking Facility	0.3
St. Marons Senior Housing	0.5

Project Name	Greened Acres
Karabots Pediatric Center	4.0
Hamilton Family Childrens Zoo	1.6
Fairmount Gardens	0.4
Montgomery Parking Garage, Temple University	2.8
Christian Street Townhomes	1.0
4240-52 Market Street	0.7
Central City Toyota	1.0
Samuel Fels High School Site Improvements	0.4
Home2 Suites by Hilton	0.2
Toll Residential Development	2.4
Diamond Green Student Housing	0.4
The Residences @ H3 Homeowners Association	0.9
Dollar General	0.3
Temple TOD	1.9
Drexel Chestnut Street Development	0.8

Project Name	Greened Acres
334-344 East Chelten Avenue	0.7
Bottom Dollar Food	2.7
Philadelphia Zoo - Zebra Garage	3.2
Proposed Commercial Development	3.7
West Philadelphia High School Athletic Field Renovations	0.0
JWS Development	1.8
33rd and Dauphin Bus Loop Improvements	0.1
Green Tree School	1.9
Penn Spruce Street Park	0.2
Temple University Science Education & Research Building	2.1
Nicetown Court II-Site 1	0.3
Nicetown Court II-Site 2	0.5
Nicetown Court II-Site 3	1.1
1900-1918 Geary Street	0.6
Southstar	0.8

Project Name	Greened Acres
Center for Educational Excellence	1.3
Building 26 HVAC Upgrade	0.1
Cancer Treatment Centers of America - OR Expansion	0.6
Spruce Street Senior Residences	0.1
1426-1430 Walnut Street	0.3
Rodeph Shalom Synagogue	0.7
Ingersoll Commons	0.9
412 North Front Street	1.2
Hunting Park - Football Field and Track	1.8
915 N.5th Street	0.8
Science and Technology Center II	1.6
Proposed Supermarket	1.0
Wissahickon Charter School	1.3
Senior Housing Building	0.4
Penn Presbyterian Medical Center	0.9

Project Name	Greened Acres
Sysco 2012 Facility Renovations	3.9
CIRA Chestnut Street Tower	2.1
701 W. Lehigh Avenue	4.7
Lincoln Financial Field Improvements	1.8
River Fields	3.3
9th Street Marketplace	4.6
Lancaster Square	1.3
Cobbs Creek Shopping Center	0.8
1901-19 Lombard Street	0.6
826-834 North 3rd Street	0.4
Halpern-Brewerytown	1.6
Cecil B. Moore Wellness Center	0.9
The Stables	1.2
Proposed Wendys Rebuild	0.9
Tacony Academy Charter School	2.1

Project Name	Greened Acres
HELP Philadelphia IV	1.8
23rd & Venango Bus Loop Reconstruction Project	0.4
1601 S. Christopher Columbus Blvd	0.9
Temple University Edberg Olson Synthetic Turf Replacement Project	4.2
Master Substation Expansion	0.6
St. Joes Prep Athletic Field Rehabilitation	5.6
Family Dollar- G Street	1.1
Drexel Vidas Field	2.6
Envirowaste Recycling Company	2.0
Vernon Park	0.6
Broad and Norris Park at Temple University	0.4
Wal-Mart Expansion #2141	8.0
Total	**423.4**

Appendix B

Pilot Program Final Report

Green City, Clean Waters

Pilot Program Final Report

Submitted to the Commonwealth of Pennsylvania

Department of Environmental Protection

As an Appendix to the Evaluation and Adaptation Plan

By the Philadelphia Water Department

October 30, 2016

Table of Contents

List of Tables

1.0 Introduction

(No tables within this section.)

2.0 Pilot Program Analysis Design

(No tables within this section.)

3.0 Performance

4.0 Construction Cost

(No tables within this section.)

5.0 Maintenance

6.0 Ease of Implementation

7.0 Community Perception

(No tables within this section.)

8.0 Pilot Program Summary and Conclusions

(No tables within this section.)

List of Figures

1.0 Introduction

(No figures within this section)

2.0 Pilot Program Analysis Design

3.0 Performance

4.0 Construction Cost

5.0 Maintenance

6.0 Ease of Implementation

7.0 Community Perception

8.0 Pilot Program Summary and Conclusions

Appendices

Glossary of Acronyms

ANOVA	Analysis of Variance
ASTM	American Society of Testing and Materials
CDF	Cumulative Distribution Function
CFM	Cubic Feet per Minute
CSO	Combined Sewer Overflow
DCIA	Directly Connected Impervious Area
CCI	Construction Cost Index
GARR	Gage Adjusted Radar Rainfall
GLM	Generalized Linear Model
GSI	Green Stormwater Infrastructure
GSIM	Green Stormwater Infrastructure Monitoring
IDF	Intensity Distribution Frequency
IET	Inter-Event Time
LTCPU	Long Term Control Plan Update
NOAA	National Oceanic and Atmospheric Administration
PADEP	Commonwealth of Pennsylvania Department of Environmental Protection
PWD	Philadelphia Water Department
QA	Quality Assured
RG	Rain Gage
ROW	Right of Way
SMP	Stormwater Management Practice
SRT	Simulated Runoff Tests
SWWPCP	Southwest Water Pollution Control Plant
USD	United States Dollar
USGS	United States Geological Survey

1.0 Introduction

On June 1, 2011, the Commonwealth of Pennsylvania Department of Environmental Protection (PADEP) and the City of Philadelphia entered into a Consent Order and Agreement that included approval of the City's Combined Sewer Overflow Long Term Control Plan Update (LTCPU) and its supplements, as amended through negotiations. The approved LTCPU and its supplements represent the City of Philadelphia's commitment towards meeting regulatory obligations. The Pilot Program was created by the Philadelphia Water Department (PWD) to evaluate the first five years of the program, a period of growth, evolution, and experimentation. This report documents the results of this evaluation. Lessons learned from the Pilot Program have improved designs; informed understanding of total stormwater management area potential; enhanced design, construction, and maintenance procedures; and refined program cost estimates.

The Pilot Program was designed to test the feasibility and measure the effectiveness of Green Stormwater Infrastructure (GSI) under the full range of potential conditions. Six goals were identified:

1. Demonstrate the feasibility of GSI
2. Assess GSI opportunity
3. Assess GSI cost effectiveness
4. Confirm GSI functions
5. Define maintenance requirements
6. Support design standard development

To accomplish these goals, the Pilot Program executed the following steps:

Step 1: Developed a Set of "Pilot Projects"

As described in Section 3.1.1.2 of the *Implementation and Adaptive Management Plan* and 4.6.1 of the *Comprehensive Monitoring Plan*, pilot projects are defined as GSI projects designed, constructed, and monitored to provide information for improved design and program implementation.

Step 2: Identified Relevant Project Variables

GSI projects take many forms, are located in a variety of settings, and consist of different technologies and materials. This complex mix of characteristics contributes to differences in performance, cost, ease of implementation, maintenance needs, and community perception among projects. However, it was hypothesized at the beginning of the program that there might be a subset of these characteristics that is most important in explaining the outcome of a given project. A key mission of the Pilot Program has been to attempt to identify this subset of variables and to use it to inform future choices on how projects are sited, designed, implemented, and maintained. In order to make this objective assessment, it was necessary to develop a standardized description of the complex variables present in each project, thereby enabling comparisons of these variables across projects. To assess these characteristics contributing to the outcome of GSI projects, 24 descriptive variables (e.g., Land Use Type) were identified, each with a set of levels to be evaluated for the relative importance of their contributions (e.g., schools, parks, streets). Variables are conditions that could affect the ability of GSI to be implemented, its ability to function as designed, or its ability to maintain its functionality over time. These variables include:

- Land Use Type
- Drainage Area Characteristics
- GSI System Type
- GSI Design Elements
  - Inlet Type
  - System Surface/Subsurface Status
  - Loading Ratio
  - Static Storage Volume
  - Vegetation Status
  - Pretreatment Type
  - Inflow Type
  - Street Crossing Type
  - Rooftop Disconnection
  - Domed Riser Depth
  - Energy Dissipator Type
- Materials
  - Primary Storage Materials
  - Permeable Pavement Type
  - Soil Type
- Physical Conditions
  - Physiographic Province
  - Tested Soil Infiltration Rate
  - Street Slope
- Policy/Partnerships
- Implementation Strategy
- GSI Visibility
- GSI Location Ownership

Each item in this list was labeled as a "Variable" consisting of several "Levels." For example, the Land Use Type Variable consists of Levels including schools, streets, parks, etc. The full list of Pilot Variables, Levels, and descriptions of each are located in Appendix A. Applicable Levels of the Variables were assigned to each pilot project. It was the intent to select projects to evaluate as many of the Variables and Levels as possible, and each pilot project is useful in testing multiple Variables.

Not every GSI project built by PWD was selected as a pilot project. Pilot projects were identified for their applicability to Pilot Program Variables and for other factors such as quality of available information, eliminating redundancy, and availability of monitoring locations.

Step 3: Evaluated the Impact of the Project Variables on Performance

Project Variables were evaluated for their effect on the following five performance criteria: hydrologic performance, construction cost, maintenance, ease of implementation, and community perception.

The results of these evaluations are described in this document, which is organized into the following eight sections:

Section 1, Introduction, provides an introduction to the report contents, a summary of the report intent, and a description of the Pilot Program.

Section 2, Pilot Program Analysis Design, provides a summary of the Pilot Program methods, including a description of the Framework and analysis.

Section 3, Performance, describes the data acquisition methods, monitoring procedures, quality control and assurance, and analysis techniques for evaluating GSI practice performance.

Section 4, Construction Cost, describes the data acquisition methods and analysis techniques for evaluating construction cost data.

Section 5, Maintenance, describes the data acquisition methods and analysis techniques for evaluating maintenance data.

Section 6, Ease of Implementation, describes the data acquisition methods and analysis techniques for evaluating ease of implementation data.

Section 7, Community Perception, describes the data acquisition methods and analysis techniques for evaluating community perception data.

Section 8, Conclusions, summarizes the findings of the Pilot Program analyses and provides a proof of concept of how GSI can be implemented more effectively, efficiently, and appropriately in support of PWD's regulatory obligations.

2.0 Pilot Program Analysis Design

2.1 Pilot Program Framework

This section describes the experimental design of the Pilot Program Framework (Framework). All of the Pilot Variables were grouped according to the categories listed in Section 1 (Introduction) so that they could be more easily tested against each other. A category was labeled as a "Variable" (e.g., Land Use Type) consisting of several "Levels" (e.g., schools, parks, streets). A list of the Variables and Levels, with definitions, can be seen in Appendix A (Pilot Variable Framework).

Pilot projects and their assigned Variables and Levels were organized in a matrix that could be used in statistical analyses. Gaps in the variable list were identified, which were used to guide designs on new project initiations. Although not every Variable and Level was met with a project constructed in the first five years of the program, a wide range of Green Stormwater Infrastructure (GSI) designs, locations, materials, implementation strategies, physical settings, and other characteristics were represented by the end of the initial five-year Pilot Program. Appendix A (Pilot Variable Framework) also shows the number of GSI systems that met each variable and level.

The Framework was created to evaluate each of the Variables and Levels associated with the wide range of projects using a variety of data sources and analysis methods. For each variable, the following questions were asked:

- Does [VARIABLE] affect performance?
- Does [VARIABLE] affect cost?
- Does [VARIABLE] affect maintenance?
- Does [VARIABLE] affect ease of implementation?
- Does [VARIABLE] affect community perception?

In order to answer each of the five main questions, different types of data were collected from the implementation, post-construction maintenance, and monitoring of GSI. The data were formulated into various performance metrics to be used in a statistical analysis, testing the Levels within a Variable against each other to see if there was a noticeable impact. If a correlation was observed from the results of the statistical analysis, further investigations were conducted to determine if there is a causal link between the Variable and observed trend in the performance metrics. Based on the results of these analyses, conclusions could be drawn to potentially inform and improve the implementation of GSI.

2.2 Statistical Analysis

The program is continuously producing a large, and growing, volume of data on GSI. It is challenging to find ways to analyze all of these data using traditional engineering methods. The Pilot Program has developed a two-step process for managing these data. The first step uses statistical algorithms to identify significant relationships and trends in the data. This step eliminates a large amount of data that do not contain significant trends, and reduces a large unmanageable problem to a smaller manageable one. Some of the relationships and trends identified as potentially significant by the automated algorithms will turn out to be significant in an engineering sense, while others may not. Statistical screening does not replace engineering analysis, but it reduces the effort required to perform engineering analysis. Once the statistical tool identifies Pilot Variables of interest, the second step involves the engineering team analyzing the results to try to identify physical explanations for the behavior that can be translated into conclusions and actionable recommendations.

What follows is a summary of the statistical concepts and tests involved. For each of the Pilot Variables identified as defined in Appendix A (Pilot Variable Framework), statistical methodologies were applied to evaluate performance metrics.

P-Value

As with any statistical testing approach, a “Null Hypothesis” is defined. The Null Hypothesis states that a significant relationship cannot be drawn between the Pilot Variables and the performance metrics. Thus, the weight falls on the “Alternative Hypothesis” to prove otherwise. P-value will be used to determine the significance between the Pilot Variables and the performance metrics. P-value is the probability of obtaining the study results with the Null Hypothesis. That is, it represents the likelihood that a result is achieved by chance. The lower the p-value, the lower the likelihood that the study results will be achieved by the Null Hypothesis; and therefore, the more likely the Alternate Hypothesis is true. Within this analysis, lower p-values indicate that there is likely an association between the Pilot Variables and the performance metrics, and higher p-values indicate that there is likely not a relationship.

Confidence Interval

The Confidence Interval consists of a range of values that is often set by the user or determined by the spread of the data values, within which a defined percentage of the sample data is likely to fall.

Data Distribution

The key to a good data analysis is to identify the type of distribution for a given set of data. Data is compared against z-score values using Quantile-Quantile (Q-Q) plots. The goal is to check for normally distributed data. A straight line in a Q-Q plot determines that the given data is normally distributed. Real world data are almost never as well behaved as would be desired. Most data do not meet the criteria needed for the distribution to fit. Since normally distributed data are easier to work with, the best approach is to transform the data to logarithmic values and test the data against z-score values. Alternatively, moments of data distribution (mean, standard deviation, skewness and kurtosis), or the Shapiro Wilk Test, can also be computed for testing the distribution for normality. As an example, a sample dataset shown in Figure 2-1 was analyzed to assess its nature of distribution using Q-Q plots.

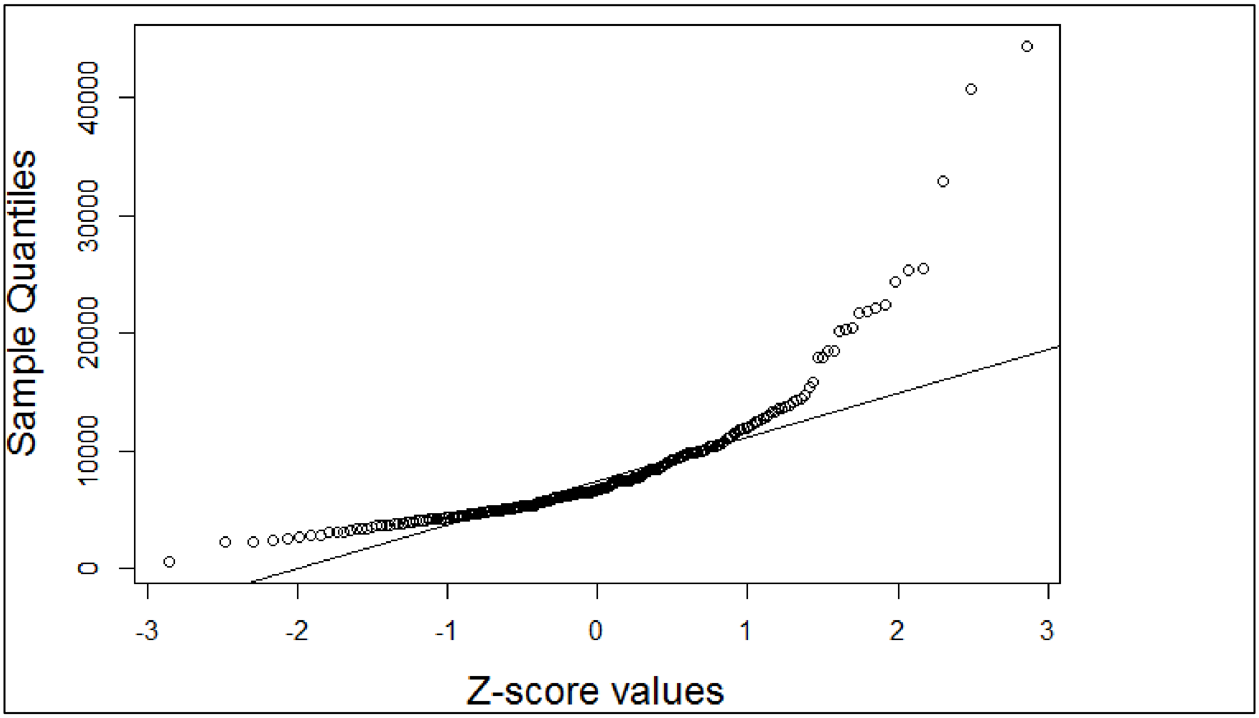


Figure 2-1: Q-Q Plots Showing Data Distribution for Sample Data

Figure 2-1 indicates that data is not normally distributed. As mentioned previously, the next step would be to check if the data is log-normally distributed. Figure 2-2 shows log-normally transformed data compared against the z-score values. This graph shows that the data is log-normally distributed.

For this analysis, Q-Q plots were used to determine if the data distribution is normal or log-normal. If the data appeared to be a classic log-normal, Analysis of Variance (ANOVA) was applied to the log-transformed data. If otherwise (data distribution is not classic log-normal), it is always better to run multiple statistical approaches to compare the consistency of the final results. In that case, statistical tests such as Generalized Linear Model (GLM) fit ANOVA and Kruskal-Wallis Test were used to obtain the p-value in order to determine the significance of the relationship between the performance metrics and Pilot Variables. A non-parametric equivalent, Tukey Honestly Significance Difference (Tukey HSD) Post Hoc Test was run to confirm where the differences in the levels occurred for significant test results. Boxplots were used to graphically represent the trends in these levels. (Figure 2-3).

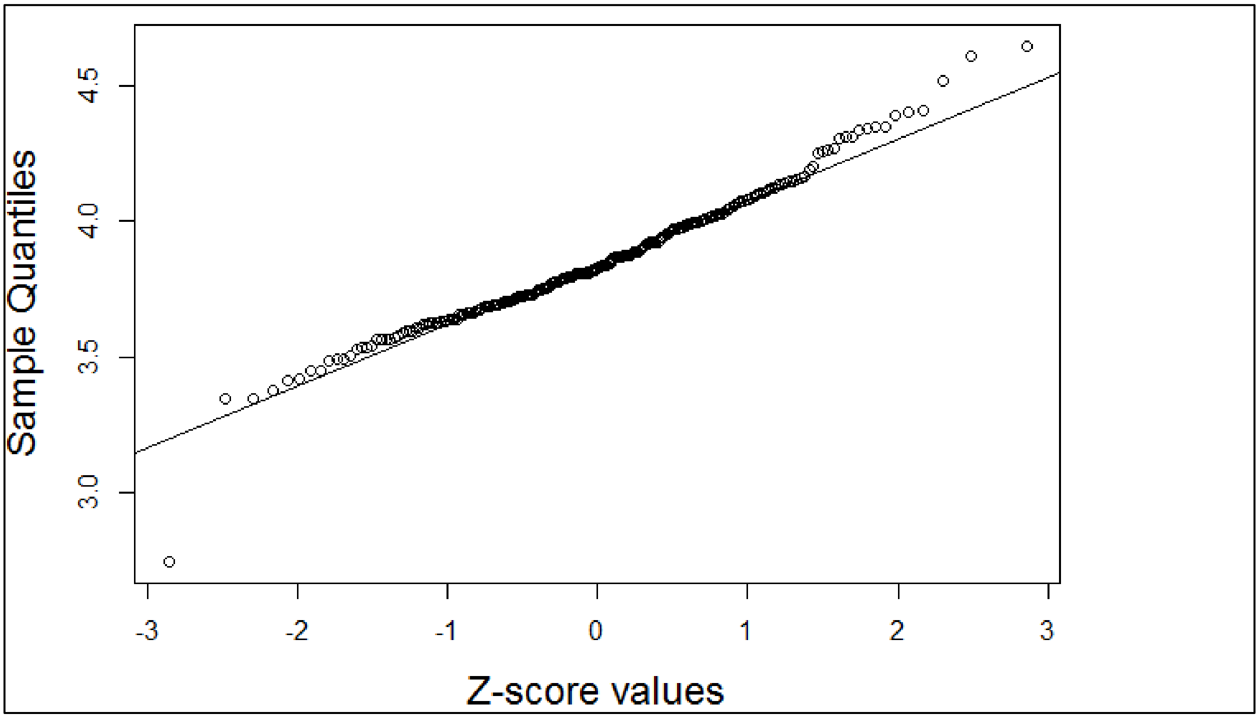


Figure 2-2: Q-Q Plot Showing Data Distribution for Log-Transformed Sample Data

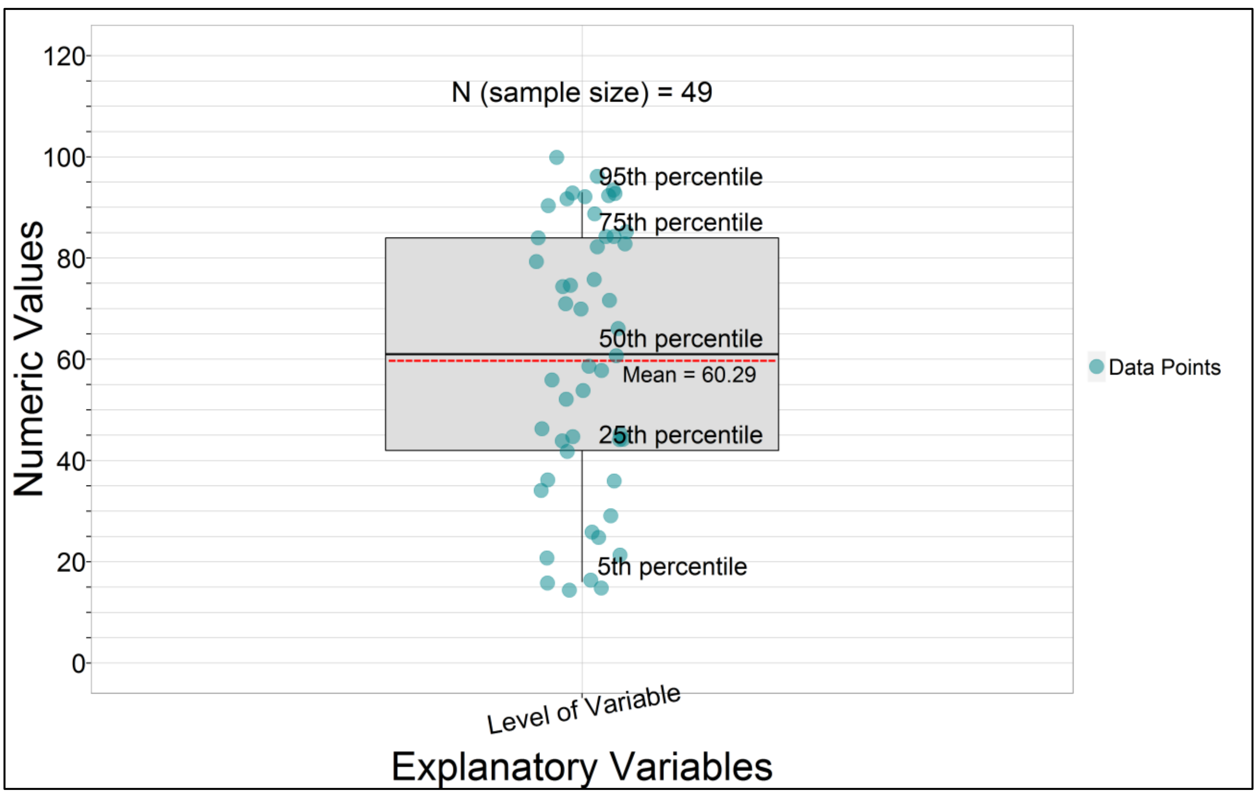


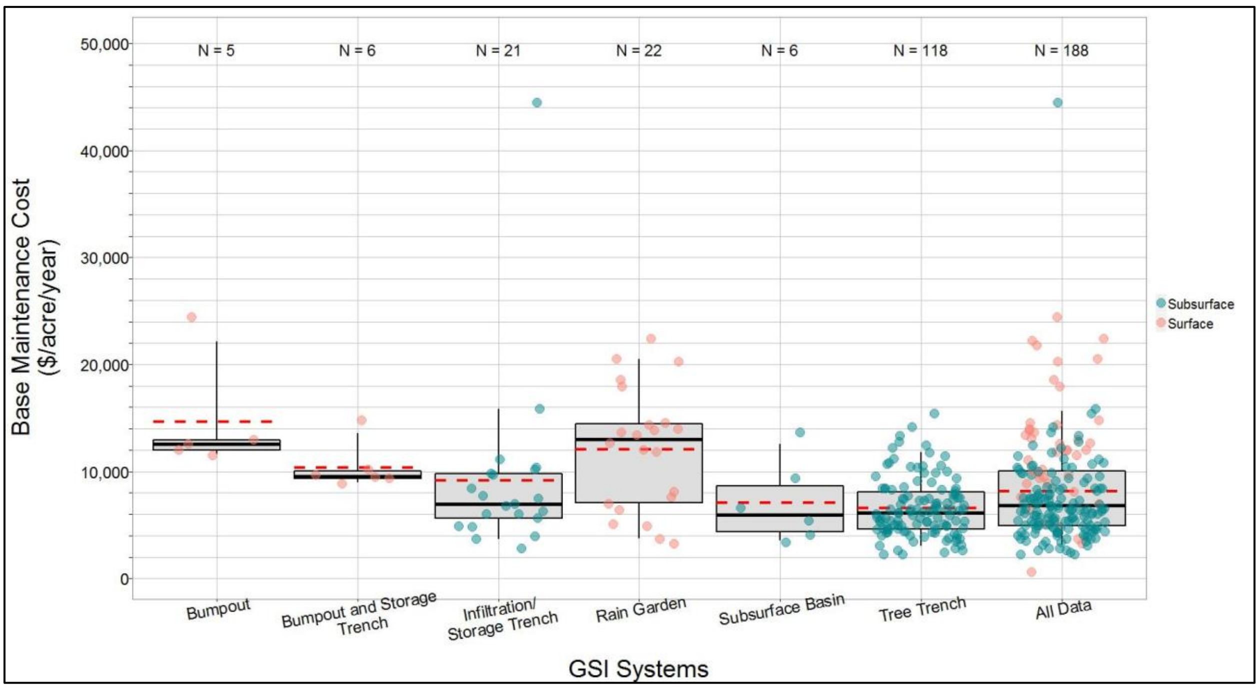
Figure 2-3: Example Box Plot

An ANOVA test is a parametric test and has two main assumptions. These include:

- The dependent variables or the y-axis variable are normally distributed.
- The groups have approximately equal variances.

As mentioned previously, real time data are seldom normally distributed. In that case, ANOVA will be applied to a log-transformed data that better fits the above assumptions. Where applicable, ANOVA on Generalized Linear Model (GLM) fit data was also used. A GLM fit model provides the flexibility to use parametric tests such as ANOVA with an option of using non-normally distributed data. The Kruskal-Wallis Test, an alternative non-parametric test to ANOVA, was also performed to compare p-values.

For a given value of significance level (alpha value), say 0.05 (an arbitrary value that is found in most studies), a p-value of less than 0.05 indicates that the probability of obtaining results by chance is very low, that the Null Hypothesis can be rejected, and that there is likely an association between the performance metrics and the Pilot Variables. Figure 2-4 shows p-values using ANOVA on log transformed data and the Kruskal Wallis Test, and boxplots of GSI surface maintenance data for annual average cost compared against various GSI system types. Lower and upper whiskers represent the 5th and the 95th percentile respectively. The lower, middle and upper hinges of the boxes represent the 25th, 50th and 75th percentiles respectively.



Pilot Variable	p-value for log transformed data - ANOVA	p-value using Kruskal Wallis Test
GSI Systems	8.31E-08	1.96E-06

Figure 2-4: Boxplot for Annual Average Maintenance Cost per Acre of Drainage Area as Performance Metrics and GSI System Type as the Pilot Variable, with Corresponding P-Values

Calculation of Error

Statistical approaches cannot eliminate uncertainty, but they can quantify uncertainty through the calculation of "Type 1 Errors" (Alpha value) and "Type 2 Errors" (Beta Value). A Type 1 Error occurs when a Null Hypothesis is rejected when it is, in fact, true (False Positive). A Type 2 Error occurs when a Null Hypothesis is accepted when it is, in fact, false (False Negative). Alpha and Beta values are ideally kept very small. The goal is to prevent false positives in order to minimize the time spent doing engineering analysis on ultimately unimportant data. This is indicated by lower Type 1 Errors. Conventional alpha values are always between 0.01 and 0.1. Thus, with hypothesis testing, the study results cannot be proven or disproven. However, the analysis does have the power to reject the Null Hypothesis. This by default means accepting the Alternative Hypothesis. If by any means the Null Hypothesis is not rejected due to not enough evidence, then it simply has to be accepted.

All of the identified performance metrics presented in this report were compared against the Pilot Variables using the statistical methodologies described in this section. Due to the availability of different types of data, the only questions that were able to be analyzed with this methodology were how Variables affect hydrologic performance, construction cost, and maintenance. Applying statistical approaches to ease and implementation and community perception data was not feasible, and those questions were analyzed using different methods described in Sections 6 (Ease of Implementation) and Section 7 (Community Perception), respectively. The performance metrics tested in the statistical analysis include:

- Infiltration rates
  - Observed post-construction infiltration rate
- Draindown time
  - Estimated recession duration for continuous water level data
  - Estimated recession duration for simulated runoff tests
- Construction cost per acre of directly connected impervious area (DCIA)
- Maintenance costs
  - Annual average maintenance cost per acre of DCIA, system footprint, and vegetated footprint
  - Total volume of material removed per acre of DCIA, system footprint, and vegetated footprint

2.3 Engineering System Analysis

After the statistical screening identified potentially significant Variables that show trends in the performance metrics, further analysis was conducted to distinguish real positives from false positives. Using an understanding of GSI system design and hydrology and hydraulics, the analysis is intended to identify possible physical explanations for the observed system behavior. Additional data analyses were conducted to back up the findings of the statistical screening, including rainfall analysis, geotechnical analysis, pre- and post-construction infiltration rate analysis, water budget analysis, and peer city and academic research.

2.4 Additional Analyses and Design Support

In addition to the Framework analysis, the objectives of the Pilot Program are to gather data, perform experiments, conduct analyses, initiate or study projects to solve implementation challenges, draw conclusions, and make recommendations to Office of Watersheds units, establishing a feedback loop that ultimately leads to faster, greener, and cheaper GSI in support of the program goals (Figure 2-5).

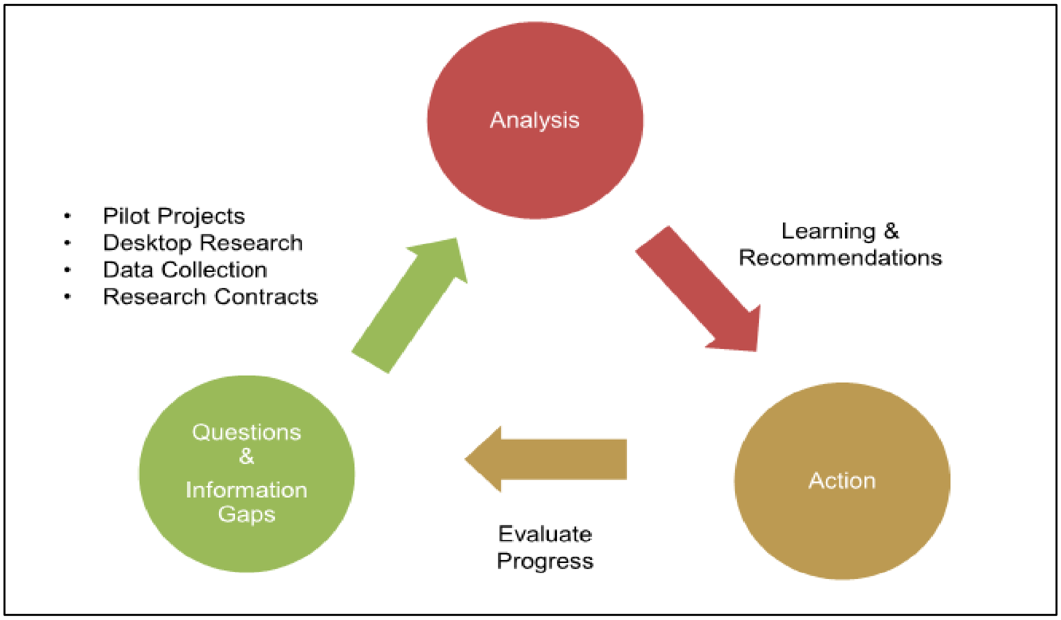


Figure 2-5: Data Collection and Feedback Loop

Through this process, the Pilot Program has provided feedback to the various groups within Office of Watersheds based on the findings of various analyses and research efforts. Many of the recommendations that were made have been incorporated into practice through updates to the *GSI Design Guidelines and Requirements* and *GSI Master Specifications*, changes in design philosophy, and initiations of new projects.

3.0 Performance

This section describes the data acquisition methods and analysis techniques for evaluating the hydrologic and hydraulic performance of monitored Green Stormwater Infrastructure (GSI) systems. In addition to attempting to determine if there is a causal relationship between the Pilot Variables and performance, several other analyses were conducted to demonstrate that PWD's GSI systems are performing as expected or better than expected. These analyses include the estimation of hydrologic water budgets, inlet testing, surface infiltration testing, comparison of pre-construction and post-construction infiltration rates, and the assessment of the number of system overflows, percentage of storage capacity utilized during rain events, and system draindown time.

3.1 Data Collection

3.1.1 GSI Performance Monitoring: Continuous Water Level Data

Proposed methods for performance monitoring were outlined in both the draft *Comprehensive Monitoring* Plan submitted December 1, 2012 and in a comment response sent to Pennsylvania Department of Environmental Protection (PADEP) and the United States Environmental Protection Agency on July 31, 2013. A revised *Comprehensive Monitoring Plan* was submitted on January 10, 2014 and approved by PADEP on May 28, 2014. Please refer to the *Comprehensive Monitoring Plan* for an outline of the methods used.

Continuous water level and storage volume monitoring of GSI systems is the primary way that PWD is evaluating hydrologic performance. As of December 31st, 2015, 63 HOBO U20-001-04 and U20L-004 water level loggers (Onset Computer Corp, Bourne, MA) have been deployed in 46 GSI systems (Tables 3-1 and 3-2; Figure 3-1). The number of water level sensors is greater than the number of GSI systems because some systems consist of multiple hydraulically connected stormwater management practices (SMPs) such as bumpouts, planters, or infiltration trenches, and some SMPs have multiple observation wells. Additionally, 15 barometric pressure sensors were also deployed throughout the City to provide compensation for changes in barometric pressure. Each barometric sensor can provide data for multiple water level loggers. A one kilometer radius is the maximum distance used between a barometric sensor and water level loggers deployed in GSI system observation wells.

The water level sensors sample data every 5 minutes, and these data are manually collected every 75 days when the sensor's memory is full. The same sensor is then redeployed in the system. The sensor samples the temperature and pressure within the observation well, which is converted to water level by comparison with the barometric sensor.

Table 3-1: Summary of Sensors Used

Sensor Type	Number Currently Deployed	Average Number of Days Deployed
Barometric Pressure Sensor	15	1017
Water Level Sensor	63	1015

Table 3-2: Summary of GSI Systems Monitored

System Type	Number of Monitored Systems
Tree Trench	21
Planter/ Planter Trench	11
Bumpout/ Bumpout Trench	4
Rain Garden	3
Stormwater Basin	0
Infiltration/Storage Trench	5
Pervious Paving*	5
Swale	0
Green Roof	0
Other	0
Total	**49**
Total (continuous water level monitoring only)	**46**

*Three of these systems do not have continuous water level monitoring, just surface infiltration testing.

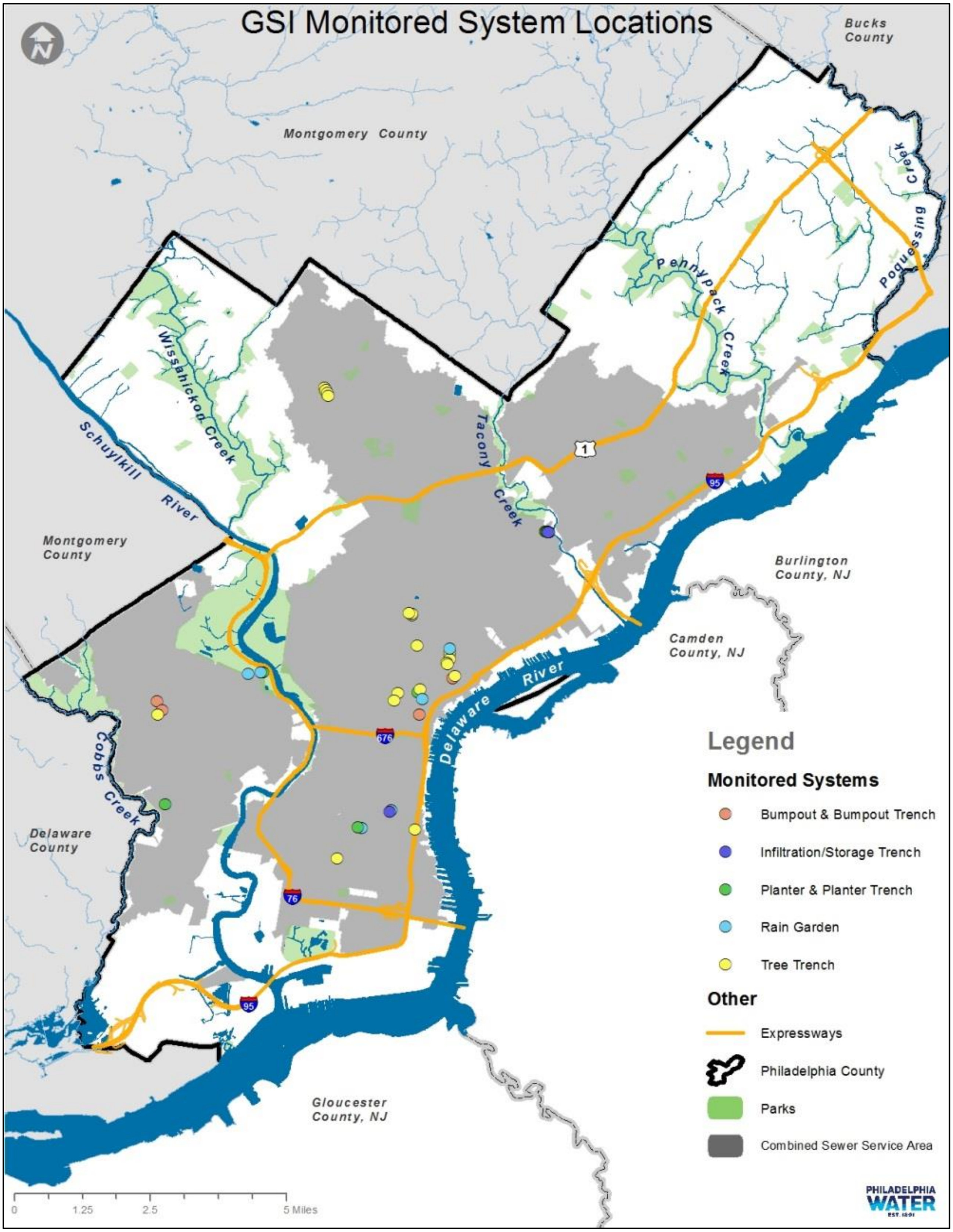


Figure 3-1: Map of Monitored GSI Pilot Systems

3.1.2 GSI Performance Testing: Simulated Runoff Tests

In addition to continuous water level monitoring, PWD performs simulated runoff tests on the monitored GSI systems. The primary advantage of a simulated runoff test over the continuous water level monitoring of real storms is that the inflow can be measured exactly. This eliminates uncertainty associated with the runoff estimates from each storm. A W-1250 Sensus Water Meter Tester is used for measuring flow applied to a GSI system during simulated runoff tests. This water meter is capable of estimating flows from 0.04 cubic feet per minute (CFM) to 167 CFM. Simulated runoff tests have been performed for each GSI system monitored in the GSI performance monitoring Section 3.1.1 (GSI Performance Monitoring: Continuous Water Level Data).

Qualitative inlet bypass tests were also performed on every system to check that inlets were performing as designed. Water was pumped past an inlet at low flow, and the approximate percentage of bypass was recorded. If a system had any bypass at low flows, an asphalt patch was used to divert flow into the inlet. This system was then retested to ensure 100% capture efficiency.

3.1.3 System Characterization

In order to evaluate the hydrologic performance of GSI systems, the system dimensions, volumes, and water level sensor location must be accurate. The typical tree trench section is shown in Figure 3-2. The engineering plans for each project were used with assumed porosity values consistent with PWD's *Green Stormwater Infrastructure Design Requirements and Guidelines Packet* to determine the storage volume in each section of a system, creating a stage-storage curve. The dimensions from the plans were verified with field surveys of the inlets, slow release orifice, and observation well invert. Systems designed and built in the early stages of GSI implementation had a variety of observation well configurations, and the depth of the observation well below the system (sump depth) was not always reflective of the plans. The sump depth was determined from looking at inflections in the monitoring data; a sharp decrease in water level indicates the water has dropped below the bottom of storage.

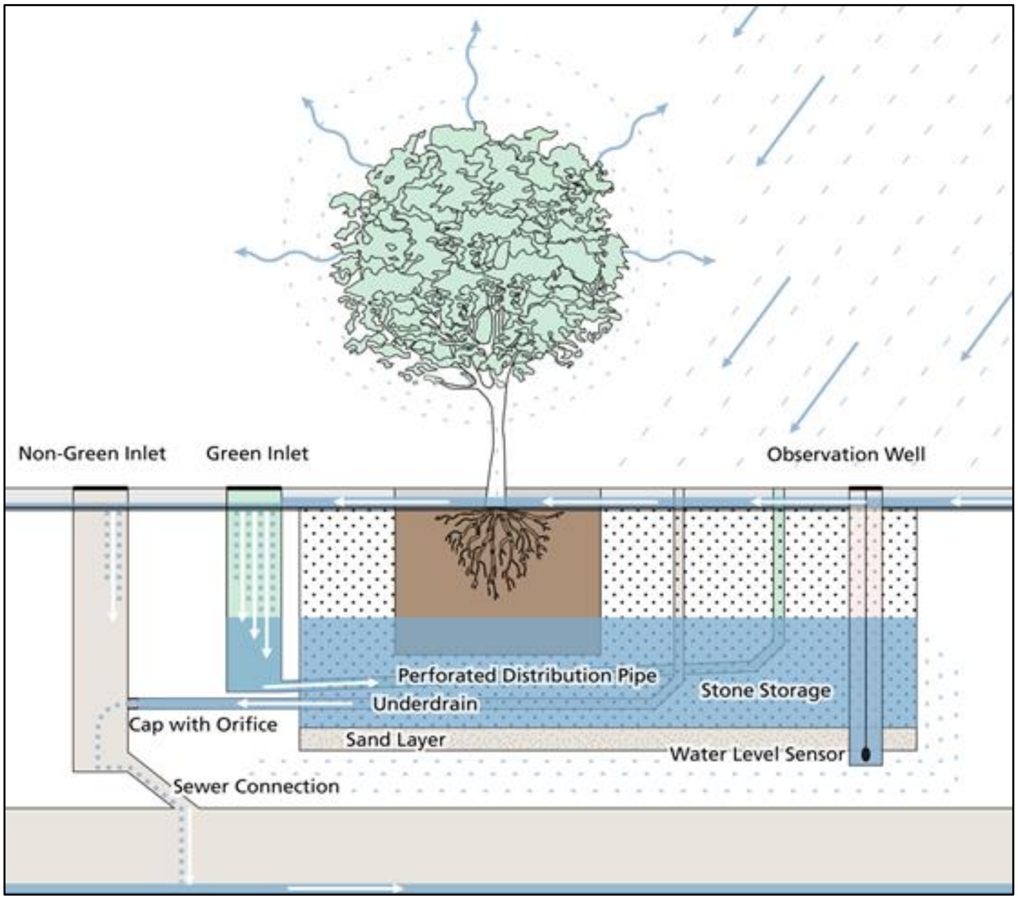


Figure 3-2: Typical Tree Trench Section View with Green Inlet, Slow Release Orifice, and Water Level Sensor

3.1.4 Hydrologic Data Collection

Gage adjusted radar rainfall (GARR) data is obtained from Vieux, Inc. and used in conjunction with the continuous water level data to develop performance metrics. Additional precipitation metrics, including snowfall, snowpack and daily temperature, are taken from the National Oceanic and Atmospheric Administration (NOAA) databases. Radar data is produced by the National Weather Service Next Generation Radar system, divided into a 1x1 km Cartesian grid and processed into 15 minute intervals. A total of 51 rain gages (35 owned by PWD, 10 from United States Geological Survey (USGS) and 6 from the National Weather Service (NWS) Automated Surface Observing System stations) were used to adjust the radar rainfall. Both datasets are reviewed manually by Vieux, and atypical radar data and inconsistent rain gage data are removed. Figure 3-3 shows the location of PWD's rain gages, radar rainfall grid.

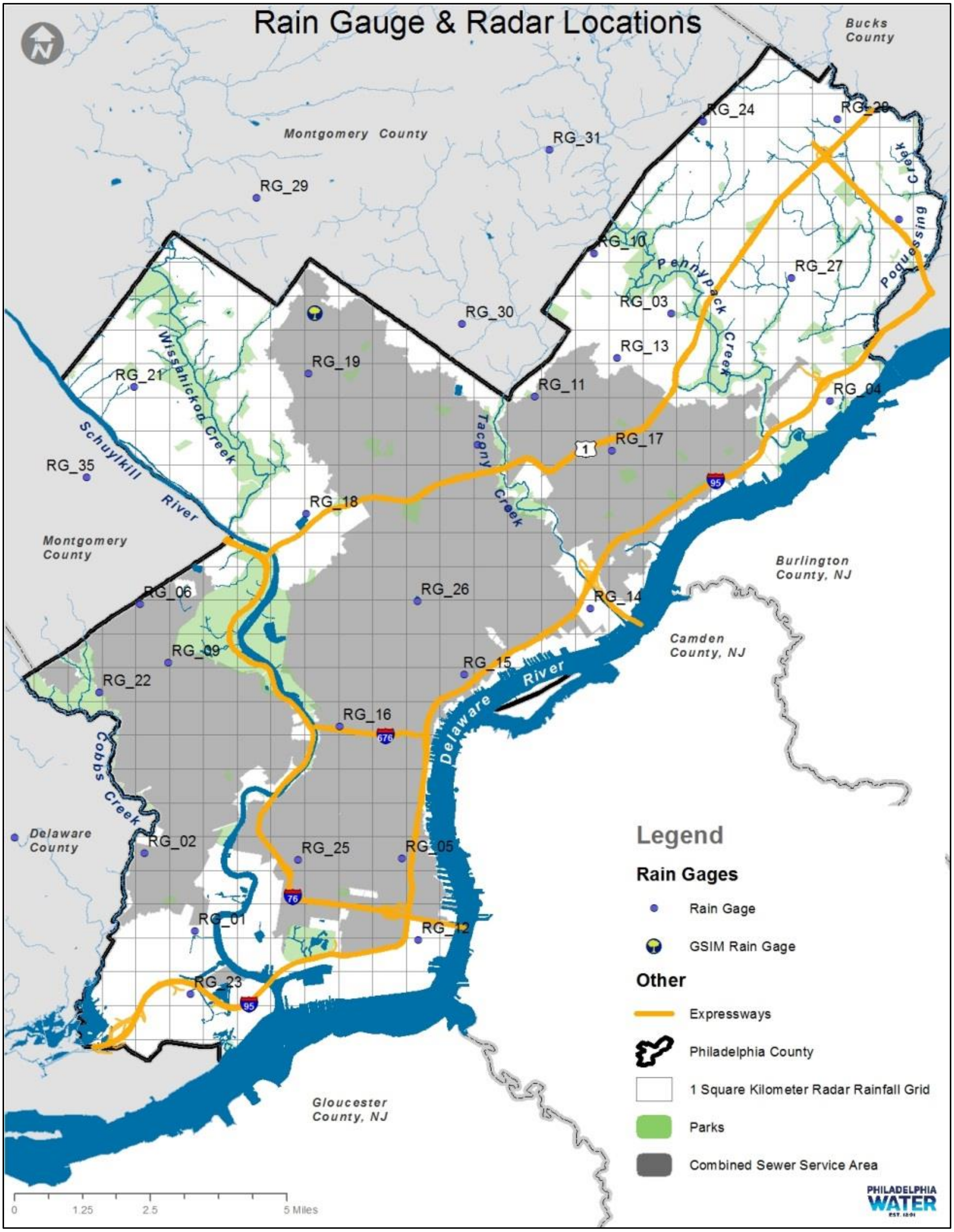


Figure 3-3: PWD Owned Rain Gage Locations

3.1.5 Geotechnical Data

Geotechnical testing is conducted on nearly all GSI projects in both the public and private sector, including soil boring and characterization and infiltration testing. Geologic borings are typically collected to a depth of 20 feet within the footprint of each GSI system following American Society of Testing and Materials (ASTM) D1586-11 and D6151-08. The advantages of sampling to this depth are to fully understand the underlying geology and determine if there are sediments at depth which are better suited for infiltration. In addition, sampling to this depth allows for a better understanding of the depth to the water table. The locations and results of a subset of geologic boring tests are included in Figure 3-4.

Infiltration testing is conducted using a double ring infiltrometer (ASTM D3385-09) or borehole infiltration testing methods. The preferred approach is the double ring infiltrometer at the bottom of a test pit, as it reduces the effect of lateral infiltration as well as allowing for the inspection of the strata within the test pit. However, excavating a test pit is not feasible in most areas of Philadelphia and borehole infiltration testing is the only alternative.

Historically, borehole infiltration testing was conducted following the procedure outlined in the *Pennsylvania Stormwater Best Management Practices Manual* (PADEP, 2006). This method involves a falling head test conducted in an unlined, open borehole. Therefore, infiltration is occurring through the sides and the bottom of the hole. To account for infiltration through the sides of the hole, the observed rate is adjusted by a reduction factor. This method assumes a uniform soil because the reduction factor is an area adjustment only and does not account for sediment heterogeneity. In addition, the method specifies a minimum of 6-inches of water be used. If a greater depth of water is used for the test, the infiltration rate will be elevated due to the head applied to the system, as compared to a test run with only 6-inches of water.

Estimating infiltration rates is critical to understanding the functioning of GSI. Results from these tests are typically documented in geotechnical reports. In order to gain a better understanding of the geotechnical conditions throughout Philadelphia, data from these reports were extracted and aggregated into a single database. These data were used to create maps to determine trends in infiltration capacity or soil types, as well as to inform inputs to the Hydrologic and Hydraulic Stormwater Management Model (SWMM5). A summary of the infiltration data collected is shown in Table 3-3, followed by a map showing infiltration testing (Figure 3-5).

Table 3-3: Infiltration Tests by Program Type

Program	Number of Sites	Number of Infiltration Tests
Public	293	1,416
Private	287	978
Total	580	2,394

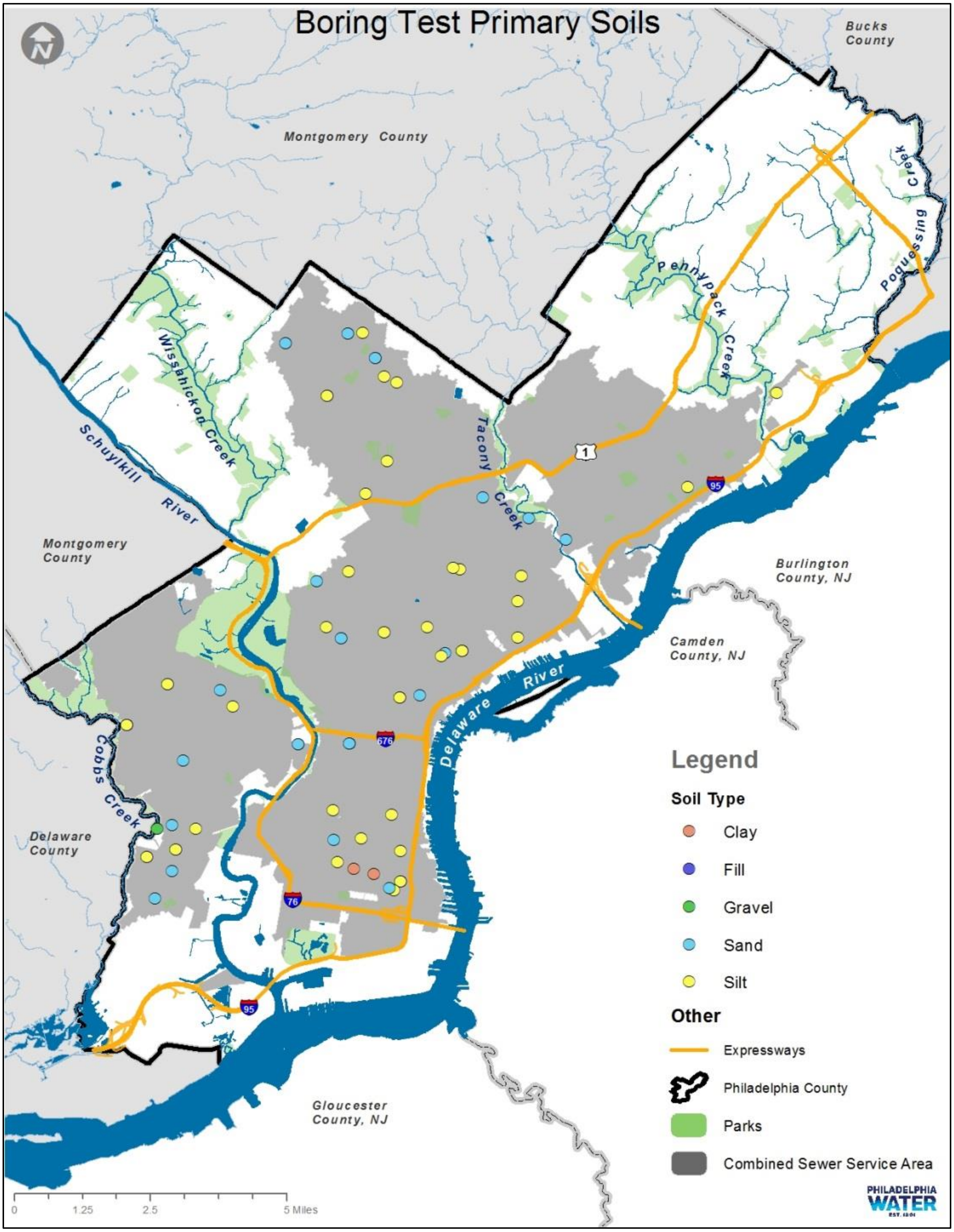


Figure 3-4: Map of Geological Boring Tests

Table 3-4: Permeable Pavement Location Name and Type

Location	Permeable Pavement Type
Percy Street	Permeable Asphalt
McMahon Street	Permeable Concrete
Mill Creek Playground	Permeable Asphalt
Herron Playground	Permeable Asphalt
Southwest Treatment Plant	Permeable Concrete, Permeable Paver Blocks, Stormcrete, Stamped Permeable Concrete, Pave-Drain

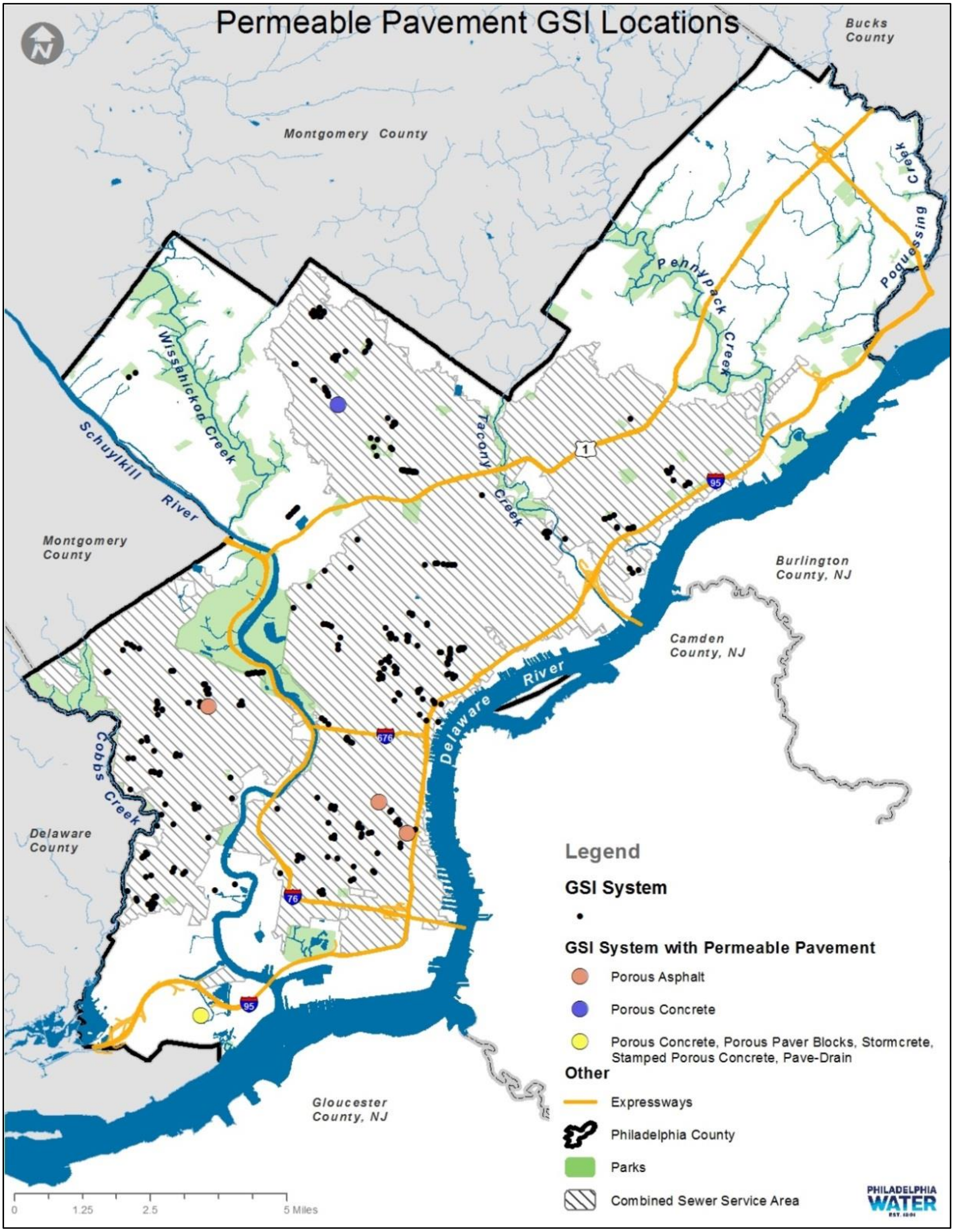


Figure 3-6: Permeable Pavement Infiltration Locations

3.1.7 Groundwater Monitoring

As stormwater infiltrates, it will continue to migrate through the vadose zone until the water table is reached. GSI adds recharge to areas at higher rates than under previous conditions, therefore the water table will rise when the infiltrated stormwater reaches it. While this phenomenon is transient in that the water table will recover to pre-storm elevations after a period of time, the amount of water table mounding is being evaluated to understand the magnitude, both vertical and areal, of groundwater mounding in order to provide guidance on potential impacts to underground infrastructure as well as siting requirements.

Groundwater is being monitored at 6 sites. At 4 of the sites, a transect of groundwater monitoring wells have been installed to monitor groundwater mounding at three distances away from the GSI. An example of results is shown in Figure 3-7 for the rain garden installed at Bridesburg Recreation Center, where groundwater wells are installed 1 foot, 10 feet, and 15 feet from the edge of the system (BRC-01, 02 and 03, respectively). In addition, a control well is located near the site, but far enough away to be outside the hydraulic influence of the GSI, in order to monitor for natural fluctuations.

In addition to monitoring the groundwater within the immediate vicinity of GSI, groundwater elevations are being monitored regionally by the United States Geological Survey (USGS) at 21 monitoring wells throughout the City.

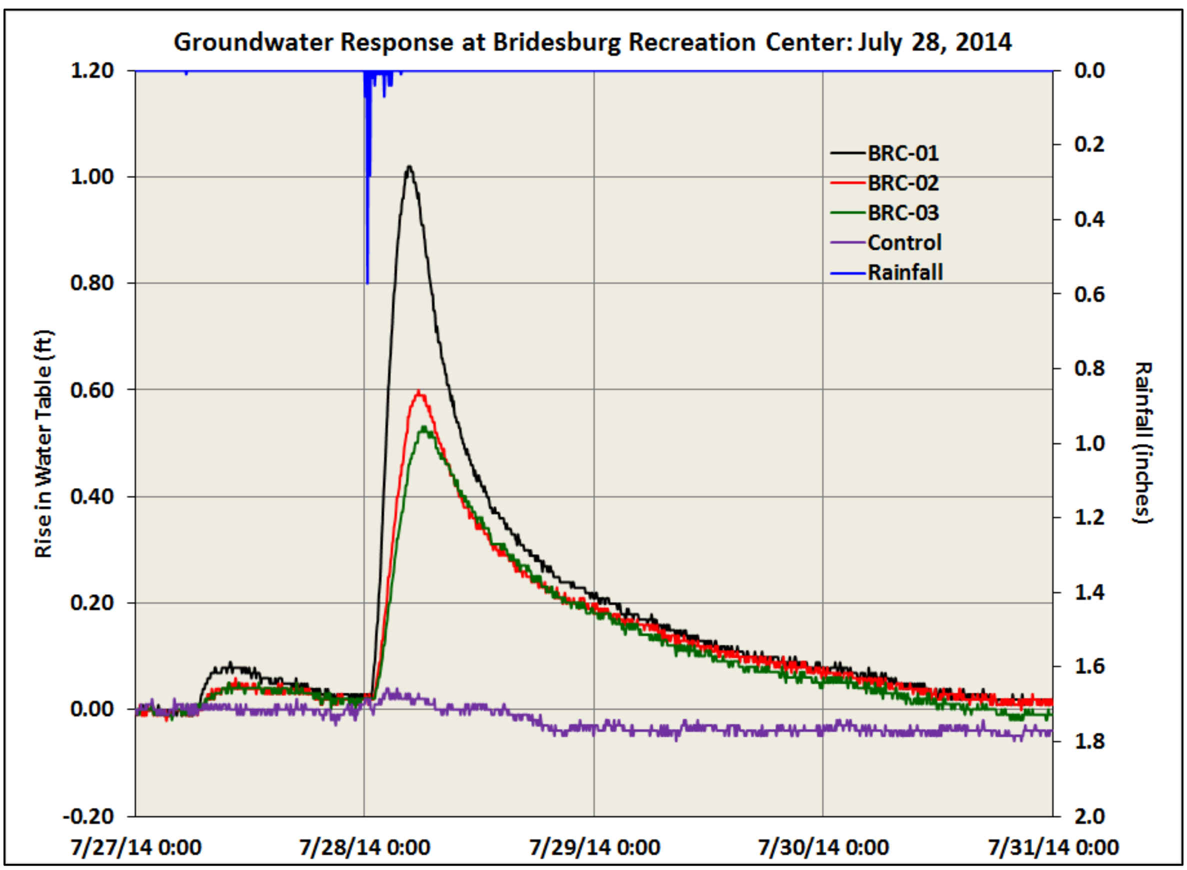


Figure 3-7: Groundwater Wells Adjacent to Bridesburg Recreation Center Rain Garden

3.2 Analysis Methods and Tools

3.2.1 Infiltration Rate Measurement Method

Infiltration rates are estimated both from pre-construction site investigation data and from post-construction water level sensor data. The range of observed infiltration rates can then be compared to determine whether pre-construction rates are serving as a suitable predictor of expected post-construction performance, and whether observed post-construction rates are sufficient to provide the expected design performance in the context of combined sewer overflow control.

3.2.2 Continuous Water Level Event Analysis

As monitoring data was collected and methods for analysis started to be developed, it became apparent that it would be a complex undertaking to accurately assess the stormwater management performance of these monitored systems. A method was developed that can estimate the water budget of the monitored systems during wet weather events, validated by controlled simulated runoff tests. This method is applied to all of the monitored systems to determine how they are performing compared to conservative design assumptions and compared to characteristics of the combined sewer collection and treatment system. Figure 3-8 outlines the water budget process.

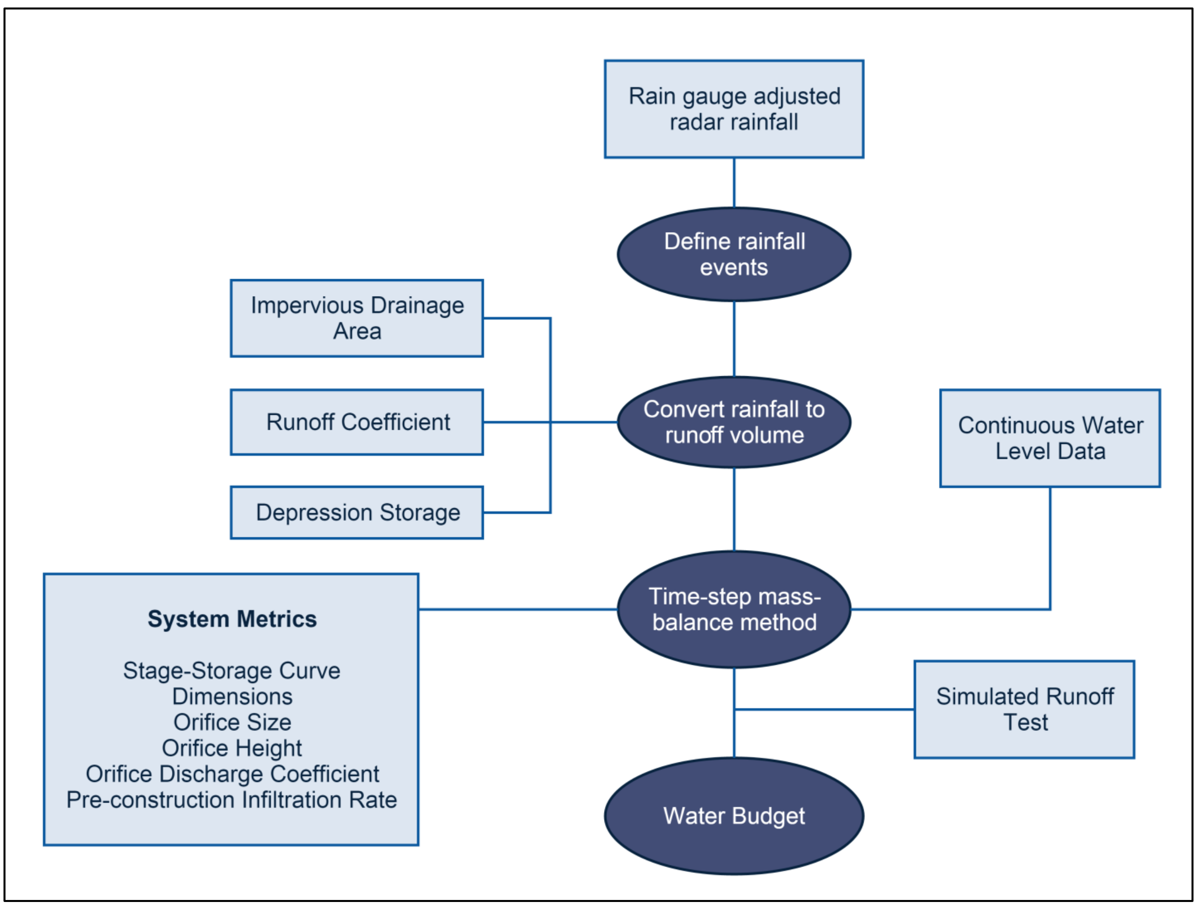


Figure 3-8: Water Budget Assessment Process

A numerical mass balance approach was developed to estimate the amount of runoff managed by the system, to compare to estimated rainfall volume, and to subdivide the volume into its hydrologic components. The mass balance equation for an event is shown as Equation 1, indicating that the volume leaving the system must be equal to the runoff entering the system after accounting for any change in storage. This approach uses two inputs: water level readings from a water level data logger placed within the system, and radar-rainfall data. The radar rainfall data and impervious drainage area are used to estimate the amount of runoff, and thus the volume of stormwater entering the system. The water level data logger records the amount of water in the system every 5 minutes.

$$Runoff = (Infiltration) + (Slow\ Release) + (Bypass/Overflow) + (Change\ in\ Storage) + (Error) \qquad \textbf{Equation 1}$$

Where:

- Runoff = runoff entering the system during the event (ft^3),
- Infiltration = infiltration into surrounding soil or fill (ft^3),
- Slow Release = volume released to the combined sewer system at a controlled rate (0 for infiltration-only systems) (ft^3),
- Bypass/Overflow = volume of runoff that exceeds available storage capacity in the system (ft^3),
- Change in Storage = difference between storage at beginning and end of event, if any (applies to back-to-back events) (ft^3), and
- Error = a term incorporating all sources of error and uncertainty in the system (ft^3), listed in Section 3.4 (Error), Table 3-7.

The slow release rate in cubic feet per second, if any, is calculated at the end of each 5 minute time step based on the head above the orifice, using the submerged orifice equation (Equation 2).

$$Slow\ Release\ Rate = C_d \times A_o \times \sqrt{2 \times g \times h} \qquad \textbf{Equation 2}$$

Where C_d is the orifice discharge coefficient (0.62 assumed), A_O is the area of the orifice (ft^2), g is the acceleration due to gravity (32.2 ft/s^2), and h is the head above the center of the orifice (ft). This release rate is then multiplied by 300 seconds (5 minutes) to calculate the slow release volume for that time step.

Infiltration volume is estimated during recession time steps, when there is no bypass/overflow, no rainfall, and thus no water entering the system. In this case, the mass balance during a 5 minute interval is represented by Equation 3. The error parameter is assumed to be negligible during a recession period, when only stage measurement error and numerical error are introduced.

$$\Delta\,Storage = Infiltration + Slow\ Release \qquad \textbf{Equation 3}$$

Infiltration volume is calculated by subtracting the slow release volume from the change in storage during the 5 minute interval. A stage-infiltration rate relationship is developed for the system using data taken during the recession limb. These infiltration rates are then used to estimate infiltration during the rainfall period by matching the stage during each time step to the corresponding infiltration rate. This method is known to introduce a conservative bias because it underestimates infiltration rates during the early part of the storm, when soil is not yet saturated. PWD is exploring alternative representations of unsaturated infiltration processes.

Bypass/overflow volume is defined as the volume of runoff that will bypass an inlet during periods when the system storage is full. Any remaining error term necessary to close the water balance in Equation 1 is the difference between the runoff volume and calculated infiltration, slow release, and bypass/overflow volumes. This value encompasses all sources of uncertainty and error discussed Section 3.4 (Error), Table 3-7.

This numerical mass balance approach was programmed in R, a statistical software environment used to analyze large datasets and create graphics. The program was then turned into a cloud-hosted application, dubbed PilotDB, which allows the user to view individual rainfall events and system responses. Each event can be viewed as a time series plot, with the estimated water budget, precipitation metrics, infiltration rates by inch stage, and raw data, as shown in Figure 3-9. After the monitoring data is uploaded, the events are individually evaluated to determine whether or not they should be included in the analysis. Events may be removed from the analysis if the water level data shows an abnormal response to the rainfall data, which could be due to snowfall/snowmelt or device error. Once the events are all analyzed in PilotDB, the data can be downloaded and manipulated in R.

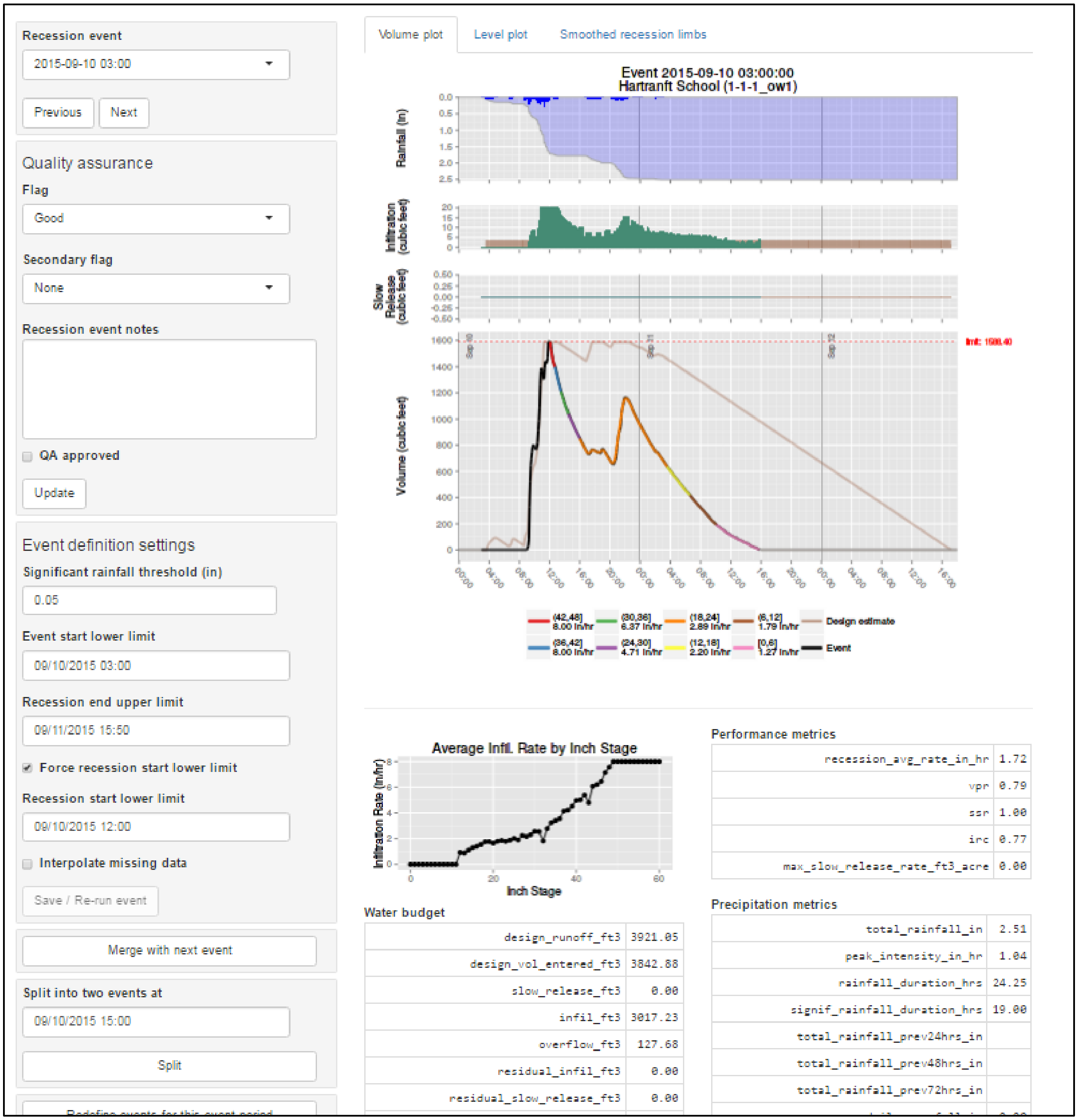


Figure 3-9: Screen Capture of PilotDB Application Demonstrating Event Time Series Plot

3.3 Quality Control Protocols

3.3.1 GSI Performance Monitoring: Continuous Water Level Data

Continuous water level data is downloaded from each system every three months, and transferred to a database. Manual water level measurements are recorded using a water tape every time the data is collected to verify water level data. A time series water level plot is created quarterly, and the plot is manually reviewed by the monitoring team for errors. This process is outlined in Appendix C of the *Comprehensive Monitoring Plan*. Errors in the barometric pressure sensors are detected through the creation of a raster plot, shown in Figure 3-10. The plot indicated anomalous readings in the barometric sensor at 8th and Poplar starting in mid-2015. The sensor at that location was replaced, and barometric data from a nearby sensor was used for the duration the sensor was installed and inoperative.

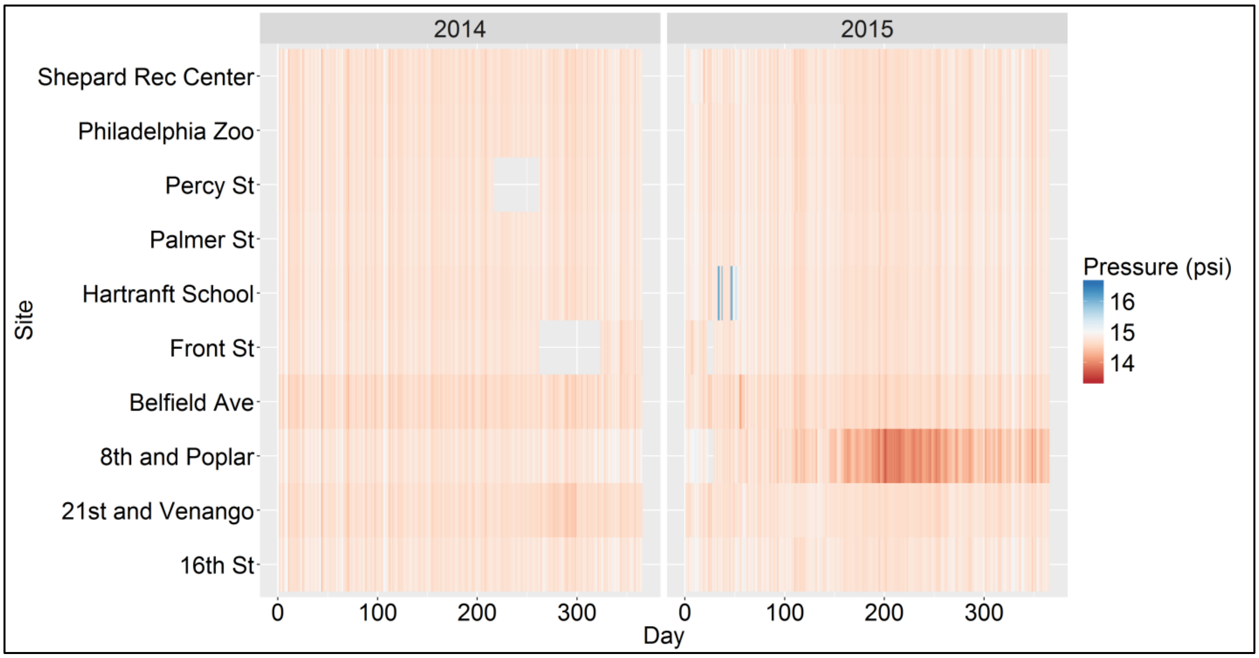


Figure 3-10: Barometric Pressure Sensor Readings, 2014 through 2015

3.3.2 PilotDB Event by Event Analysis

Once new data is added into the PilotDB program, it is quality controlled using the flags in Table 3-5. Each event has a notes section to include any observations not covered by the flags. In addition to flagging, the event settings can be changed, including event start and end time, recession start time, the significant rainfall threshold, and interpolation of missing data. This is especially useful for systems that have standing water within the stone storage for a period of time, because the event start and end times need to be redefined based on the height of water sitting in the system.

Table 3-5: Quality Control Flag Types and Definitions

Flag	Type	Description	Reasoning
Good	Primary	Events to include in the analysis	Responds normally
Censor	Primary	Events that are not to be included in analysis	Snowfall or snowpack Sensor error Increase in volume where there is no rainfall
Needs Review	Primary	Events that need to be reviewed before including in analysis	Response inconsistent with the rest of the data
Not QAed	Primary	Events that have not been reviewed yet	
Great	Secondary	One storm, no trailing rainfall	Used for reports
Snowfall	Secondary	Auto QAed by program using NOAA snowfall data	Snow during the event Snowpack during the event
Bypass	Secondary	Auto QAed by program	No response from system during rainfall

During preliminary examination, it was discovered that small fluctuations in the water level sensors caused overestimates in the water budget. A locally weighted polynomial regression (loess) curve with a bandwidth of 30 minutes was applied to the raw data, and this smoothed data was used for all data analysis.

3.3.3 Hydrologic Data

PWD collects monthly rain gage data and sends it to Vieux, Inc., which then provides the Department with gage-adjusted radar rainfall (GARR). The rain gage and radar rainfall data are reviewed manually by Vieux and inconsistent data are removed. Reasons for excluding gage data include clogs, significant under- or over- reporting and failure to meet statistical criteria.

The Green Stormwater Infrastructure Monitoring team (GSIM) also installed a rain gage at Morris Leeds (system 179-5) in May 2015 in support of the Science to Achieve Results (STAR) grant collaboration with Villanova University. The GSIM rain gage event totals were compared against the GARR totals to assess the accuracy of the GARR. Figure 3-11 shows the volume difference compared to storm size, and Table 3-6 summarizes these results. Note that the errors tend to be large as a percent difference for the very small storms, but relatively small for the larger storms.

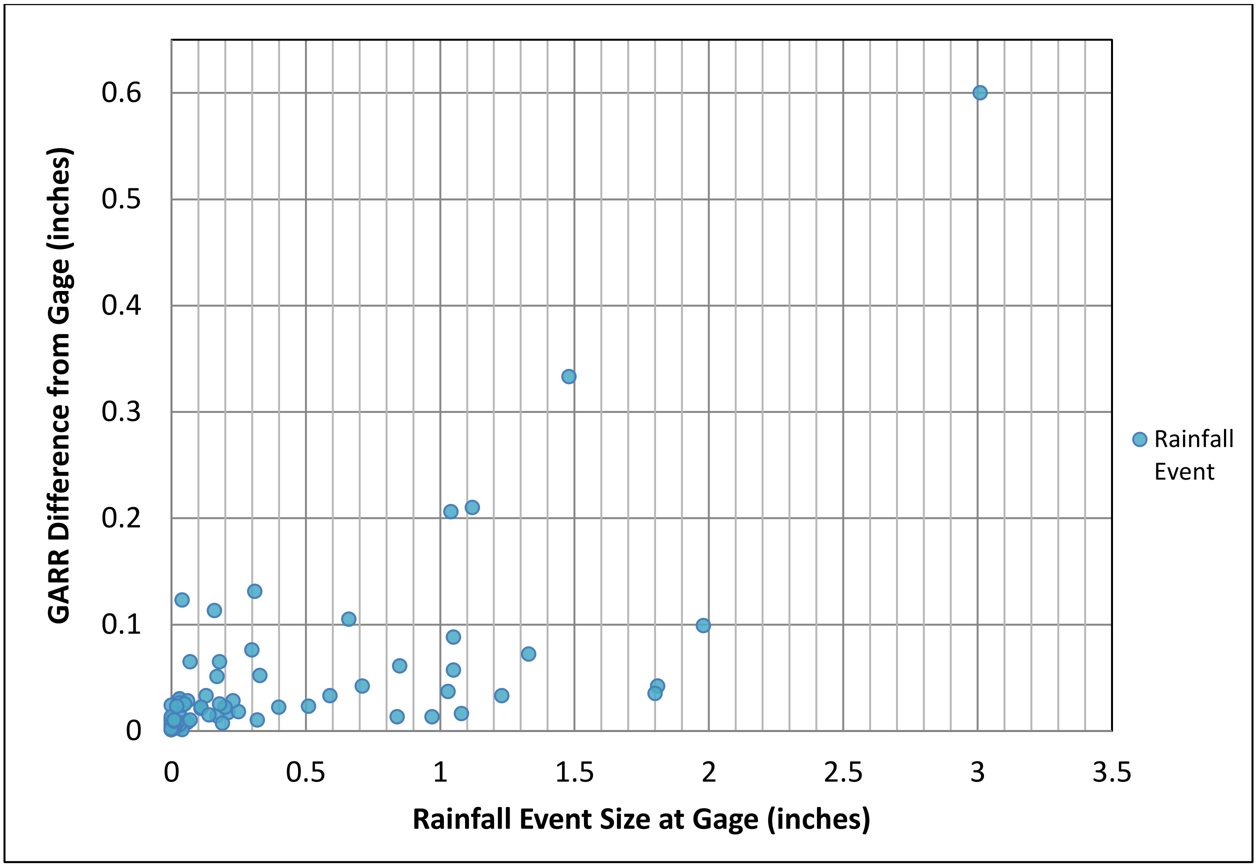


Figure 3-11: Absolute Difference in Total Event Rainfall between GARR and GSIM's Rain Gage by Storm Size

Table 3-6: Summary of GARR-GSIM Gage Comparison

Rainfall Events (greater than 0.1 inches of rainfall)	
Number of Events	41
Average percent difference	22.6%
Minimum percent difference	1.34%
Maximum percent difference	308%
Average size difference (in.)	0.074
Maximum size difference (in.)	0.60
Size difference standard deviation (in.)	0.106

Each system's drainage area was verified before the analysis was conducted. Although drainage areas are initially surveyed during the design phase, street slopes and inlet heights often change when streets are repaved. PWD currently only takes credit for runoff from the right-of-way (public streets and sidewalks) for its public retrofit projects, however many private properties have runoff from downspouts, driveways, and yards draining into the right-of-way. In order to create an accurate water budget, wet weather field surveys were conducted, and runoff from private property was included in the drainage area for modeling purposes.

3.4 Error

Sources of error in the methods described in Section 3.2 (Analysis Methods and Tools) are outlined in Table 3-7. These have been broken into four primary categories: system elements measurement uncertainty, runoff uncertainty, mathematical representation of physical processes, and numerical error.

Table 3-7: Sources of Error and Descriptions

Source of Error	Description	Error Breakdown
System Elements Measurement Uncertainty	Uncertainty in measurement of system physical elements and dimensions, such as constructed system dimensions, properties of porous media, and stage-storage relationships	Porous Media System footprint Inlet configuration System piping Sump depth Elevations Instrumentation error
Runoff Uncertainty	Uncertainty in spatial and temporal measurement of environmental data, including rainfall, water depth, and drainage area characteristics	Rain Gage geo-spatial error Radar prediction error Drainage area error
Mathematical Representation of Physical Processes	Simplification in mathematical representations of complex physical processes, such as rainfall-runoff, infiltration, unsaturated and saturated flow in porous media, soil moisture and evapotranspiration, and behavior of flow control structures such as inlets, outlets, orifices, and risers	Orifice configuration/size/coefficient Unsaturated infiltration Lateral infiltration Evapotranspiration Soil moisture
Numerical Error	Errors introduced by numerical integration in time-step-based computational methods	Volume calculations for infiltration

The error from process modeling includes the modeling omission of unsaturated infiltration and evapotranspiration rates. Work outlined in a conference paper illustrates ongoing work to account for unsaturated infiltration[1]. The orifice coefficient is derived from the *City of Philadelphia Green Streets Design Manual* (Mayor's Office of Transportation and Utilities,

[1] White, S., et. al, "Green Infrastructure Performance Model in the Real World: Modeling Natural and Simulated Runoff Events." Paper presented at the EWRI International Low Impact Development Symposium, Portland, ME, August 2016

2014). This coefficient is used for various types of orifice discharge situations; further work with research partners should offer quantification of these errors.

Numerical error is largely attributed to the assumptions built into the water budget method used by PilotDB. Integration over each time step may over- or under-estimate actual conditions. Comparing simulated runoff test datasets to similar rainfall events can allow some of these errors to be quantified and could account for error in volumes outside of the range of volume errors attributed to the sensors and geometry of the system.

3.5 Findings

3.5.1 Rainfall Analysis

A statistical data analysis was performed on observed precipitation data in order to provide context when assessing the efficiency and performance of Pilot Program monitored systems. To provide this context, rainfall data were examined for the same period when monitoring instrumentation was present in GSI systems, then compared to trends observed in longer term precipitation records.

Both rain gage (RG) data and radar reflectivity-derived rainfall estimates were analyzed. The location of GSI monitoring sites/systems within a radar-rainfall grid cell was identified using a geographic information system (GIS), and observed rainfall data were obtained using both gage adjusted radar rainfall estimates and real time PWD rain gage data. Gage adjusted radar rainfall estimates are obtained using rainfall rates from 1 km^2 radar pixels that are adjusted using rain gage data to determine the true rainfall estimates on the ground.

An event based analysis was applied to the available short-term and long-term rainfall data by identifying independent rainfall events using minimum inter-event time (IET) as a criterion. For this analysis the IET was chosen as greater than 6 hours. As described in the *Long Term Control Plan Update*, the minimum IET was chosen for event definition so that the coefficient of variation (the ratio of the standard deviation to the mean) of inter-event times most closely approximates unity. This follows an exponential distribution on inter-event times for which the mean equals the standard deviation, and is based on the results of National Urban Runoff Program (Environmental Protection Agency 1993).

A minimum total event depth of 0.10 inches was assumed as a storm depth likely to produce a significant, observable response in stormwater flows potentially contributing to Combined Sewer Overflow (CSO) discharges. For all records where hydrological data is missing, a precipitation value was filled using either a spatial correlation approach or a simple regression.

Several systems were chosen to assess rainfall trends during the period when monitoring data was present in the GSI systems (2012-2015), and placed within the context of longer term rainfall records over 26 years (1990-2015). Their corresponding rain gage numbers and grid cell values are also provided in Table 3-8.

Table 3-8: Rain Gages by System Number and Monitoring Period

Rain Gage	Grid Cell	GSI System Number	Monitoring Period Start Date	Monitoring Period End Date
RG-5	107348	326-1	12/18/2012	12/28/2015
RG-5	107346	187-3	10/07/2013	12/30/2015
RG-5	107346	14-1	10/31/2013	12/30/2015
RG-15	105049	8-1	12/18/2012	11/19/2015

Using available rainfall records, event depths were ranked in ascending order and an empirical cumulative distribution function (CDF) was generated with fractional ranks computed by dividing each rank by the denominator n+1, where n is the number of events. To break ties within data (when two or more event volumes have the same depth values), tied elements were assigned to the lowest rank. In this manner empirical CDFs were generated for the short term monitoring period datasets, selected individual calendar years (2012-2015), the long-term 26-year dataset (1990-2015), and PWD's "typical year" dataset as depicted in Figures 3-12 and 3-13. The typical year dataset is a representative year (2005 observed data, with modifications) that was chosen to represent the average annual historic rainfall data using rain gage data as explained in PWD's *Long Term Control Plan Update*.

Figure 3-12 shows long-term precipitation data (1990-2015) compared with data from rain gage 5 (2012-2015) and the typical year. All follow similar trends, maintaining the integrity of a CDF graph. For each period, 90% of the rainfall events are under a 2-inch total event depth. This includes years 2013 and 2015, which were comparatively wetter years, while the drier year, 2012, had nearly 90% of the events under 1-inch total event depth.

Figure 3-13 shows a CDF for three different systems (14-1, 326-1 and 187-3) located near rain gage 5 and monitored over different periods of time. These are compared with long-term data (1900-2015) observed at rain gage 5. Rainfall data for each of these systems were obtained from gage adjusted radar rainfall estimates. The likelihood of an event with rainfall depth greater than 3 inches is quite low (approximately 1 event per year or less). The projected event depths between the range 50 and 20 events per year indicate that systems have monitored relatively larger precipitation volumes than the long-term precipitation data for the time period 2012-2015.

An intensity-duration-frequency (IDF) analysis was also performed using a tool called NetSTORM. NetSTORM is a computer program for precipitation data assessment that takes in hourly rainfall data as an input file and generates an output file with statistics for each hour of the day, each day of the week, each month of the year, annual statistics, and the largest "N" hour totals, where "N" identifies periods with the greatest precipitation over selected durations over the period of record. Durations are user-specified. For this analysis, the largest N hour totals chosen were 1 hour, 2 hours, 3 hours, 6 hours, 12 hours, 24 hours, and 48 hours. Minimum inter-event time and minimum total event volume were set to 6 hours and 0.1 inches, respectively. Intensity-duration-frequency curves were developed using hourly rainfall data from individual rain gages, with data for rain gage 5 shown as an example in Figure 3-14.

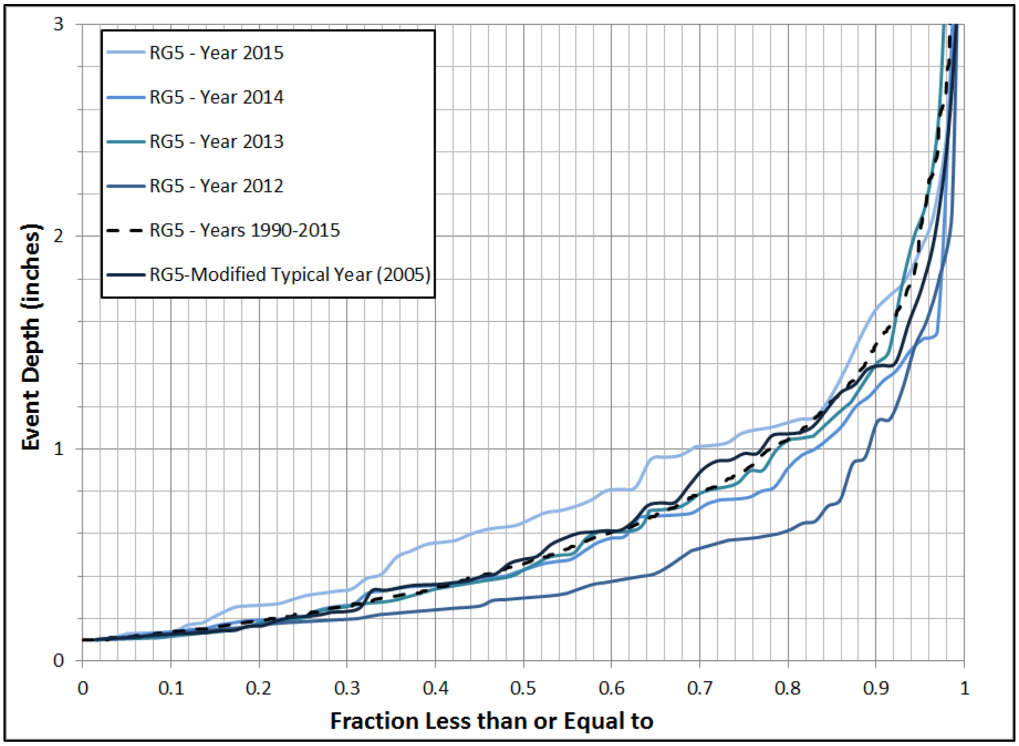
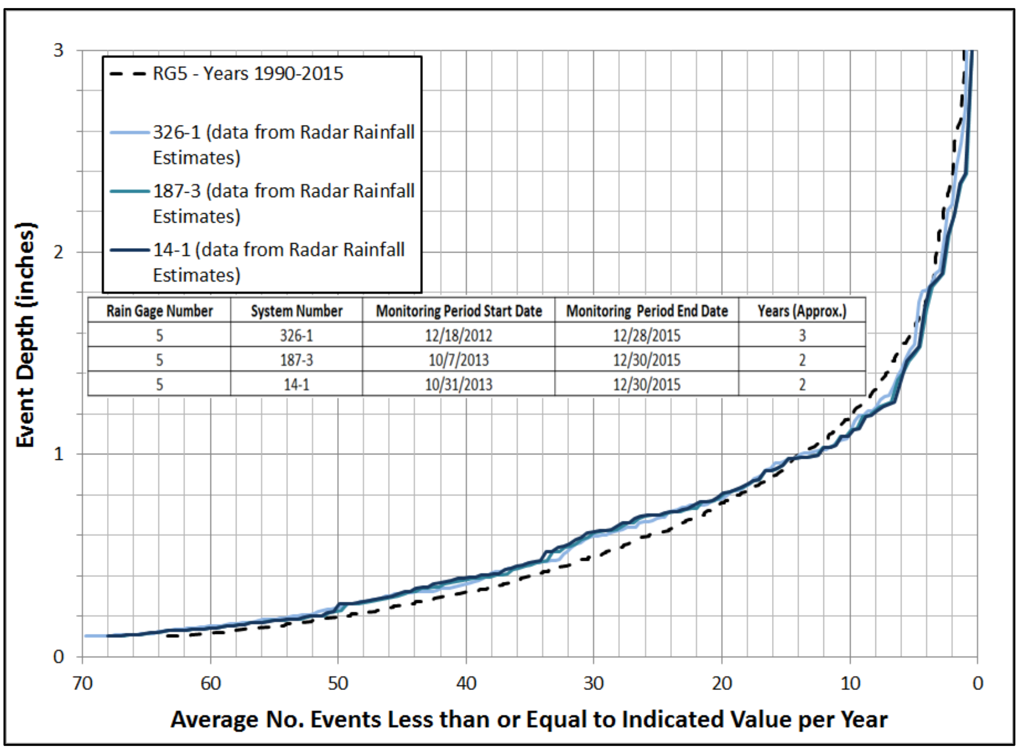


Figure 3-12: CDF for Years 2012-2015 Compared with Long-Term (1990-2015) and Typical Year (modified 2005) Rain Gage 5



Rain Gage Number	System Number	Monitoring Period Start Date	Monitoring Period End Date	Years (Approx.)
5	326-1	12/18/2012	12/28/2015	3
5	187-3	10/7/2013	12/30/2015	2
5	14-1	10/31/2013	12/30/2015	2

Figure 3-13: CDF for Monitored Periods from Radar-Rainfall Pixels Containing Systems 14-1, 326-1 and 403-1 and Long-Term (1990-2015) Using Radar Rainfall Estimates and Rain Gage 5 Data, Respectively

The IDF curves were developed using 1990-2015 precipitation records. Rainfall data for the period 2012-2015 (subset of the full 26 year dataset) was plotted against the IDF curves as shown in Figure 3-14. Simulated runoff tests for the period 2013-2015 were also plotted against the IDF curves. Depth lines (3 inches, 2 inches, 1.5 inches, 1 inch and 0.5 inches) were plotted to indicate their frequency of occurrences. The 0.05 inches/hour intensity line is also drawn, which is the approximate wet weather treatment rate divided by the impervious combined sewer drainage area. For conceptual planning purposes, it is assumed that a runoff intensity greater than this threshold will initiate CSOs.

The “Greatest Depth Storm” (approximately 5 inches of rainfall) is an extreme event with a large volume of rainfall over an extended duration (approximately 40 hours), resulting in an expected frequency of 0.4 events per year. In other words, such an event has the probability of occurring 4 times given a 10-year time period or 40 times given a 100-year time period. The “Most Intense 1-inch Storm” has an expected frequency of 4 events per year. The largest proportions of rainfall events during the period 2012-2015 had event depths less than 1.0 inch (small events) with a return interval ranging between 15 and 50 events per year. Simulated runoff tests replicate larger storms, with total rainfall depths between 1 and 2 inches, and durations between 1 to 2 hours. These characteristics are presented in the IDF graphical representation in Figure 3-14, and can be used as a baseline to analyze the performance of systems for different monitoring periods, as well as being used to assess the frequency of small, medium, and extreme sized rainfall events.

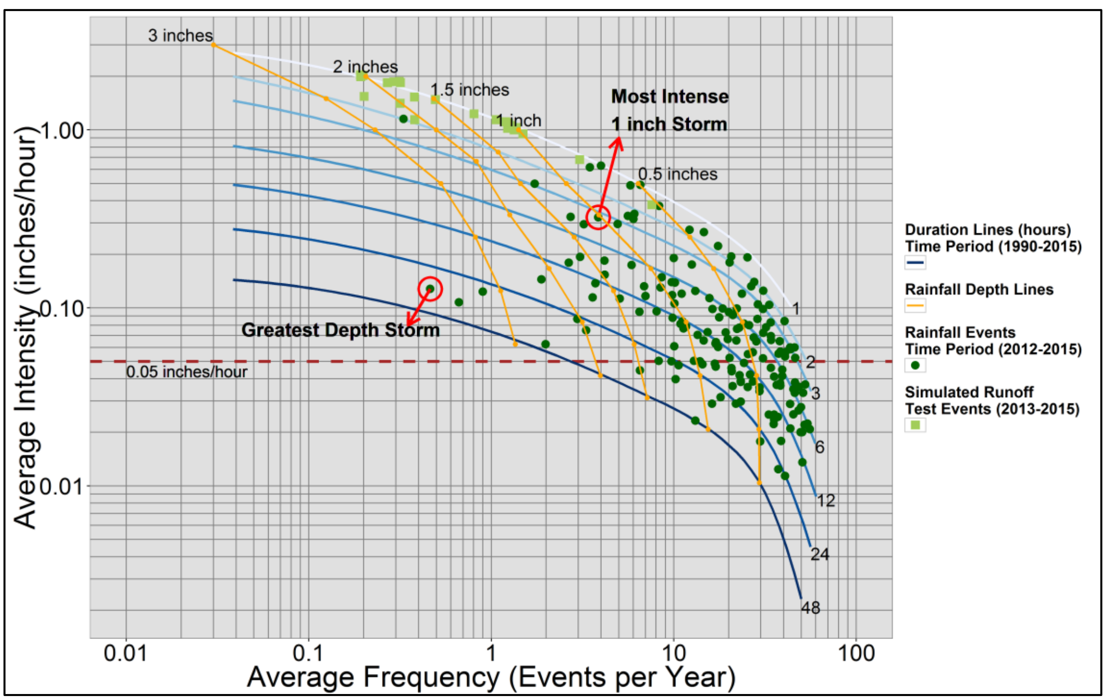


Figure 3-14: Event Depth (inches) for the Monitoring Period November 2012-December 2015, Compared against Intensity-Duration-Frequency Curves Using 26 year (1990-2015) RG 5 Data for N Durations in Hours

3.5.2 Pre and Post-Construction Infiltration Rates: Pilot Variable Screening

A number of performance metrics were examined to characterize GSI system performance during the periods when monitoring equipment was present. Observed infiltration rates provide a "snapshot" of system performance at a particular point in time and at one water level depth.

Post-construction observed infiltration rates were analyzed within the Pilot Variable Framework to help identify design or programmatic choices that may have had an impact on performance. Prior to engineering analysis, one or more of the statistical screening procedures identified the following Pilot Variables as potentially having a relationship to outcomes:

- GSI System Type
- Pretreatment Type
- Physiographic Province

It is acknowledged that sample sizes are relatively small and the different categories within each of these Variables may not satisfy all requirements of the statistical tests, such as equal variances. The statistical screens are intended only to help identify potential relationships that might have been overlooked in traditional engineering analysis. These potential relationships identified by the statistical screens are then examined in more detail using engineering methods.

It is also acknowledged that infiltration rates are head-dependent, and the infiltration rates presented here were measured at different heads. Therefore, these results are best interpreted as order-of-magnitude accuracy when comparing rates among sites.

Variables reflecting certain design choices, including Pretreatment Type and GSI System Type (Figure 3-15), have plausible physical connections to post-construction infiltration performance. Effective pretreatment could be expected to prevent the development of a clogging layer either at the surface/media interface or at the storage media/native soil interface. However, the presence of multiple pretreatment technologies within individual systems complicates this comparison and leads to inconclusive results from an engineering perspective. For the GSI System Type Variable, there could be a plausible connection if differences in geometry in a particular design led to more flow exiting the sides of the storage element compared to other designs. Another plausible physical mechanism would be that in systems with well-established trees and vegetation, root growth into underlying soil could increase infiltration rates compared to un-vegetated systems or systems with less established or less deeply rooted vegetation. However, none of these cases clearly applies to PWD's systems, as storage bed geometry is similar among design types, and establishment of deep-rooted vegetation has not been an explicit objective of designs during the proof of concept phase of the program. These factors, along with relatively small sample sizes in each of the categories, suggest that results of analysis on these system design Variables are inconclusive.

Of the three Variables identified as potentially significant, Physiographic Province may have the most likely physical connection to performance since it is linked to properties of the underlying geologic formations that can affect infiltration rate. Figure 3-16 groups post-construction infiltration rate estimates by physiographic province showing that rates are generally higher in the Piedmont province than in the Coastal Plain. The difference in the medians is approximately half an order of magnitude, which can be considered potentially significant from an engineering perspective.

The effect of geologic formations is supported by analysis of a much larger pre-construction infiltration testing dataset. Again, it must be acknowledged that these tests are performed using a variety of methods and under a variety of heads. Still, the pattern observed is consistent with the one in the post-construction monitoring data, with sites underlain by the Wissahickon Formation of the Piedmont province generally showing higher infiltration rates than sites underlain by the Coastal Plain (Figure 3-17).

The geology of Philadelphia may help explain these results. The Piedmont Province in Philadelphia is made up of the Wissahickon Formation and the Pennsauken and Bridgeton Formations, while the low-lying Coastal Plain includes the Trenton Gravel Formation (see Figure 3-5 in Section 3.1.5 (Geotechnical Data)). The relatively high infiltration rates measured within the Wissahickon Formation may be attributed to weathering processes and depositional environments, as compared to the Coastal Plain. In extensively weathered bedrock, the resulting sediments may be isotropic, that is to say that any preference for water to move horizontally (or vertically) is reduced. In general, sediments that have been deposited from glacial or alluvial processes (like the Coastal Plain) can result in a preferential horizontal flow direction. A general rule of thumb is that the vertical hydraulic conductivity (measure of how easily water can pass through sediments) is about 1/10 of horizontal hydraulic conductivity in these formations. This is known as anisotropy. In general, schist can also have an anisotropy with a horizontal preference, but if it is completely weathered, that anisotropy may not exist, in which case, flow rates will be generally the same in the horizontal and vertical directions, or isotropic. Similarly, if there are fractures in the rock, it will also dictate flow preference. The schist underlying GSI systems is extensively weathered, so that could result in isotropic conditions and a higher apparent vertical infiltration rate.

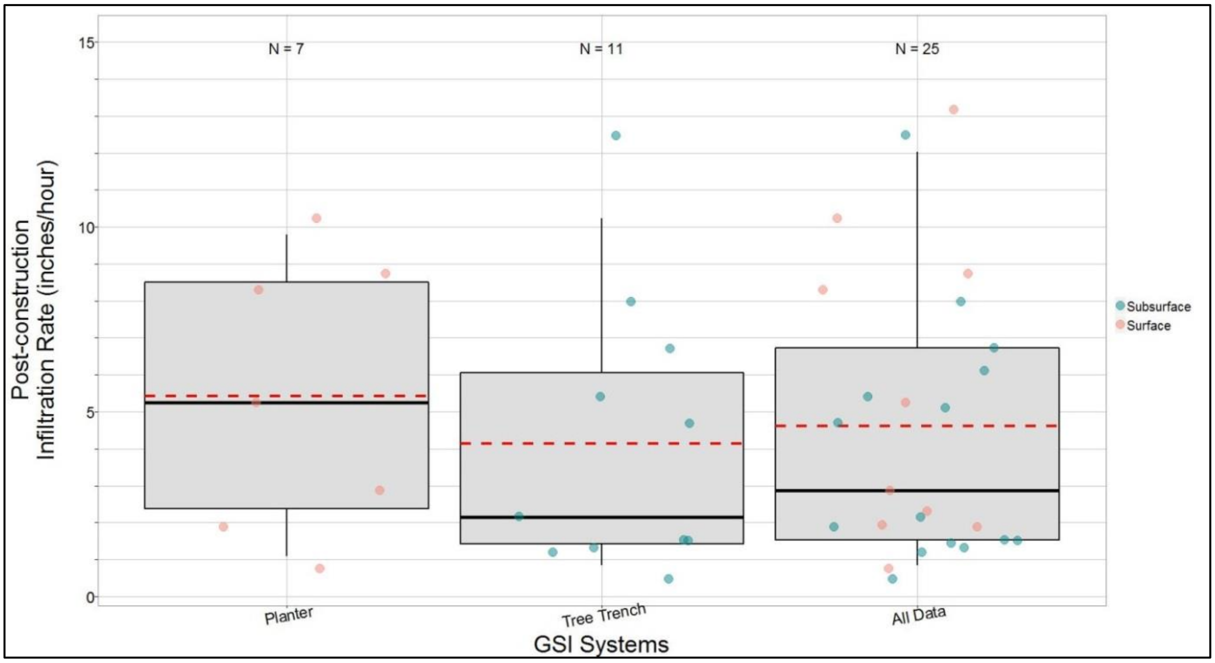


Figure 3-15: Post-Construction Observed Infiltration Rates for Several GSI System Design Types

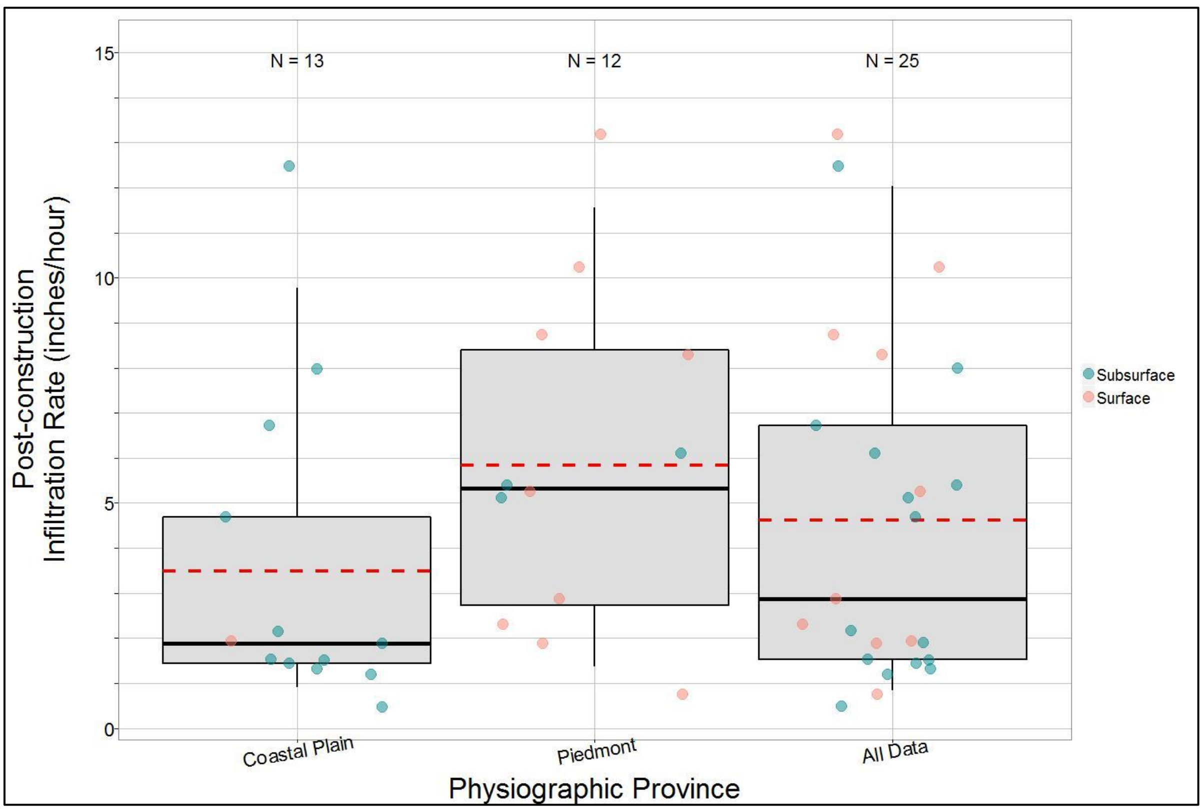


Figure 3-16: Comparison of Observed Post-Construction Infiltration Rates by Physiographic Province

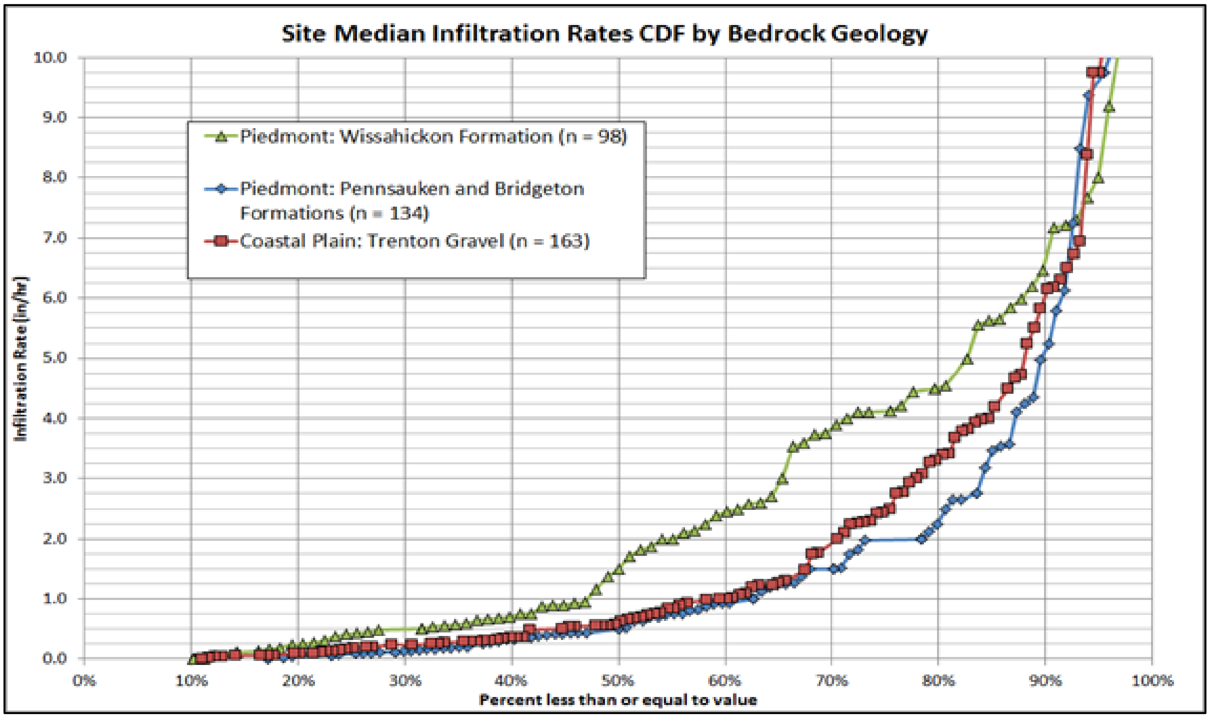


Figure 3-17: Comparison of Observed Pre-Construction Infiltration Rates by Physiographic Province and Geologic Formation

3.5.3 Pre and Post-Construction Infiltration Rates: Comparison

Where sufficient data exists, observed post-construction water level recession rates were compared to pre-construction infiltration tests performed at or close to the same location. For systems where the only outflow path for the managed volume is infiltration into the native soil or fill (i.e., no controlled release back to the sewer system, and neglecting evapotranspiration), the observed water level recession rate is the best approximation of the effective infiltration rate that develops over the system footprint in operation. This vertical rate of change in the water level will account for processes such as flow in unsaturated soil, flow in macropores, and horizontal movement through the sides of the system, all of which contribute to the actual operating performance of the system. By contrast, pre-construction infiltration tests are intended to provide estimates of vertical infiltration rate into saturated soil over a small footprint under field conditions. This distinction is significant because these saturated vertical infiltration test results are the basis of infiltration assumptions used in PWD's engineering designs. There were 25 systems meeting the criteria for comparison. Two of these systems had two monitoring wells, leading to a total of 27 datasets where this comparison could be made.

Because infiltration rate is head-dependent, post-construction water level recession rates (i.e., effective infiltration rates over the system footprint) were determined at the same head that was present during the pre-construction test. For pre-construction infiltration tests conducted in bore holes, 12 inches of head was typical, while for double ring infiltrometers, 24 inches of head was typical. The actual head present in each pre-construction test was obtained from geotechnical investigation reports when available. Figure 3-18 is an example of a pre-construction geotechnical investigation report. For each system, the comparison between pre-construction infiltration test results and post-construction water level recession (effective infiltration) rates was made for each monitored wet weather event during which sufficient head developed to match the head present in the pre-construction test.

Double Ring Infiltrometer
Data Collection Form - Metric

Liquid Level Maintained Using:	○ Flow Valve	○ Float Valve	◉ Mariotte Tube
Project Number:	13499.100.94		
Test Location:	TB-3 (near Blair and Berks)		
Liquid Used:	Water	pH:	7
Tested by:	RJ	DP	
Depth to GW:	N/A feet		

Constants	Area [cm²]	Liquid Depth [in]
Inner Ring:	729.66	7
Annular Space:	2188.98	7
Ring Penetration	Inner: 4 in	Outer: 6 in

Liquid Containers Number	Vol / ΔH [cm³ / cm]
3000 mL	51.72
10000 mL	172.41

Ground Temp	°F
At Depth	feet
Time	
Weather:	PC, Light Rain

Trial No.		Date 2009	Time [hr:min]	Elapsed Time Δ / (total) [min]	Inner Ring Reading [cm]	Inner Ring Flow [cm³]	Annular Space Reading [cm]	Annular Space Flow [cm³]	Liquid Temp [°F]	Incremental Infiltration Rate Inner [cm / hr]	Incremental Infiltration Rate Annular [cm / hr]	
1	S	9/16		15	55.0	2208.62	54.0	5879.31		12.11	10.74	Test run at 4.083 ft below existing grade.
	E				12.3		19.9					
2	S			20	56.0	2105.17	55.5	8465.52		8.66	11.60	
	E				15.3		6.4					
3	S			20	56.0	2544.83	55.5	6534.48		10.46	8.96	
	E				6.8		17.6					
4	S			20	56.0	2700.00	55.5	6965.52		11.10	9.55	
	E				3.8		15.1					
5	S			20	56.0	2115.52	55.5	4241.38		8.70	5.81	
	E				15.1		30.9					
6	S			20	56.0	2094.83	55.5	6068.97		8.61	8.32	
	E				15.5		20.3					
7	S			20	56.0	2053.45	55.5	5810.34		8.44	7.96	
	E				16.3		21.8					
8	S			20	56.0	2079.31	55.5	5172.41		8.55	7.09	
	E				15.8		25.5					
9	S			20	56.0	2058.62	55.5	5534.48		8.46	7.59	
	E	9/16			16.2		23.4					
10	S											
	E											
11	S											
	E											
12	S											
	E											

Figure 3-18: Example of a Pre-Construction Geotechnical Investigation Report

Figure 3-19 shows a storm response, with the recession rate from 6 to 8 inches highlighted, while Figure 3-20 illustrates the relationship between water level recession rate and head at each observed time step. Data points measured at a 5-minute interval exhibit significant noise or random variation. Two steps were taken to reduce noise present in the observed post-construction water level signal. First, the data were smoothed using a 30-minute moving average. Second, the data were smoothed over a vertical interval extending from 1.0 inch above to 1.0 inch below the head of interest from the pre-construction test.

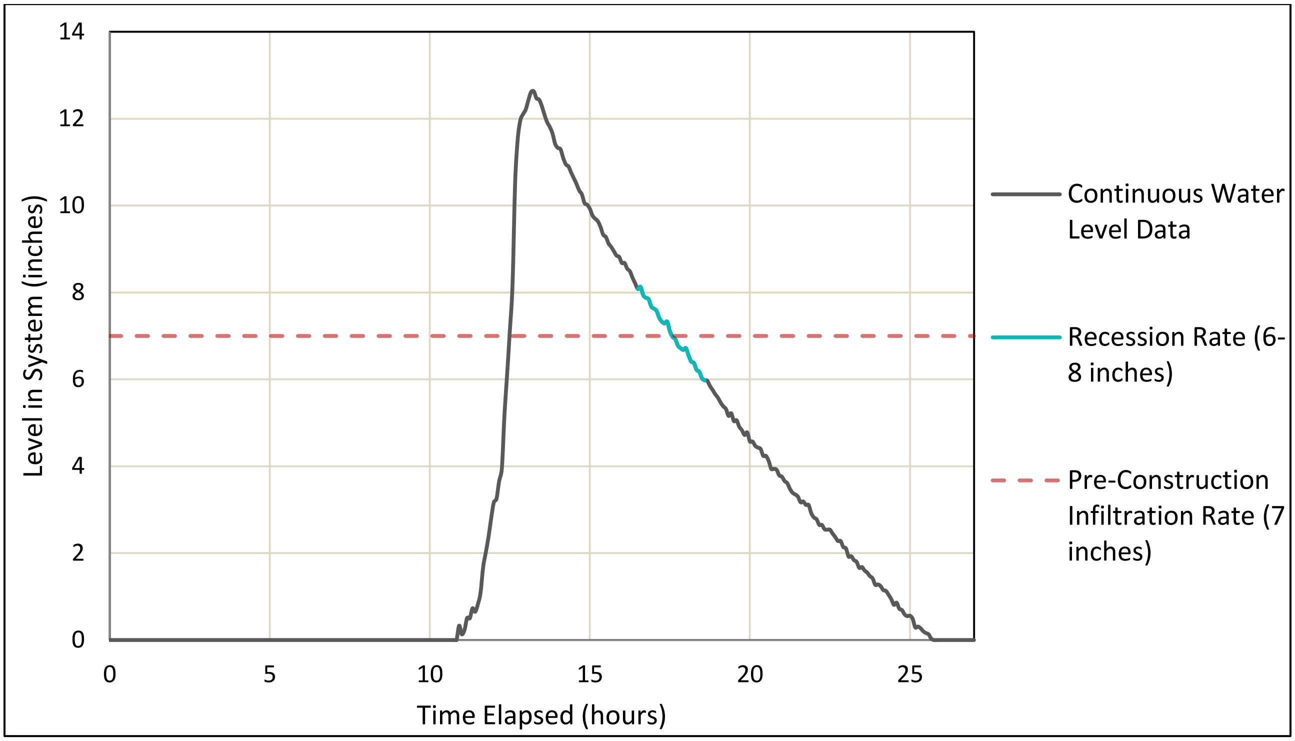


Figure 3-19: Water Level Response to a 1.86 inch Rainfall Event at Blair St (170-1) on April 20, 2015

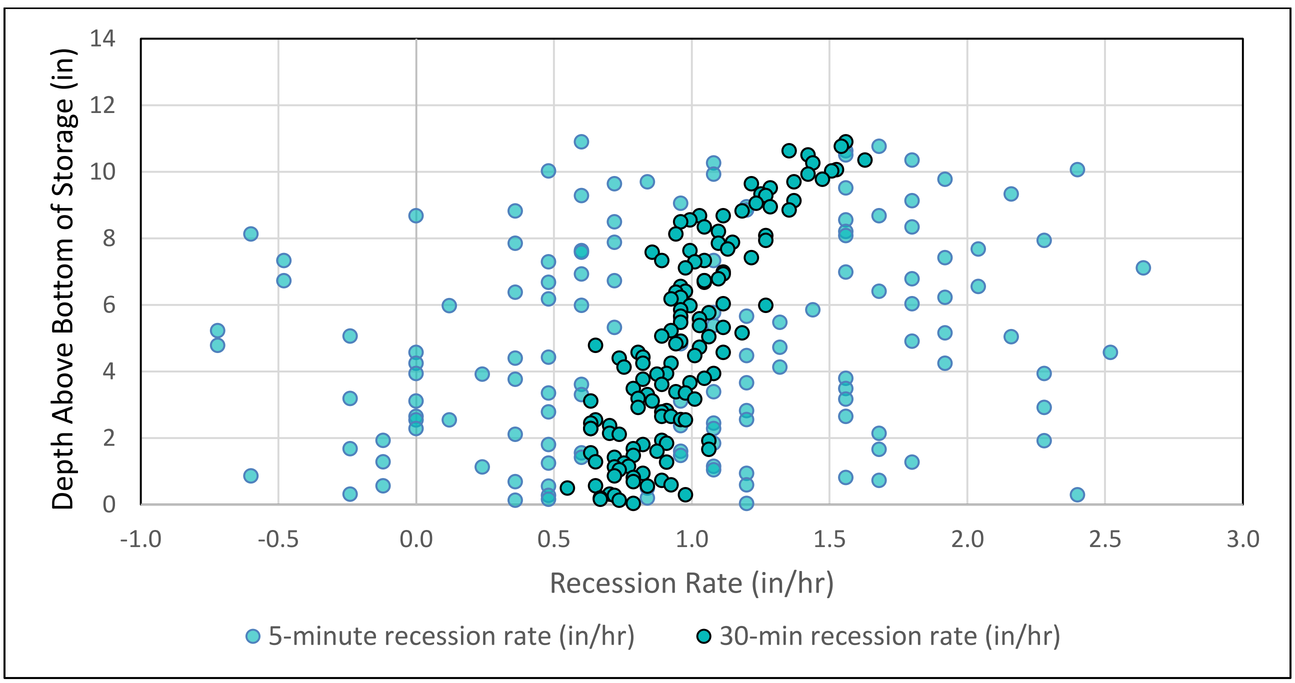


Figure 3-20: Raw and Smoothed Infiltration Rates for a 1.86 inch Rainfall Event at Blair St (170-1) on April 20, 2015

A comparison of pre-construction infiltration test results and post-construction water level recession (effective infiltration) rates was performed for all systems and events with sufficient data (Figure 3-21). Although the results show significant variation, it is clear that observed post-construction recession rates exceed the saturated vertical infiltration rates observed in pre-construction testing for most sites and events. This suggests that using the pre-construction test results as design assumptions will lead to conservative (i.e., over-performing) engineering designs. Even for sites with some events where the observed post-construction recession rate did not exceed the pre-construction infiltration rate, the post-construction rate exceeded the pre-construction rate for most events. Of the 25 systems tested, there were only three systems where the post-construction recession rate never exceeded the pre-construction infiltration test rate.

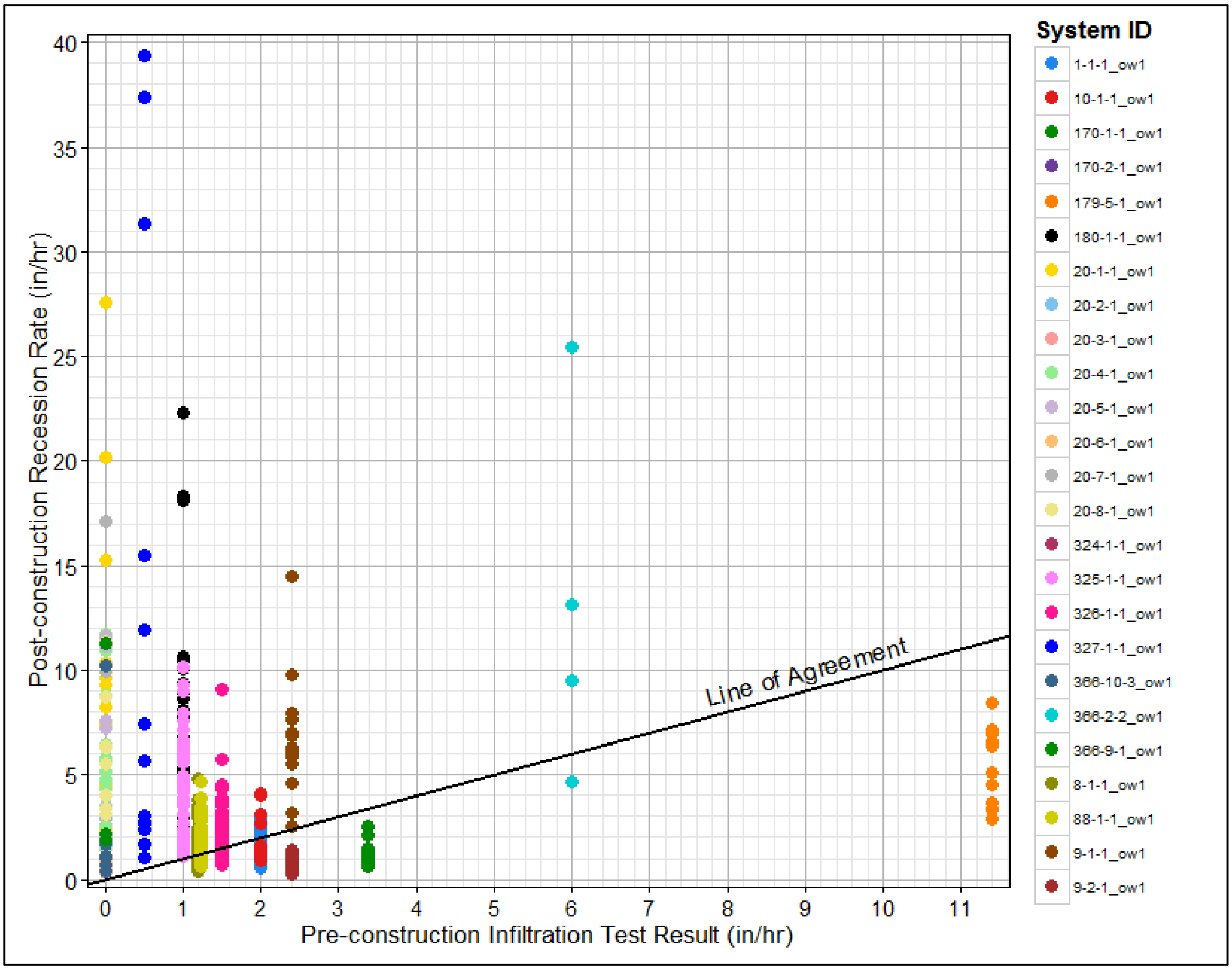


Figure 3-21: Comparison of Post-Construction to Pre-Construction Testing Rates for All Systems and Events where the Comparison can be made

Comparison of pre-construction infiltration and post-construction recession rates at specific heads provides one useful comparison of post-construction performance to the level of performance expected from design assumptions. However, it provides only a snapshot of the rate at which the system is draining at an instant in time, rather than a picture of how a system performs over the course of a wet weather event. Another metric that provides a useful picture of draindown characteristics is the amount of time the system takes to drain following the end of rainfall.

3.5.4 Recession Durations and Overflows

Philadelphia's GSI systems are conservatively designed to have a static storage capacity equal to runoff from a certain sized storm (typically 1.0 inch rainfall depth or more assumed to fall instantaneously) over their drainage area. PWD chooses to design systems in this manner to ensure reliable performance. Any rainfall above this amount is presumed to bypass the system and enter the sewer. Operating GSI systems are known to be dynamic, continuously infiltrating, and/or slowly releasing flow to the sewers, which leads to reliably better performance than that expected from conservative static design assumptions. The amount of times a system fills and overflows storage can be determined by looking at the amount of times the water level reaches the top of storage.

Figure 3-14 in Section 3.5.1 (Rainfall Analysis) highlights two events, the most intense 1 inch storm, and the greatest depth storm. Three systems, Columbus Square Rain Garden (14-1), Columbus Square Planters (187-3) and Front Street Tree Trench (326-1), were in close proximity to rain gage 5, and thus were chosen to assess system performance during the 1 inch design storm, and the 5 inch greatest depth storm. The rainfall CDFs for these system's monitoring periods are included in Figure 3-13. Figures 3-22 and 3-23 show the system responses during the 1 inch storm and the 5 inch storm respectively. All three systems were designed to handle less than a 1.3 inch storm, but were able to hold the intense 1 inch storm, filling between 20% and 80% of total storage. The Columbus Square systems did not reach maximum storage during the 5 inch event, while the tree trench on Front St. managed most of the event, reaching maximum storage for around 5.5 hours. Once the system reached maximum storage, additional runoff drained to a downstream sewer-connected inlet until the level in the system decreased.

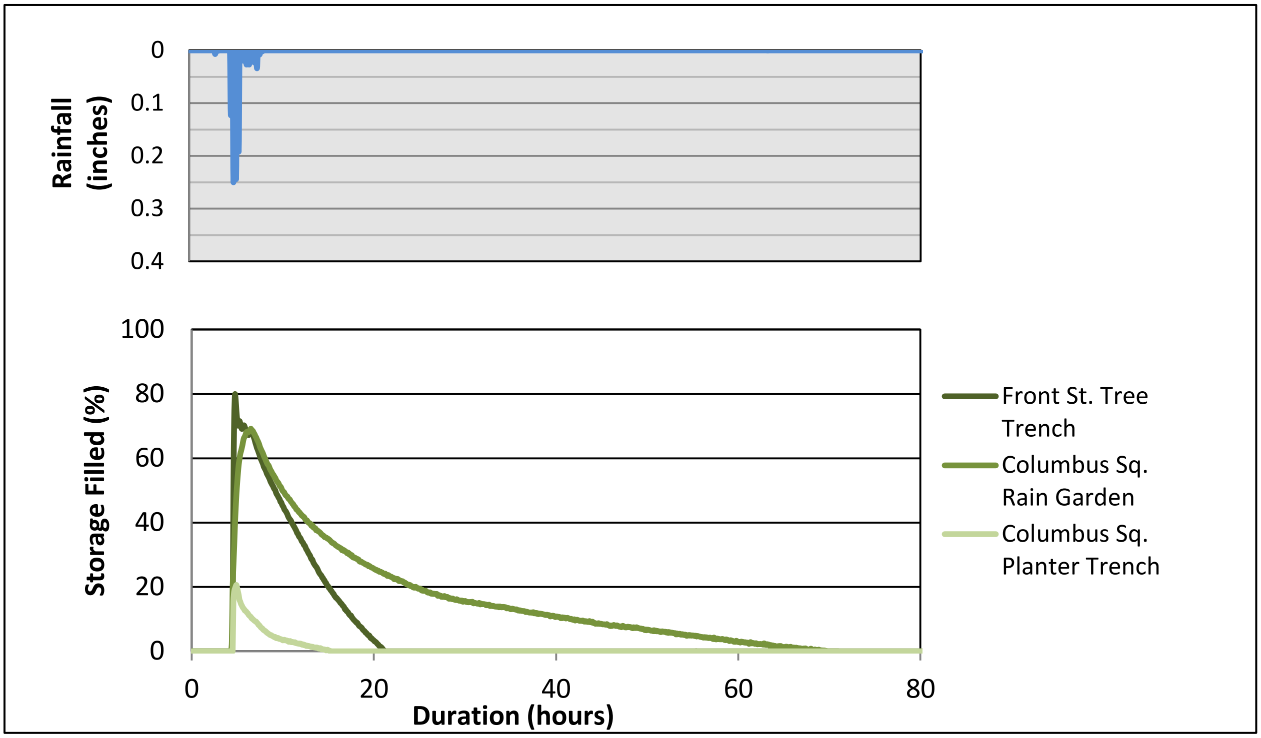


Figure 3-22: System Response at Columbus Square and Front Street to a 1 inch Event on June 27, 2014

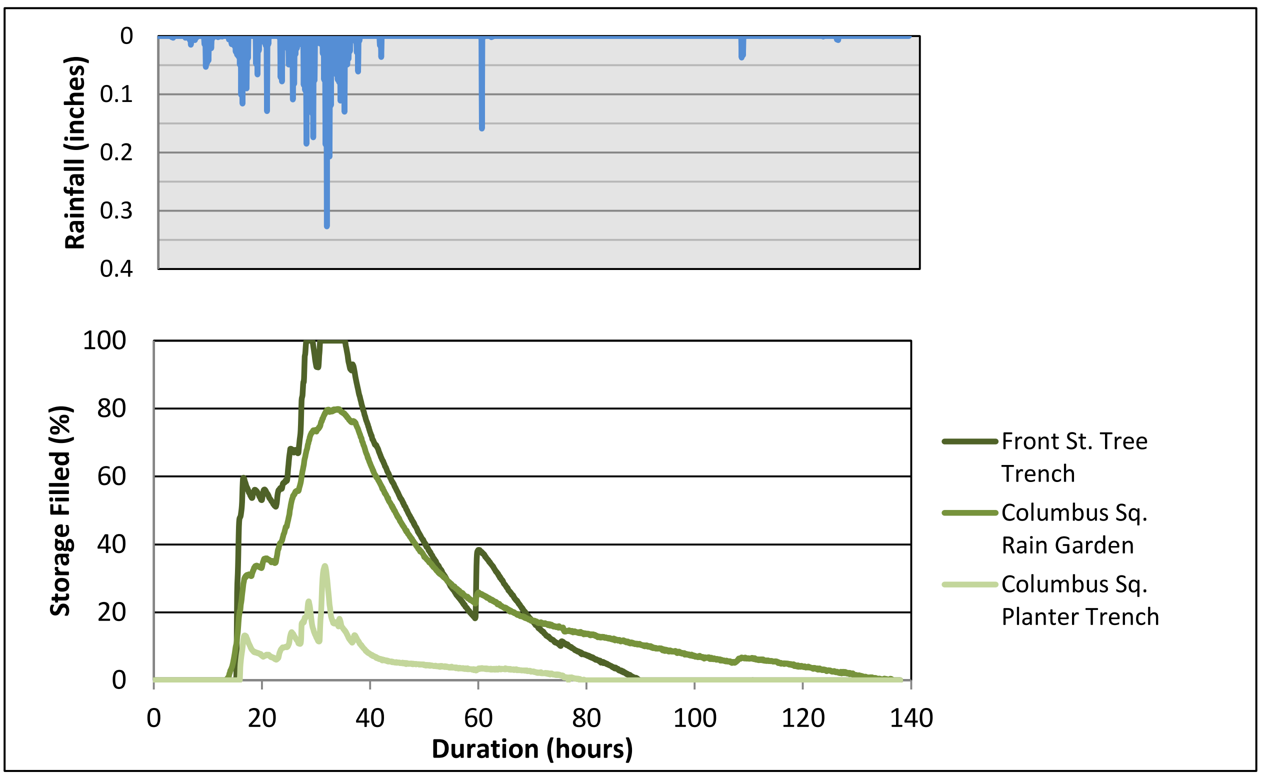


Figure 3-23: System Response at Columbus Square and Front Street to a 5 inch Event on April 29, 2014

Figure 3-24 shows 5,027 monitored system-storms, of which 497 were expected to overflow under design assumptions, but only 22 overflowed. At no time was storage overtopped when conservative design assumptions would not have predicted it. These results confirm that the design assumptions used by PWD during the five-year proof of concept phase are conservative and observed system performance exceeds expected performance.

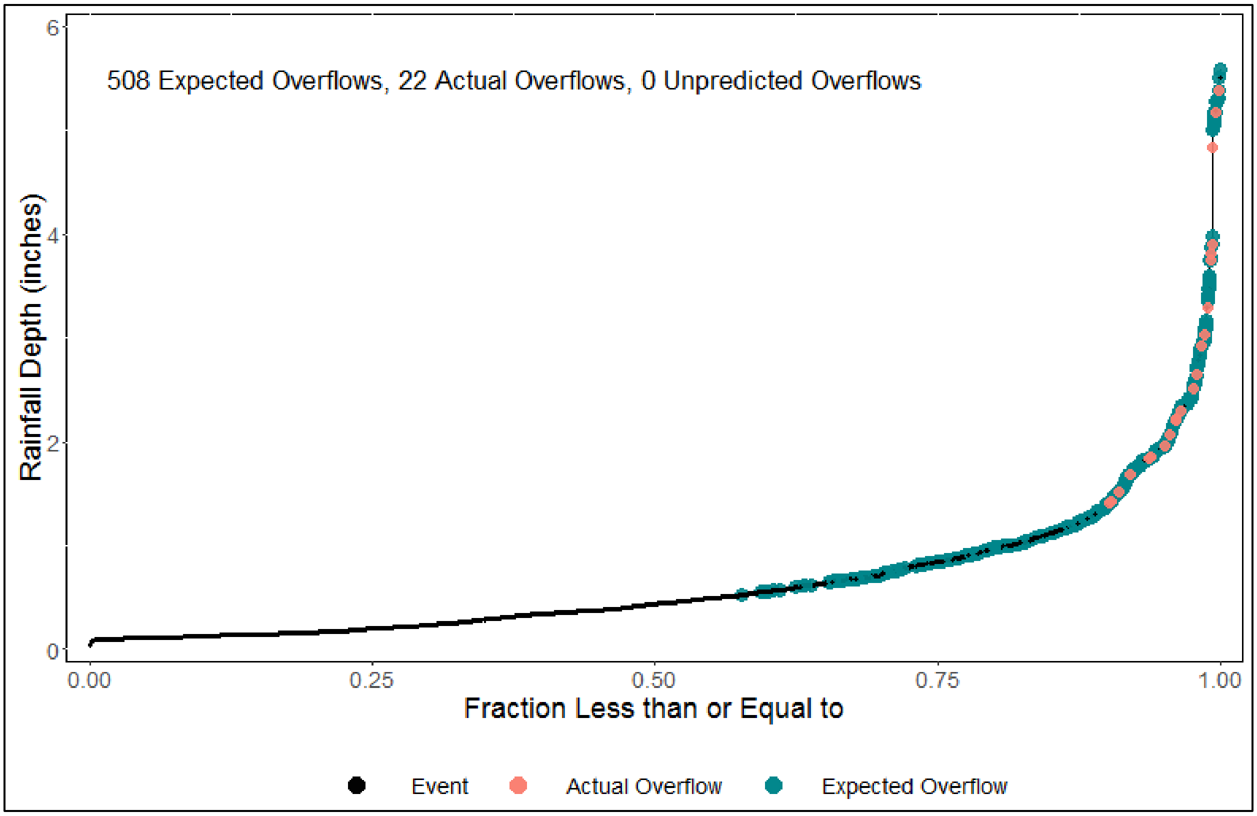


Figure 3-24: CDF of Rainfall (inches) per System-Event (Period: 08/23/2012-12/30/2015)

The overflow events occurred at five systems of the 46 systems monitored: Hartranft tree trench, Philadelphia Zoo rain garden overflow trench, Front Street tree trench, Palmer tree trench, and Columbus Square rain garden trench. Of these five systems, three are known to have larger drainage areas in operation than assumed in design. Hartranft tree trench manages excess runoff from a nearby church during high intensity storms, Front Street was initially designed as two systems but was reduced to one while still managing the same drainage area, and Columbus Square manages excess runoff from a large park and ball field. The Philadelphia Zoo trench is an overflow structure for a rain garden, and when this storage fills up the excess runoff does not enter the sewer but rather ponds higher in the garden. The Palmer tree trench is in series with another system, therefore any overflow will enter another tree trench, which has never reached maximum storage. Consequently, only three of the systems bypass runoff directly into the sewer. Figure 3-25 shows the overflow events for one system, Hartranft tree trench. The dashed line indicates the total rainfall in inches, while the colored areas indicate the amount of rainfall designed to be managed, and the amount of rainfall estimated as managed. The area between the dashed line and "Designed Rainfall Managed" area is what should have overflowed into the combined sewer given design assumption, but the amount of rainfall that actually overflowed to the sewer (area between the dashed line and "Actual Rainfall Managed") is much smaller.

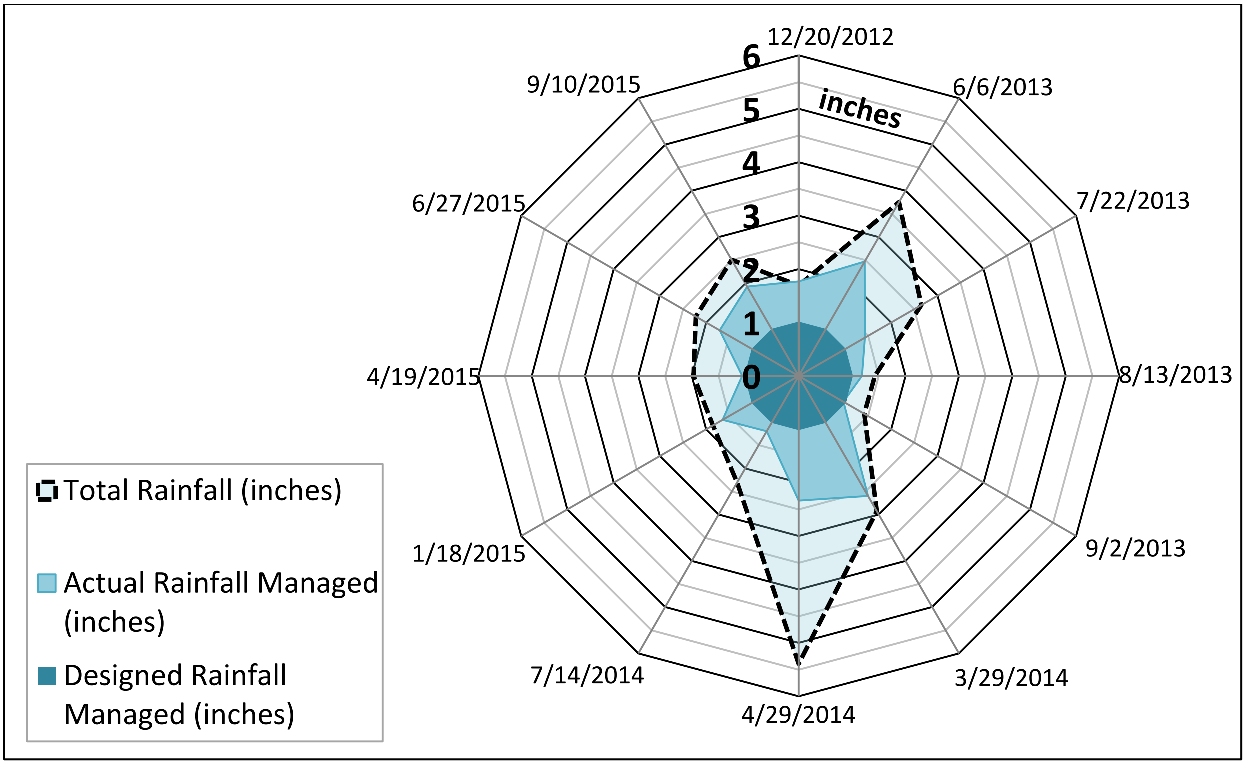


Figure 3-25: Hartranft Tree Trench Overflow Events: Inches of Rainfall Managed by Storm

Philadelphia experiences rainfall every 3 days on average, so GSI systems are designed to completely empty within 72 hours or less, ensuring storage is available under most conditions for the next storm. One way this design criteria is ensured is by taking pre-construction infiltration rates into account during design; if a rate is below 0.25 in/hr then an underdrain is installed, allowing slow release back to the sewer. Therefore, the amount of time required for a system to drain following a runoff event is influenced both by the infiltration rate of the underlying soil and the design configuration of a slow release structure, if any.

The recession duration (from peak storage) was analyzed for each system for both the continuous water level data, and the simulated runoff test data. Only two systems reached peak storage and drained down completely (with no trailing rainfall). Recession duration from peak storage was estimated for the other systems by calculating the volume not filled during large storms, and dividing it by the observed infiltration rates at the maximum height to get a duration, as shown in Equation 4.

$$\begin{aligned} &Recession\ Duration \\ &= (Max\ Storage - Observed\ Storage) * Observed\ Max\ Infiltration\ Rate \\ &+ Observed\ Recession\ Duration \qquad \textbf{Equation 4} \end{aligned}$$

The results showed that six systems could be at risk of having recession durations longer than the 72 hour limit within the continuous water level dataset and two systems within the simulated runoff test dataset. However, during the monitoring period only one instance has been observed where a recession duration impacted the next event and caused the system to overflow. In this instance, the excess water overflowed into another GSI system, and was thus managed and did not enter the sewer system.

The estimated recession durations for the continuous water level and simulated runoff test data were compared with the Variables in the Pilot Program Framework. The comparison with the continuous water level data did not yield any statistically significant results, however the simulated runoff test recession duration comparison indicated that vegetated systems and systems with larger static storage volumes take longer to drain down, as expected. Some of the longer recession systems were a group of planters (Bureau of Laboratory Services, system 20), that had experienced street reconstruction which impacted their performance. These were removed and the analysis was rerun, yielding similar results, which are outlined in Figures 3-26 and 3-27.

Another interesting result was that the loading ratio (ratio of impervious drainage area to system footprint) had no significant effect on the draindown duration, as shown in Figure 3-28. A larger loading ratio could be expected to introduce more fine sediments and garbage per area, which could reduce the performance of a system. However, if this effect does exist it could be a long-term effect that won't be detected until more data is analyzed for a longer period of time. The physiographic province had a relationship to draindown duration, consistent with the relationship between infiltration rate and physiographic province. Possible explanations for this relationship are discussed in Section 3.5.2 (Pre and Post-Construction Infiltration Rates: Pilot Variable Screening).

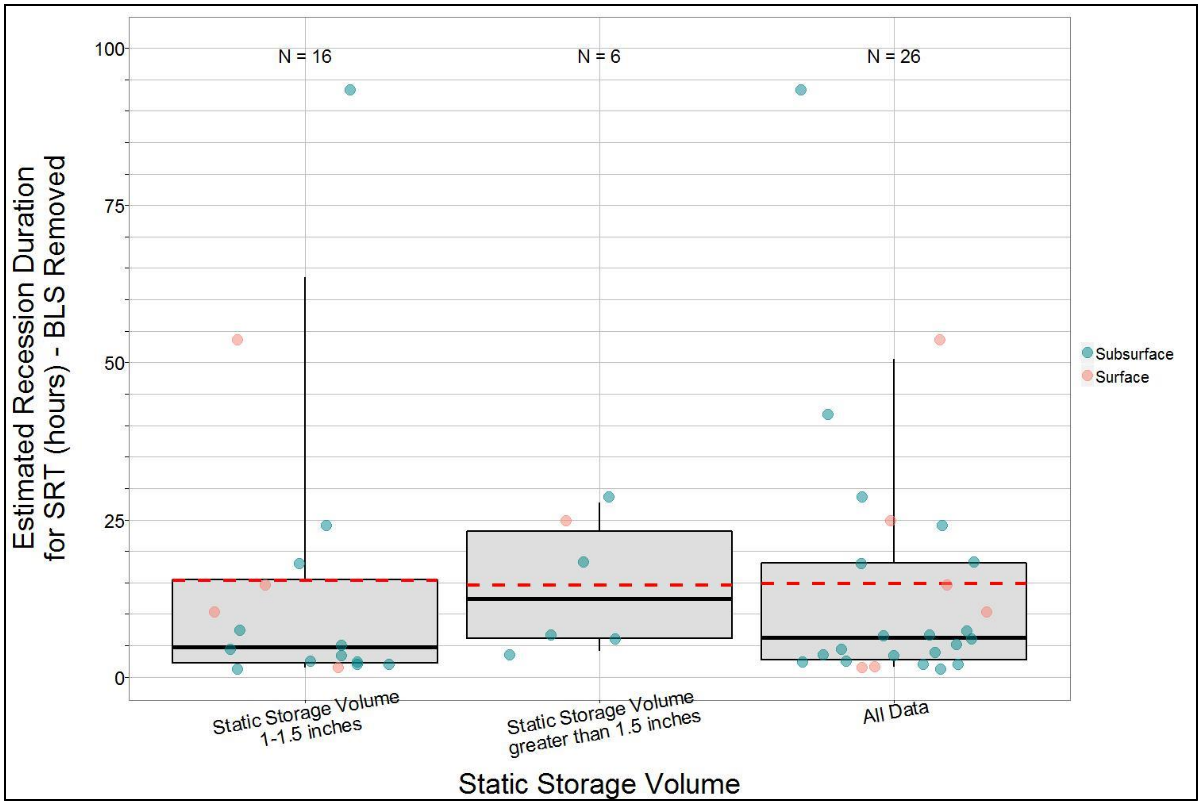


Figure 3-26: Recession Duration by Static Storage Volume

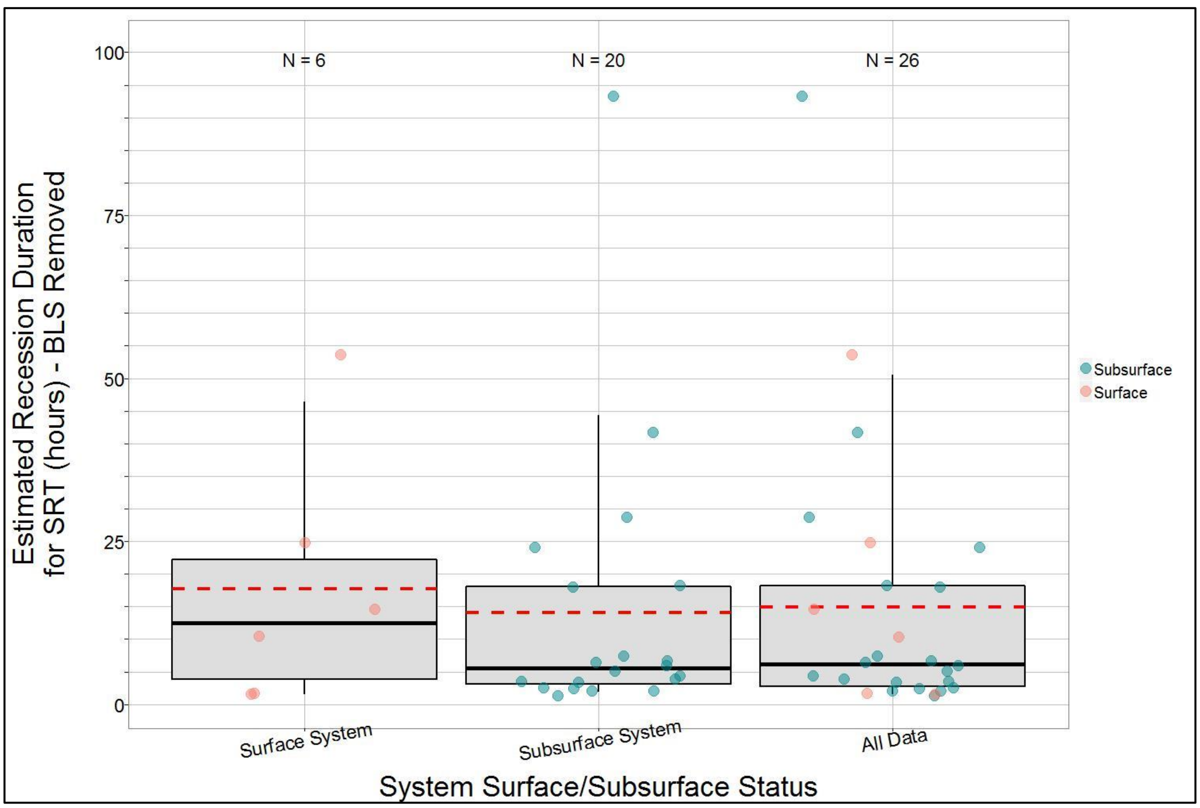


Figure 3-27: Recession Duration, Subsurface v. Surface Systems

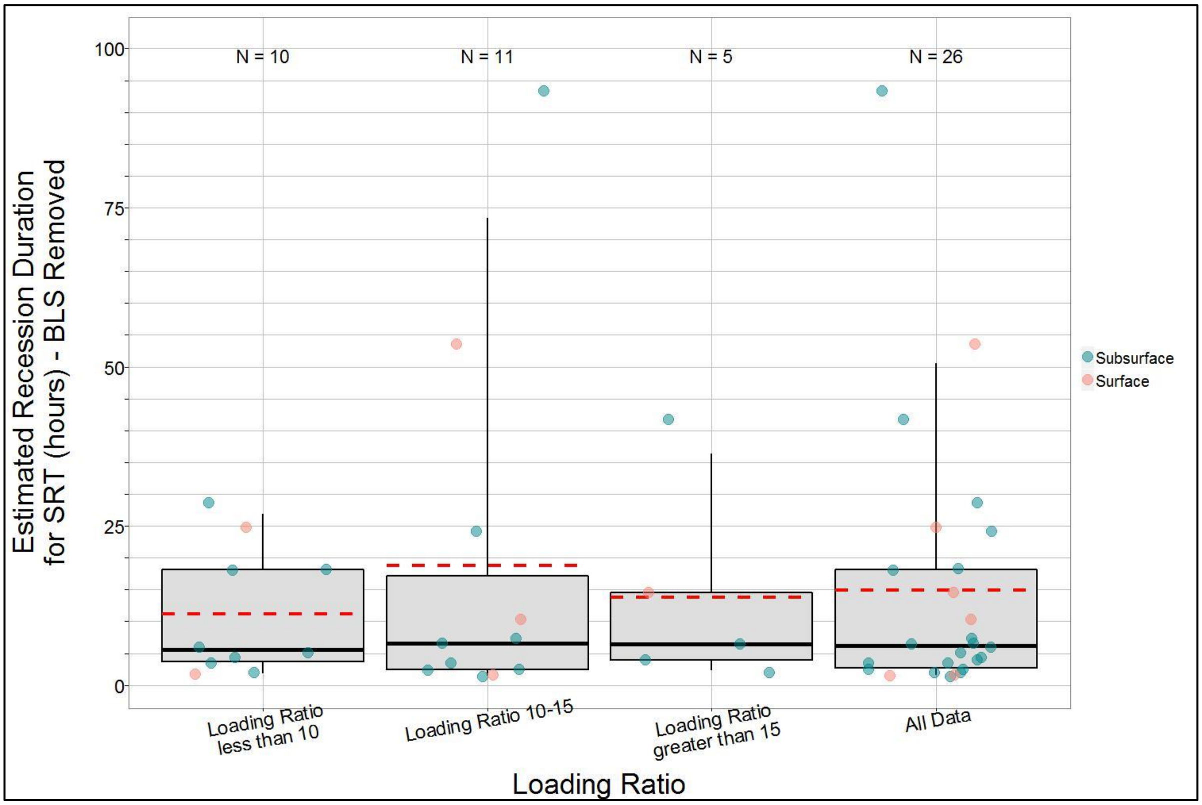


Figure 3-28: System Recession Duration by Loading Ratio

3.5.5 Inlet Performance

Initial analysis of monitoring data indicated that several systems did not regularly fill with water during rainfall events, even during large storms. Field investigations to every monitored system revealed that some had inefficient inlets, as shown on the left in Figure 3-29. This impacted the performance during small events, when runoff would flow between the inlet and the curb, bypassing the system. Every monitored inlet was tested by pumping water past the inlet at low flow, and inlets with inefficiencies were modified to ensure proper drainage. These inlets were then tested again to ensure 100% efficiency, as shown on the right in Figure 3-29.

Figure 3-29: Inlet Modification, Before (left) and After (right)

3.5.6 Percent of Storage Used

A useful indicator of system performance is the amount of available storage that is filled over a range of hydrologic conditions. The metric describing this indicator is the percent of system storage used during a rainfall event and is defined as follows:

$$Percent\ of\ Storage\ Used = \frac{Storage\ Volume\ Used\ during\ Event}{Maximum\ Storage\ Volume} \times 100 \qquad \textbf{Equation 5}$$

The percent of storage used was analyzed for different rainfall depths for all monitored systems. As discussed in Section 3.5.5 (Inlet Performance), several systems received inlet modifications to increase capture efficiency. These systems were not included in the analysis because the percent of storage used was impacted by the inlet efficiency, which reduced the amount of water entering the system. Figure 3-30 shows that most events do not fill the system; only those events 2 inches and above had a mean percent storage used above 50%. This indicates that the systems are able to consistently manage rainfall events that exceed their designed static storage capacity, which range from 1.0 to 2.0 inches over the impervious drainage area. Only three systems (with efficient inlets) reached the maximum capacity, for a total of 16 system-storms.

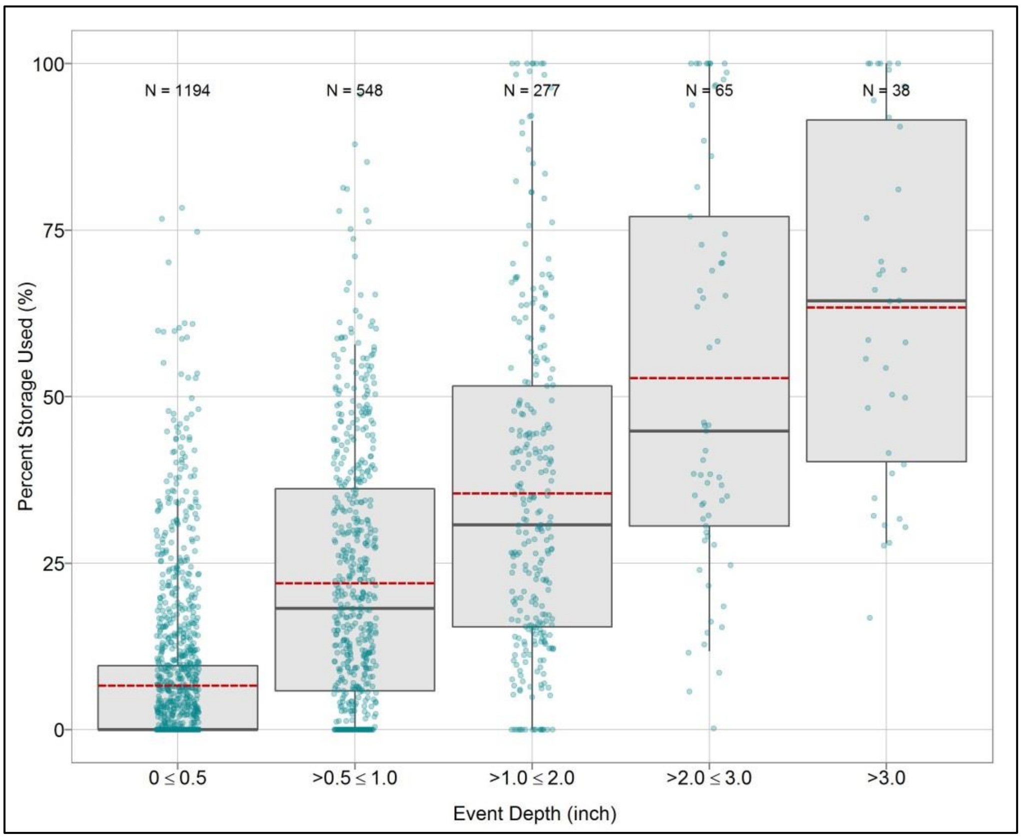


Figure 3-30: Percentage of Storage Filled for 16 Systems (2,120 events) Separated into Rainfall Depth Ranges

As discussed in Section 3.1.2 (GSI Performance Testing: Simulated Runoff Tests), simulated runoff tests were performed on all systems to assess performance under the design storm, while removing runoff estimation uncertainties. The test volumes ranged from 0.55 to 2.78 inches over the impervious drainage area, and in duration from half an hour to almost two hours. Although there are 46 monitored systems, two of these are permeable pavement systems which did not undergo a simulated runoff test, and nine had inconclusive data, resulting in 35 systems with suitable simulated runoff data. Figure 3-31 shows a CDF of the percent of storage used for the simulated runoff tests. Half of the systems used less than 55% of their storage when subjected to the design storm, with only two systems filling to 100%, which both overflowed into an adjacent rain garden.

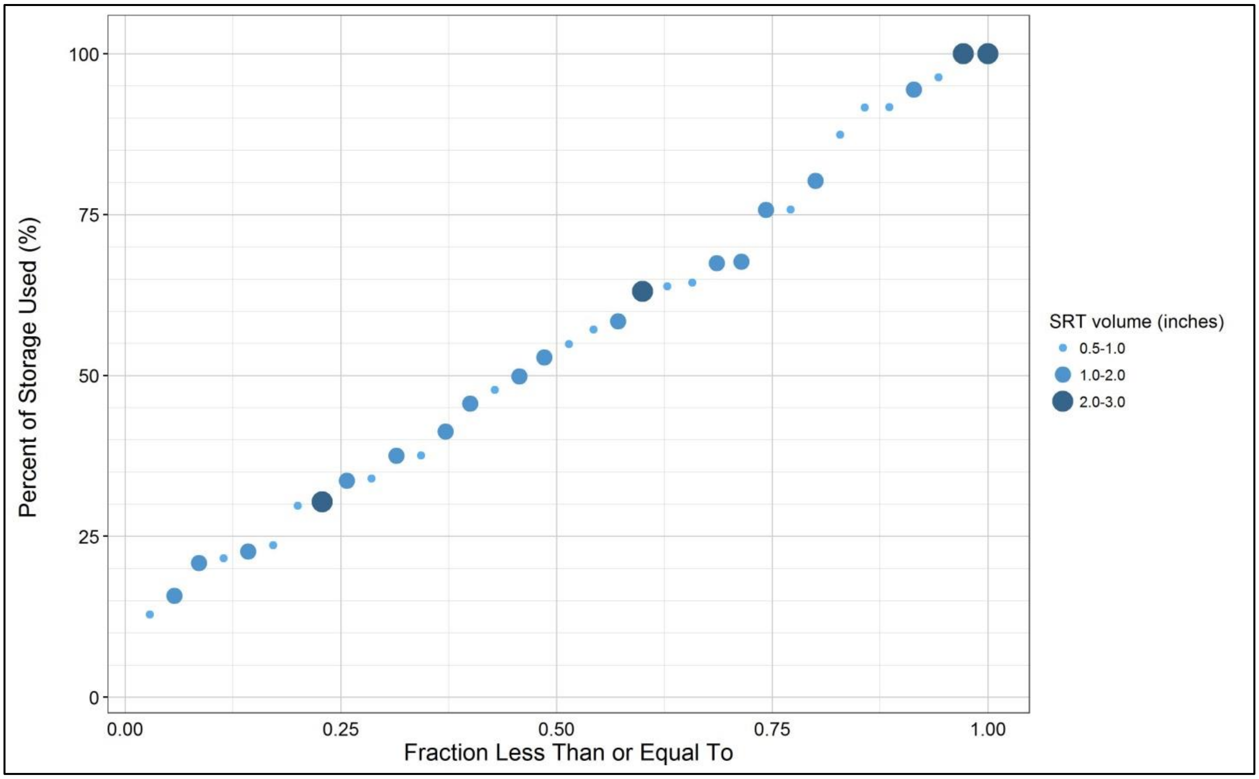


Figure 3-31: Percent of Storage Used for the Simulated Runoff Tests for 35 Systems

3.5.7 Water Budget

The range of performance metrics discussed in the Sections 3.5.1-3.5.6 is sufficient to make a case that PWD's GSI systems are functioning as well as or better than expected under conservative design criteria. Although development of an urban water budget was not necessary in addition to the metrics already discussed to make a case that GSI systems are performing as expected, it was undertaken for scientific purposes and to serve as a baseline for future studies.

Of the 46 monitored systems, 36 have enough continuous water level data to create a water budget. As discussed in Section 3.2.2 (Continuous Water Level Event Analysis), the following equation is used to create a water budget:

$$Runoff = (Infiltration) + (Slow\ Release) + (Bypass/Overflow) + (Change\ in\ Storage) + (Error) \qquad \textbf{Equation 6}$$

These water budget components are calculated on an event by event basis using the PilotDB application, shown in Figure 3-32 and Table 3-9. For this analysis, the water budgets have been summed across events, and are presented for each system's period of record.

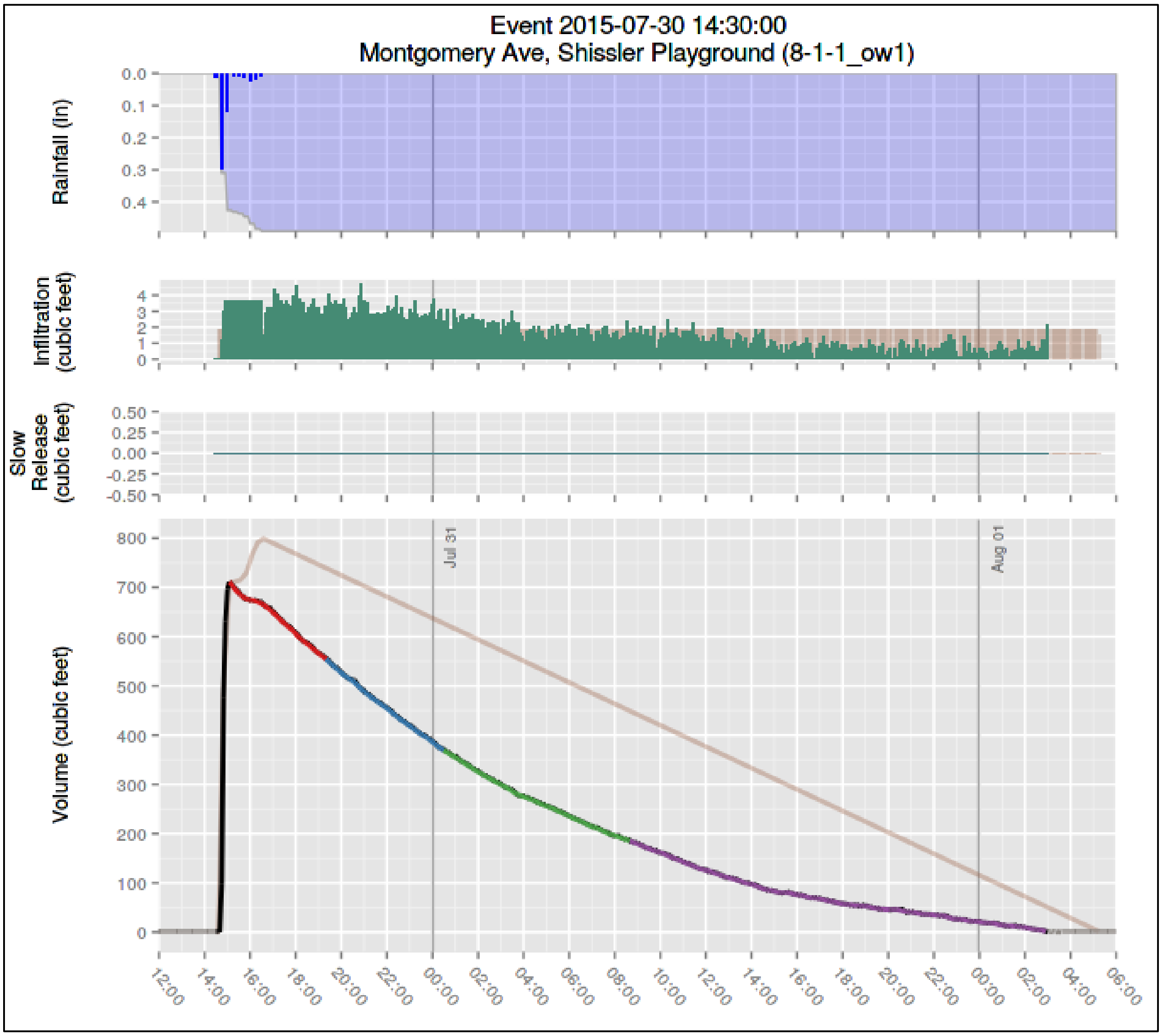


Figure 3-32: Screen Capture of Pilot DB Application Single Event Time Series

Table 3-9: Water Budget Volumetric Breakdown for Event Shown in Figure 3-32 Using Equation 6

Event 2015-07-30 14:30:00 Montgomery Ave, Shissler Playground (8-1-1_ow1) Water Budget (cubic feet)						
Runoff	Infiltration	Slow Release	Bypass/ Overflow	Change in Storage	Measurement Error	Total Managed
843	753	NA	0	0	90	**843**

Figure 3-33 shows the estimated water budget for Hartranft tree trench 1, (system 1-1-1), separated into designed and measured performance. Although this site's storage volume was conservatively designed to instantaneously hold all runoff from a 1.0 inch storm without infiltration, the pre-construction infiltration tests indicated a rate of 0.48 in/hr, allowing it to dynamically manage more runoff over the course of a longer-duration event. Therefore, the design performance includes the 0.48 in/hr infiltration rate in the time step calculations. Figure 3-33 indicates that the system is performing better than designed, with less unmanaged (bypass/overflow) volume than expected.

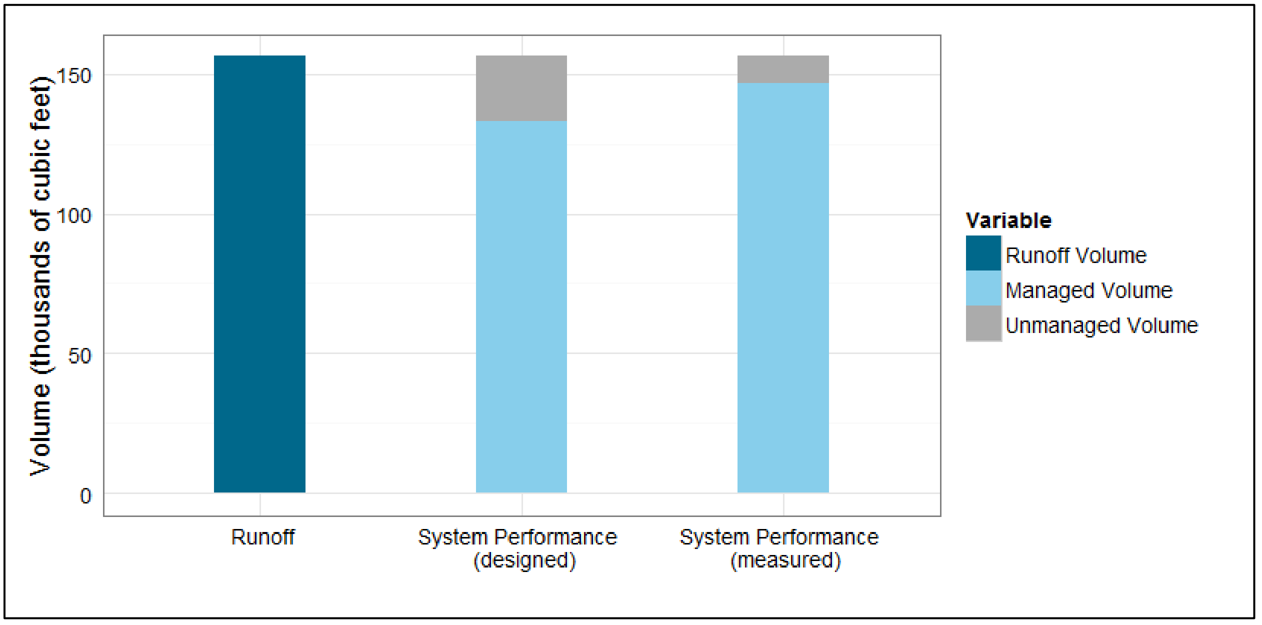


Figure 3-33: Water Balance of Hartranft School Tree Trench 1

Table 3-10: Data Summary for Figure 3-33, Hartranft School Tree Trench 1

Period of Record	Length of Data (days)	Total Rainfall Volume (inches)
11/12/2012 to 12/14/2015	1,099	106.6

The measured performance of the system can be further broken down into the components in Equation 6. The error term can partially be accounted for using the simulated runoff tests (SRT) described in Section 3.1.2 (GSI Performance Testing: Simulated Runoff Tests). During a simulated runoff test, a known amount of water is pumped into a system, minimizing any uncertainty in the runoff calculations. Therefore, the only significant sources of error are those inherent in the mathematical representation of the physical properties, numerical error, and system element measurement uncertainty error. Table 3-11 shows how the SRT helps account for variables in Equation 6.

Table 3-11: Description of Water Budget Component Estimates During Simulated Runoff Tests

Runoff	Infiltration	Slow Release	Bypass/Overflow	Change in Storage	Error
The inflow is known; the SRT removes uncertainty in the drainage area and radar rainfall accuracy.	Measured by monitoring the water level.	Estimated from the submerged orifice equation, verified by visually monitoring the orifice outflow.	Term removed by limiting bypass and not allowing overflow.	Not applicable to an SRT.	Can be attributed to unsaturated infiltration, preferential pathways, and numerical error.

Figure 3-34 shows the percent of the known volume into the system which was accounted for by the analysis of continuous water level data during the simulated runoff test for each system, and conversely the volume within the system not able to be measured by the analysis of continuous water level data. This unmeasured volume is due to the errors discussed in the previous paragraph, and is considered managed.

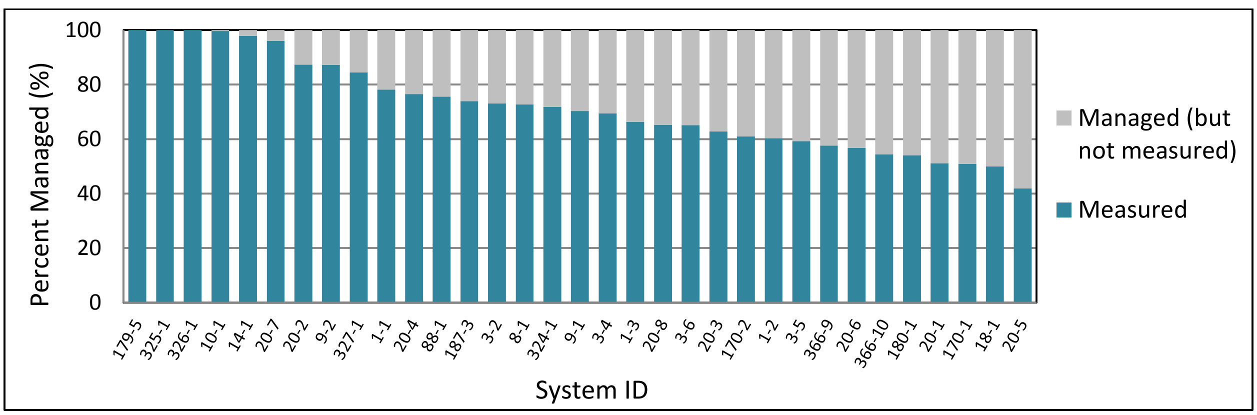


Figure 3-34: Simulated Runoff Test Breakdown of Measured Volume and Managed but not Measured Volume

This volume measured within the system during the synthetic runoff analysis, as a percentage of the total volume known to have entered the system, can be used to remove some of the error in the overall water budget during real events. The remaining error during real events is due to rainfall/runoff measurement uncertainty, and any system elements that correlate with monitoring well response, such as the distance between the observation well and inlet. Figure 3-35 shows the water budget breakdown for Hartranft tree trench 1, (system 1-1-1). Water budget results for all monitored systems can be found in Appendix B (GSI System Examples and Monitoring Fact Sheets).

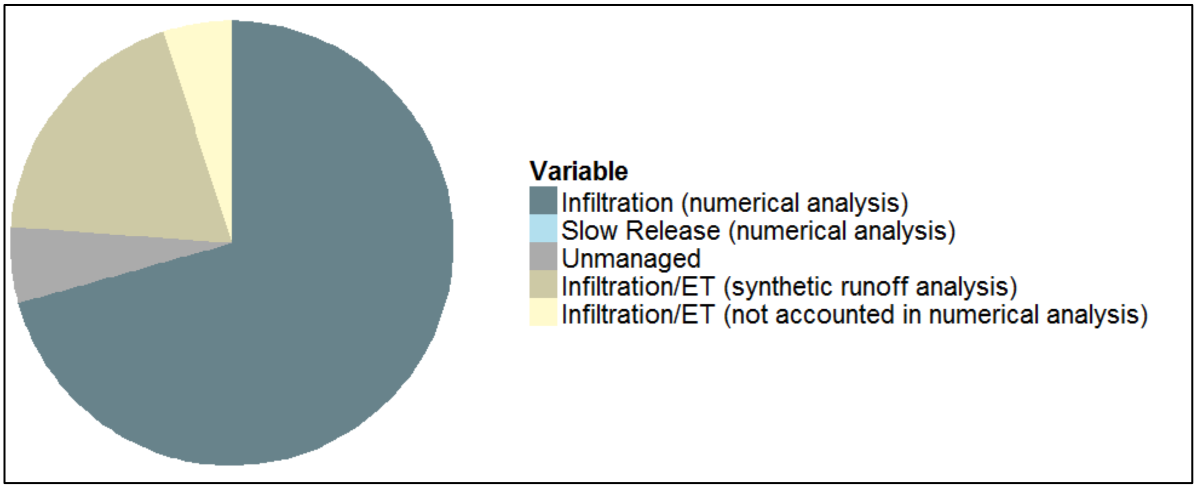


Figure 3-35: Hartranft Tree Trench 1 Volume Breakdown

3.5.8 Permeable Pavement Surface Infiltration Testing

Five of the monitored systems consist of permeable pavement with an underlying stone trench, and two of these have continuous water level monitoring. Percy Street is a public permeable asphalt street, while the Southwest Water Pollution Control Plant (SWWPCP) has a private parking lot that consists of six types of permeable surfaces, outlined in Table 3-12. Surface infiltration testing is conducted biannually at each site.

Table 3-12: Permeable Pavement Types

Surface ID	Surface Type	Product	Method Used
PA	Permeable Asphalt	PWD Standard Permeable Asphalt Wearing Course Design	ASTM C1701
PB1	Permeable Interlocking Concrete Paver	Eagle Bay Aqua Bric	ASTM C1781
PB2	Permeable Articulating Concrete Block/Mat	Pave Drain	ASTM C1781
Surface ID	Surface Type	Product	Method Used

PB3	Modular Permeable Concrete	Stormcrete	ASTM C1701
PC	Permeable Concrete	PWD Standard Permeable Concrete Mix Design	ASTM C1701
PSC	Permeable Stamped Concrete	NA	ASTM C1701

Results from SWWPCP testing show that average infiltration rates of the 6 different permeable surface types range from 120 in/hr to over 2,000 in/hr (Figure 3-36). Although most of the infiltration rates have dropped between 2% to 30% over the past year, they are still functioning as designed and have infiltration rates higher than the underlying media, allowing for maximum flow into the system. The system can effectively capture and manage a 2.5 in/hr intensity, which is the peak 15-minute rainfall intensity during a typical year in Philadelphia. The small changes among the three tests can also be attributed to the errors present in the testing methods. Future testing and analysis of the continuous water level monitor data will help to determine the long-term performance and maintenance needs of the six permeable surface types.

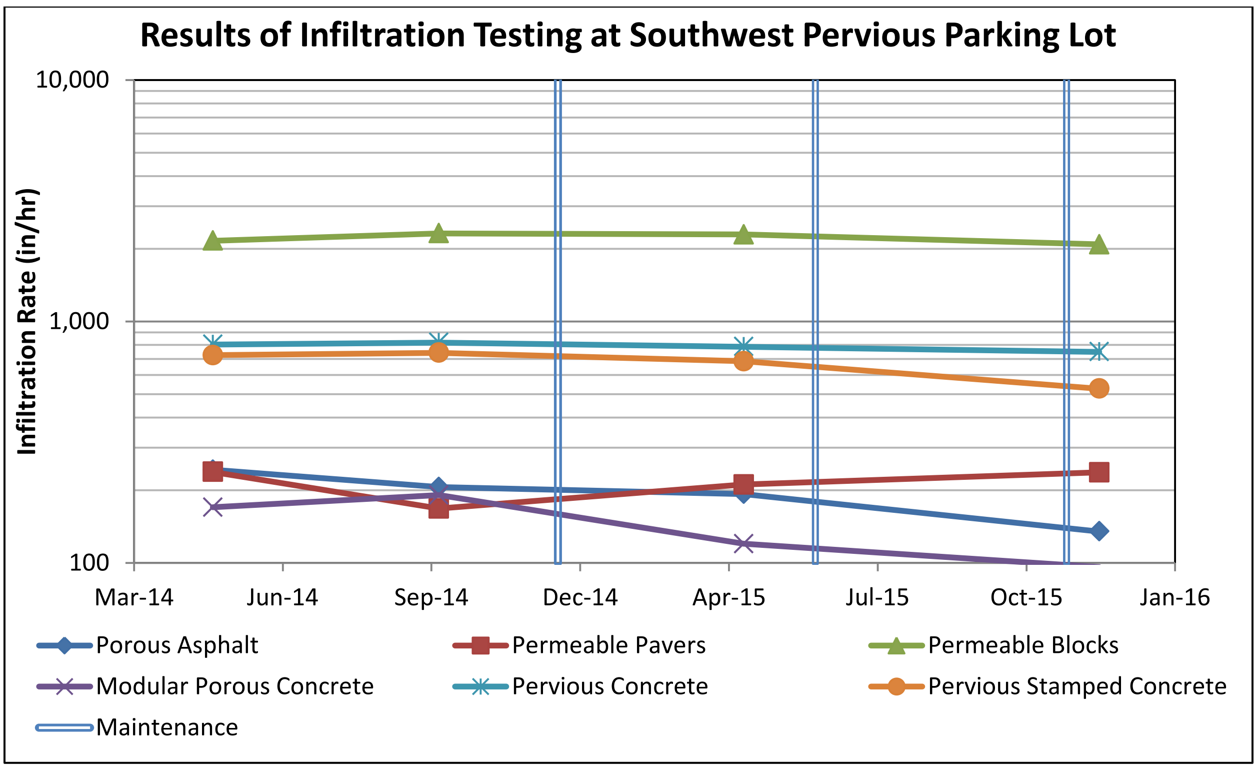


Figure 3-36: Infiltration Test Results at Southwest Permeable Parking Lot

Similar testing was performed at Percy Street, shown in Figure 3-37. Testing results have been split into three sections of the street, although 16 locations were tested at various times. The results have similar conclusions to the SWWPCP tests: the system is still infiltrating at rates high enough to manage the design storm, and although the performance has changed over time, the errors of magnitude are within that of the test for such high infiltration rates.

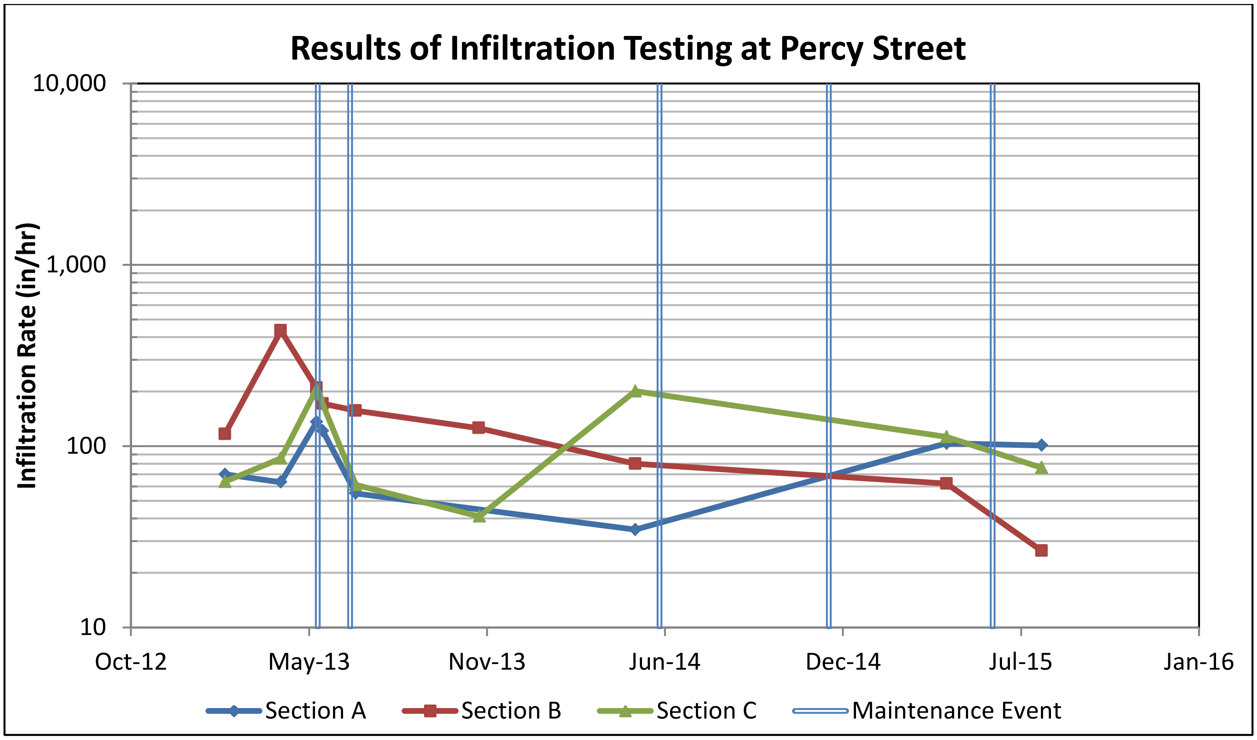


Figure 3-37: Infiltration Test Results at Percy Street

3.5.9 Groundwater Monitoring

Groundwater monitoring analyses have indicated that mounding is essentially non-existent when the water table is relatively deep (approximately 20+ feet). For example, groundwater is being monitored adjacent to a stormwater tree trench along 21st Street, north of the intersection of 21st Street and Venango Street. From a 1.3-inch rain event on November 19, 2015, it appears that the water table responded by approximately 0.2 feet. However due to the presence and almost identical response observed in the control well (located more than 250 feet north of the tree trench), it can be concluded that the response was due to natural fluctuation as opposed to the stormwater trench. Much of the infiltrated water is likely trapped in the vadose zone and slowly infiltrates down to the water table but at a slow rate. The water table at this site is located within the Wissahickon Schist and may be acting like a confined or semi-confined unit, responding to changes in barometric pressure.

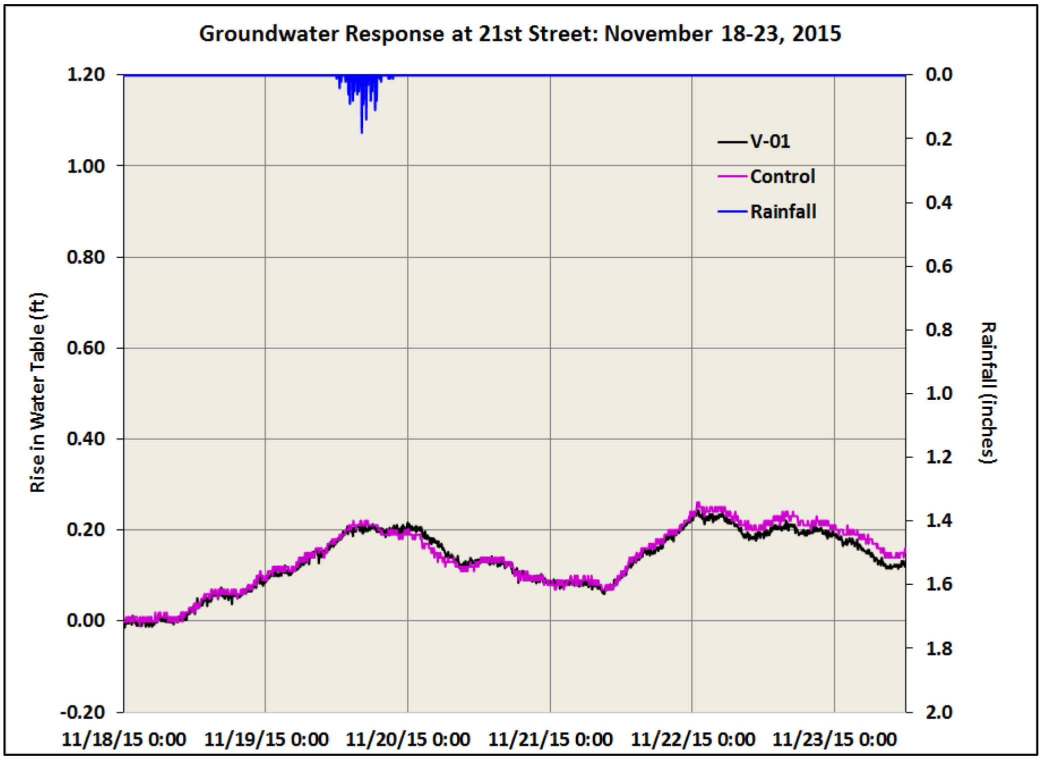


Figure 3-38: Groundwater Response of 21st St. and Venango

3.6 Discussion

The analysis of infiltration rate, recession duration, inlet performance, and water budget all indicate that the GSI systems are outperforming their conservative design specifications. Monitoring analysis and field observations have led to modifications that increased performance and verify subsurface water movement. This includes inlet modifications which helped increase capture efficiency.

The rainfall analysis revealed that two of the four monitoring years were comparatively wetter than the long-term average, however no reduction in performance was seen during these periods. An analysis of three systems' response to a 5 inch storm, the largest event during the monitoring period, revealed that two of the systems completely managed the event, and the other managed most of the runoff.

The observed post-construction recession rates exceeded the saturated vertical infiltration rates observed in pre-construction testing for most sites and events. Only three of the 25 systems had consistently lower infiltration rates than the pre-construction test, and these rates were still within the same order of magnitude. The higher post-construction recession rates also led to faster draindown durations and less system overflows. Of the 5,027 monitored system-events, the systems filled to capacity only 22 times, resulting in 18 instances where runoff overflowed into the downstream combined sewer. Six systems had events where the storage was estimated to take longer than 72 hours to drain completely, however there was only one instance where the recession duration impacted the next event and caused the system to overflow. In this instance, the excess water overflowed into another system, and was thus managed and did not enter the sewer system.

An analysis of the percent of storage used during rainfall events showed that events 2 inches and below had a mean percent of storage used of less than 50%, with many systems managing a storm greater than 3 inches. During the simulated runoff tests, which are intended to subject a system to its design storm, only one of the systems completely filled, with an average storage use of 55%. This indicates that the systems are consistently able to manage rainfall events in excess of their designed capacity.

Two of the monitored systems are permeable pavement and were analyzed to assess infiltration performance. The permeable surfaces at the Southwest Water Pollution Control Plant (SWWPCP) parking lot have infiltration rates ranging from 120 in/hr to over 2,000 in/hr. The permeable asphalt at Percy St. has relatively lower rates due to heavy use, with sectional rates ranging from 30 in/hr to 400 in/hr. However, both systems can effectively capture and manage a 2.5 in/hr intensity, which is the peak 15-minute rainfall intensity during a typical year in Philadelphia.

4.0 Construction Cost

This section describes the data acquisition methods and analysis techniques for evaluating the relationship between the Pilot Variables and construction cost performance metrics. It also discusses findings for significant relationships identified during the analysis.

4.1 Data Collection

As explained in the Long Term Control Plan Update (LTCPU) supplemental documentation Volume 3, Basis of Cost Opinions, capital cost consists of construction and non-construction components. Capital costs are considered implementation costs and include the costs incurred until an infrastructure asset is considered operational. Construction cost includes the cost of building new facilities, upgrading or expanding existing facilities, and rehabilitating existing facilities. Since PWD contracts design and construction separately, the total construction cost is represented by the construction contractor's bid. Construction costs include general conditions, overhead and profit, mobilization, demobilization, contractor's bonds and insurance, and subcontractor markups. Non-construction costs include all costs other than the contractor's costs such as design, site investigation, and construction management costs. For the purposes of the Pilot Program Final Report this section will only evaluate and discuss the analysis of construction cost for projects and systems PWD implements on public property, primarily in the right of way. Operation and maintenance cost is discussed and evaluated in the Section 5 (Maintenance) of this report.

PWD records costs for public projects in the Capital Program Integrated Tracking (CAPIT) database by the Work Number, which is typically a package of one or more site locations where Green Stormwater Infrastructure (GSI) is designed and implemented. More detailed data are tracked in the “GreenIT” database, a regulatory compliance tracking database. Additionally, PWD has developed the Master Access Database (MAD), to pull data from several databases, and synthesize data that is otherwise not available together through the respective interfaces. Construction cost data in this analysis is from MAD.

As noted, this section evaluates and discusses analyses of construction cost for projects and systems constructed by PWD on public property. Programmatic costs would be inclusive of all projects funded by the capital program of PWD. Other GSI implementation avenues (Stormwater Management Incentive Program and Greened Acre Retrofit Program) are known to have lower costs to PWD per unit of impervious area managed through leveraging other property owners’ actions and investments in stormwater management.

4.2 Analysis Methods and Tools

The analysis of construction cost categorized values by Work Numbers and by individual GSI systems. In addition, cost data were categorized by respective bid opening years, contractors, hydraulic loading ratios, and GSI system types, as applicable. Linear regressions were applied to investigate the potential significance of the relationship between cost and drainage area at both the Work Number and GSI system level. Results of the analyses are presented in graphical form, most frequently presented as a boxplot.

To adjust for market inflation over time, the Engineering News Record Construction Cost Index (ENR CCI) is used to adjust all projects' construction costs from their bid opening year to the most current index value. The January CCI of each year was selected for the CCI for that entire year.

In order to determine if any of the Pilot Variables have an impact on construction cost of GSI, the construction cost for each system in 2015 dollars, normalized by directly connected impervious area in acres, was formulated into performance metrics to be run through the Framework statistical screen. Box plots of construction cost by Variable were generated and evaluated to determine any potential drivers of cost. Levels of each Variable where the sample size was less than five were excluded from the box plots.

4.3 Findings

The median construction cost per unit of impervious drainage area was $353,719/ac, as shown in Figure 4-1 (all cost values are given in 2015 dollars unless otherwise noted). This number can be placed in the following context:

- The *Long Term Control Plan Update* planning assumption range was $155,000/ac-$332,000/ac.
- Median construction cost per unit of storage volume (Greened Acre) is $248,365/ac-in ($9.65/gal) (Figure 4-2).

In data from the first five years of the program, a clear trend could not be identified in construction cost with respect to time or with respect to cumulative implementation amount. This is visualized by Figure 4-3 and Figure 4-4, respectively.

Several economy of scale effects are evident in the data:

- Construction cost per unit area exhibits economies of scale with respect to both contract size (measured by total drainage area), as demonstrated in Figure 4-5, and with respect to drainage area per individual system, shown in Figure 4-6.
- The economy of scale effect is also visible with respect to cost per unit storage volume, as seen in Figure 4-7.

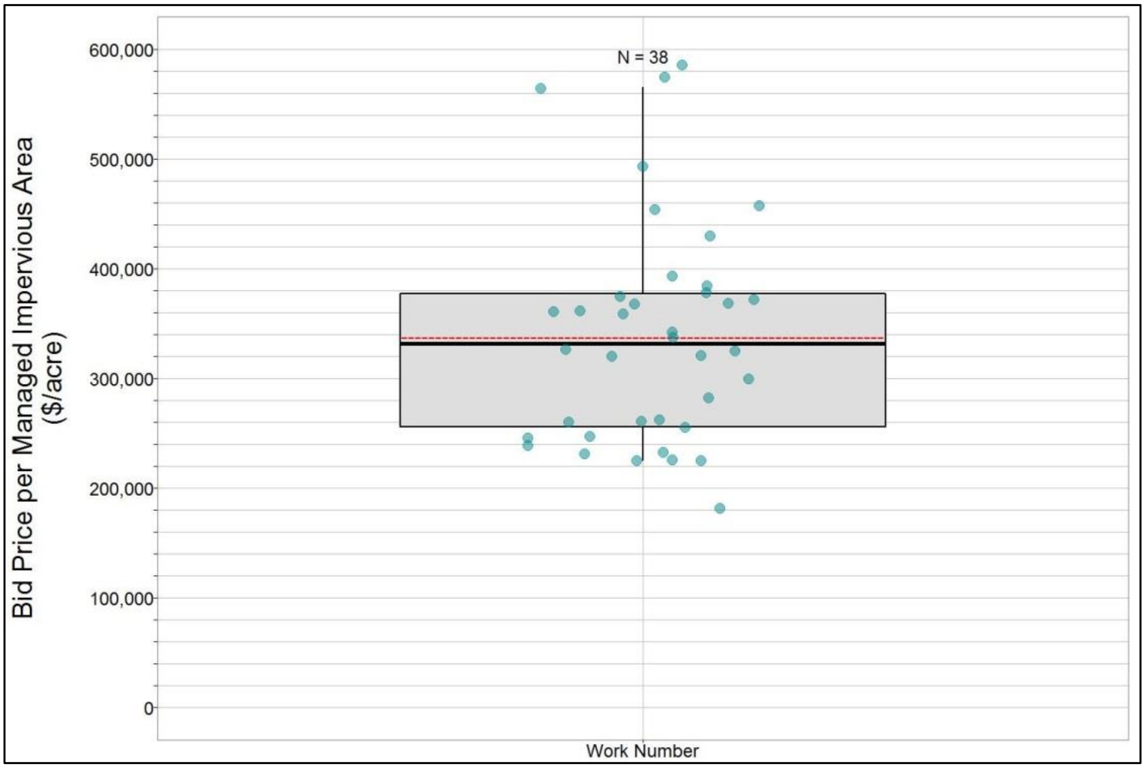


Figure 4-1: Bid Price per Managed Impervious Area in 2015 USD, by Work Number

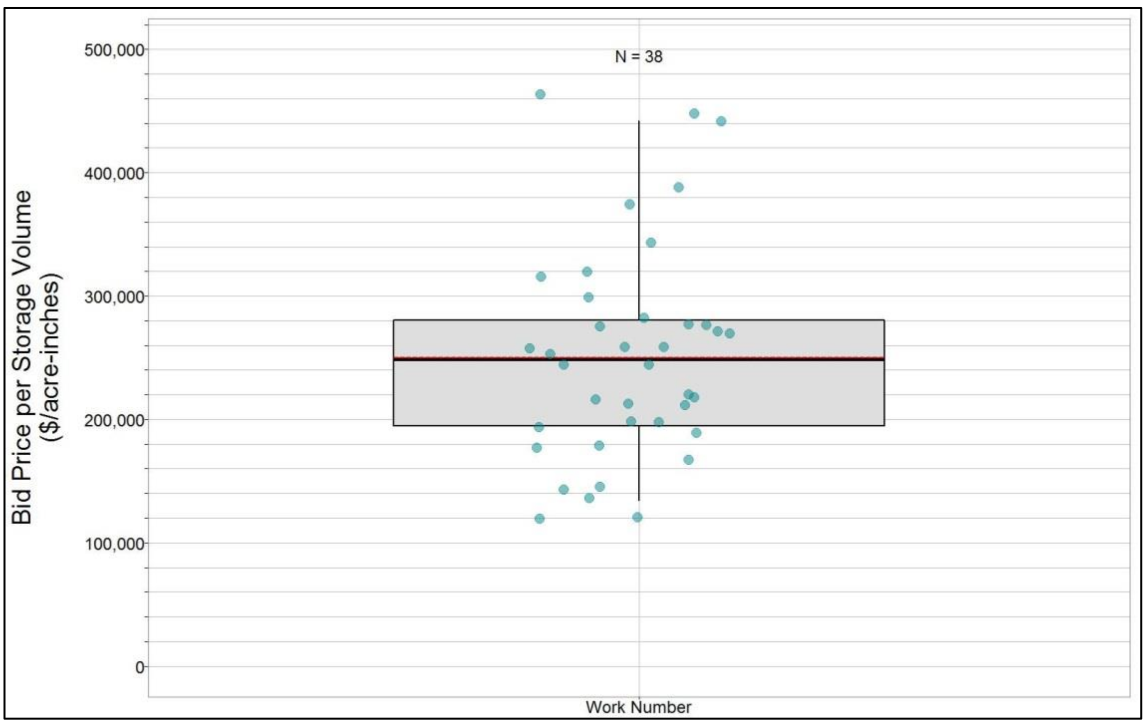


Figure 4-2: Bid Price per Storage Volume in 2015 USD, by Work Number

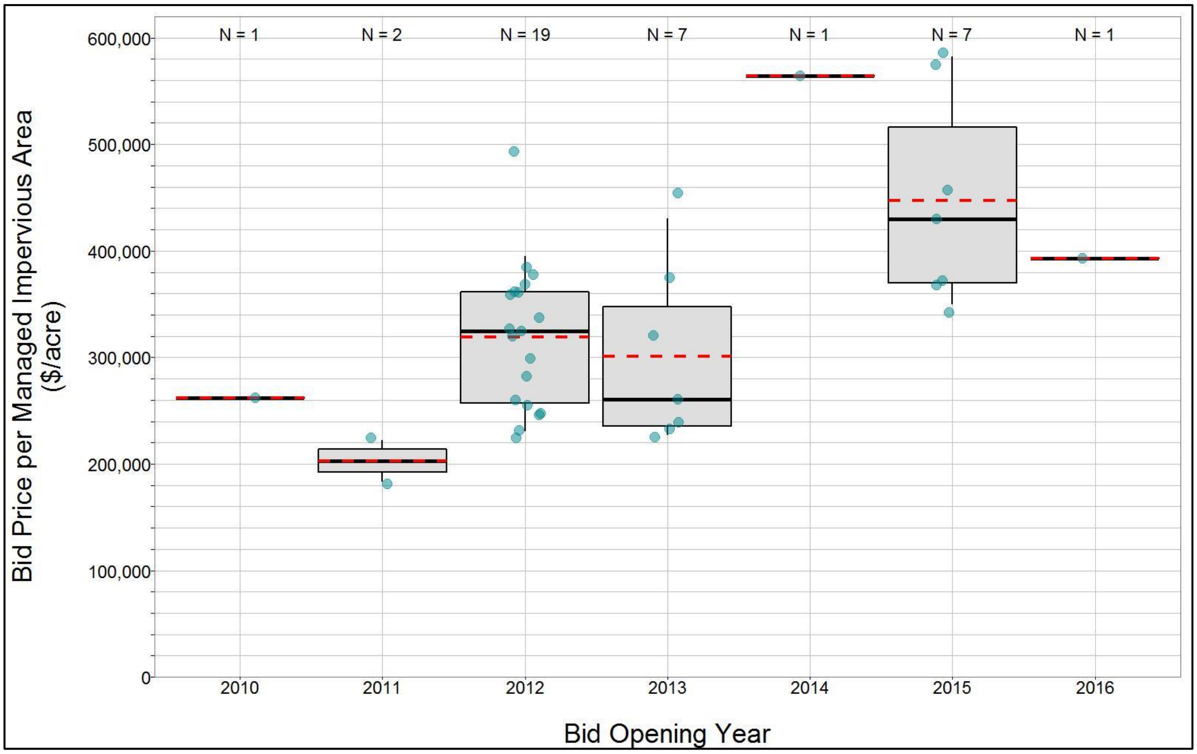


Figure 4-3: Bid Price (2015 USD) per Managed Impervious Area by Bid Opening Year

Figure 4-4: Learning Curve (Bid Price per Managed Impervious Area by Cumulative Managed Impervious Area)

Figure 4-5: Bid Price (2015 USD) per Managed Impervious Area by Total Managed Impervious Area per Work Number

Figure 4-6: Bid Price (2015 USD) per Managed Impervious Area by Total Managed Impervious Area per System

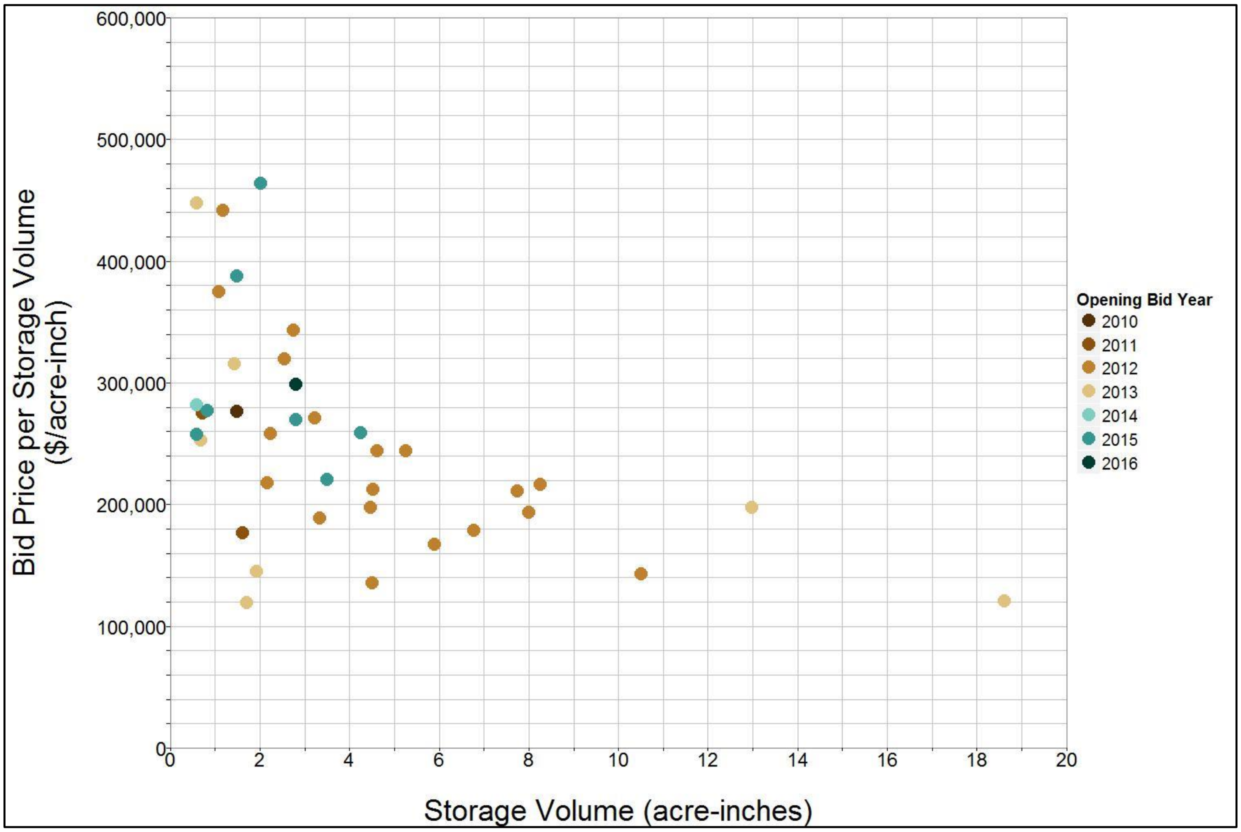


Figure 4-7: Bid Price per Storage Volume by Storage Volume per Work Number

4.3.1 Domed Riser Depth

This Variable is defined as the distance between the domed riser grate opening and the soil surface. Levels of this Variable include the following: Shallow (≤ 3 inches), Medium (4 - 6 inches), Deep (> 6 inches), and No Domed Riser.

Systems with the deeper ponding depth (with risers highest above the soil surface) tended to have a lower construction cost (Figure 4-8).

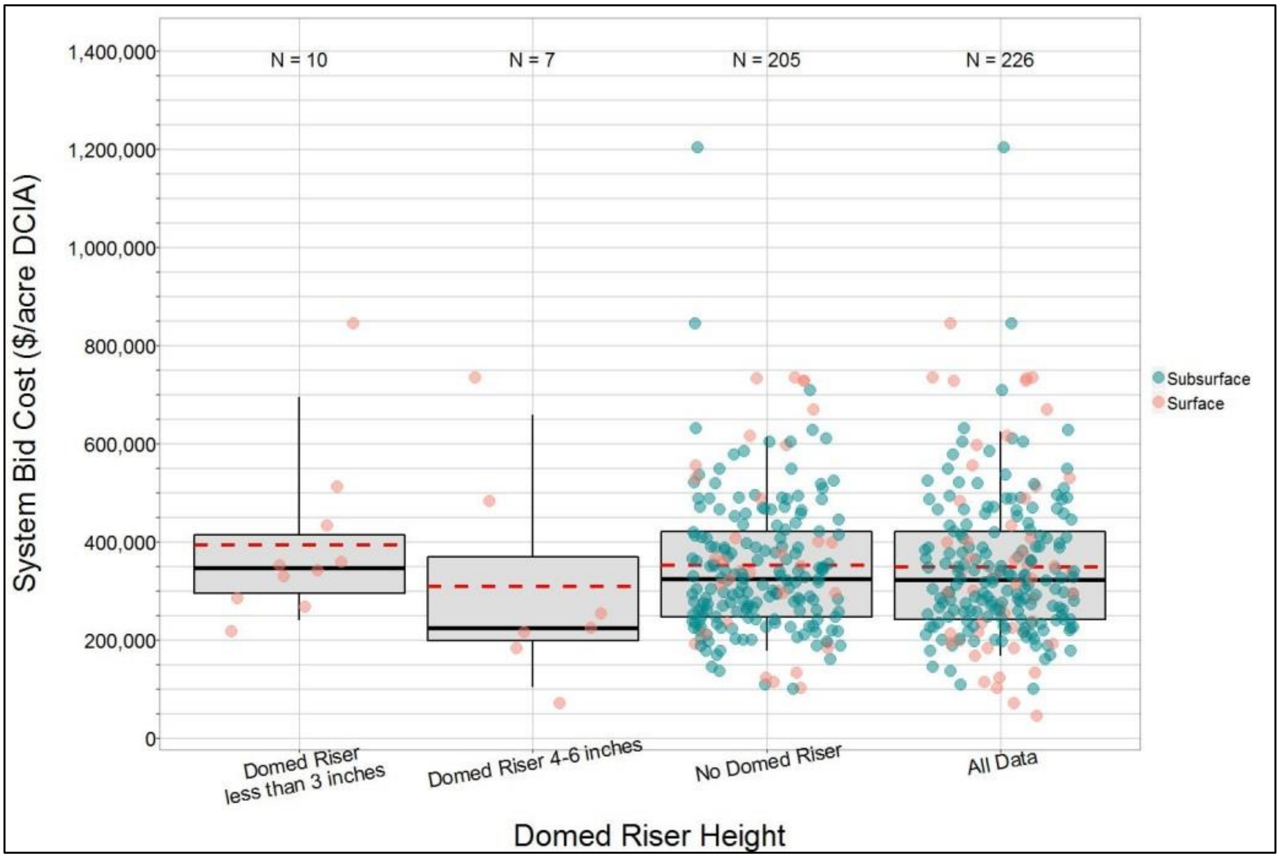


Figure 4-8: Bid Price per Managed Impervious Area (2015 USD) by Domed Riser Height

4.3.2 GSI System Type

This Variable is defined as the type of GSI system design. Levels of this Variable include the following: Bumpout, Bumpout and Storage Trench, Planter, Planter and Storage Trench, Tree Trench, Infiltration/Storage Trench, Subsurface Basin, Permeable Pavement, Rain Garden, Rain Garden with Extended Storage, Swale, Green Roof, Blue Roof, and Drainage Well.

Figure 4-9 shows the bid costs broken down by GSI system type. Some clear trends are seen, with higher unit costs for infiltration/storage trenches and systems with planters.

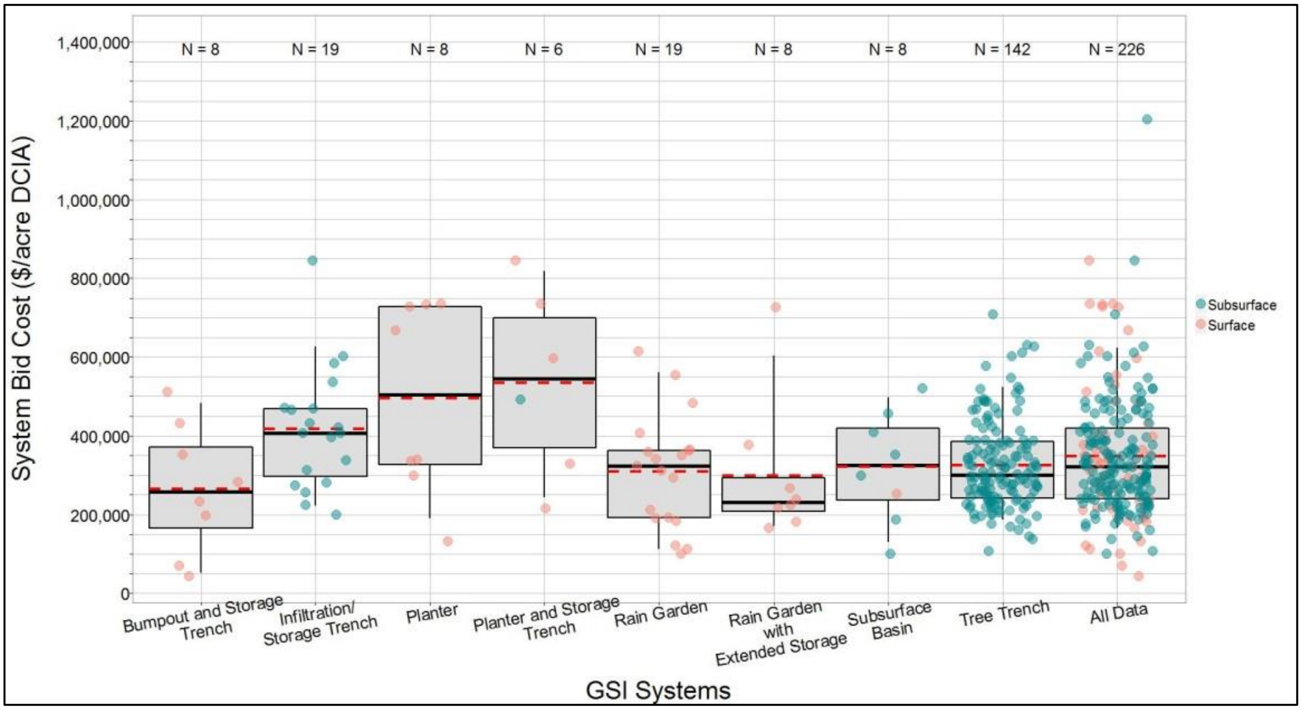


Figure 4-9: Bid Price per Managed Impervious Area (2015 USD) by GSI System Type

4.3.3 Loading Ratio

This Variable is defined as ratio of the Directly Connected Impervious Area (DCIA) to the system footprint. Levels of this Variable include the following: Low (<10), Medium (10 – 15), and High (>15).

Systems with lower loading ratios had higher construction costs per unit drainage area than systems with loading ratios above 10:1.

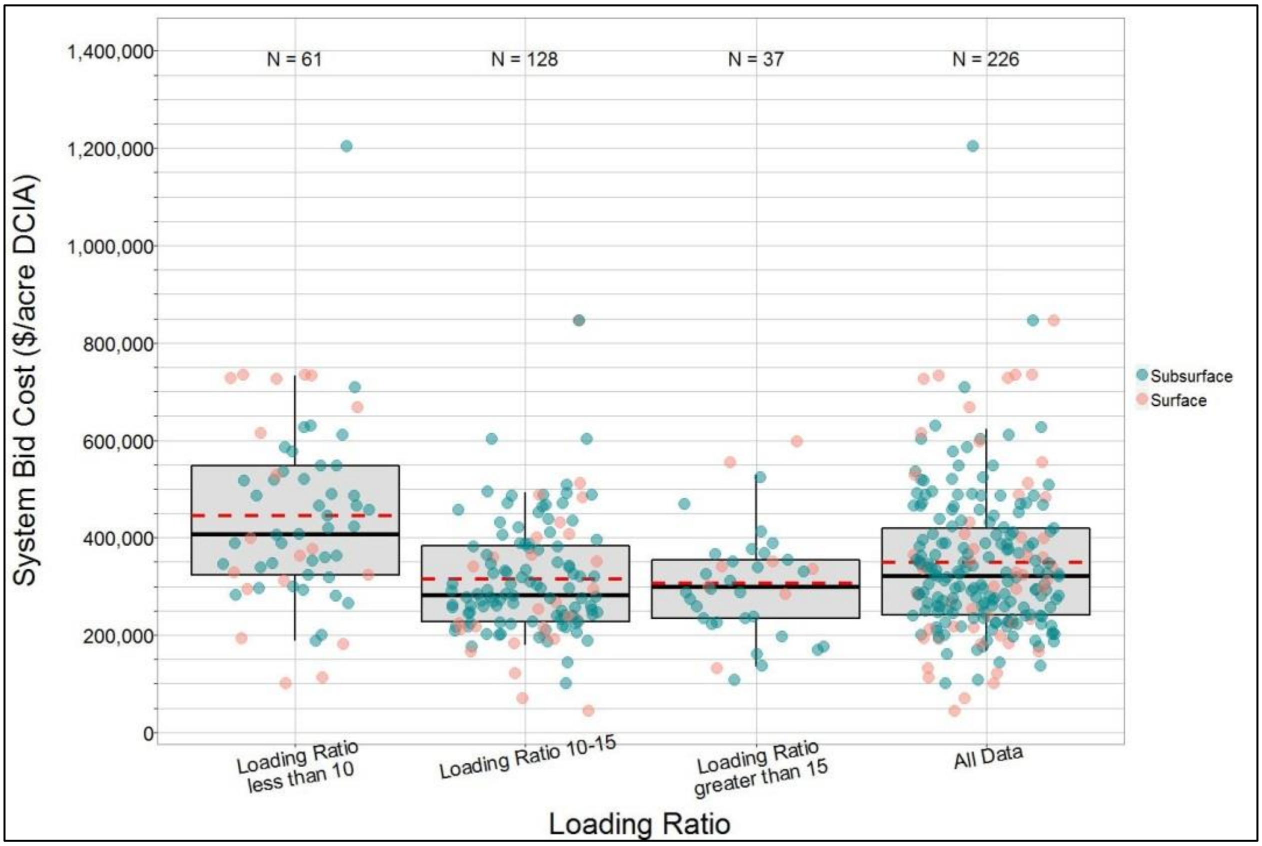


Figure 4-10: Bid Price per Managed Impervious Area (2015 USD) by Loading Ratio

4.3.4 Physiographic Province

This Variable is defined as the physiographic province in which the GSI system is located. Levels of this Variable includes the following: Piedmont and Coastal Plain.

Systems located in the Piedmont physiographic province had lower unit cost than those located in the Coastal Plain.

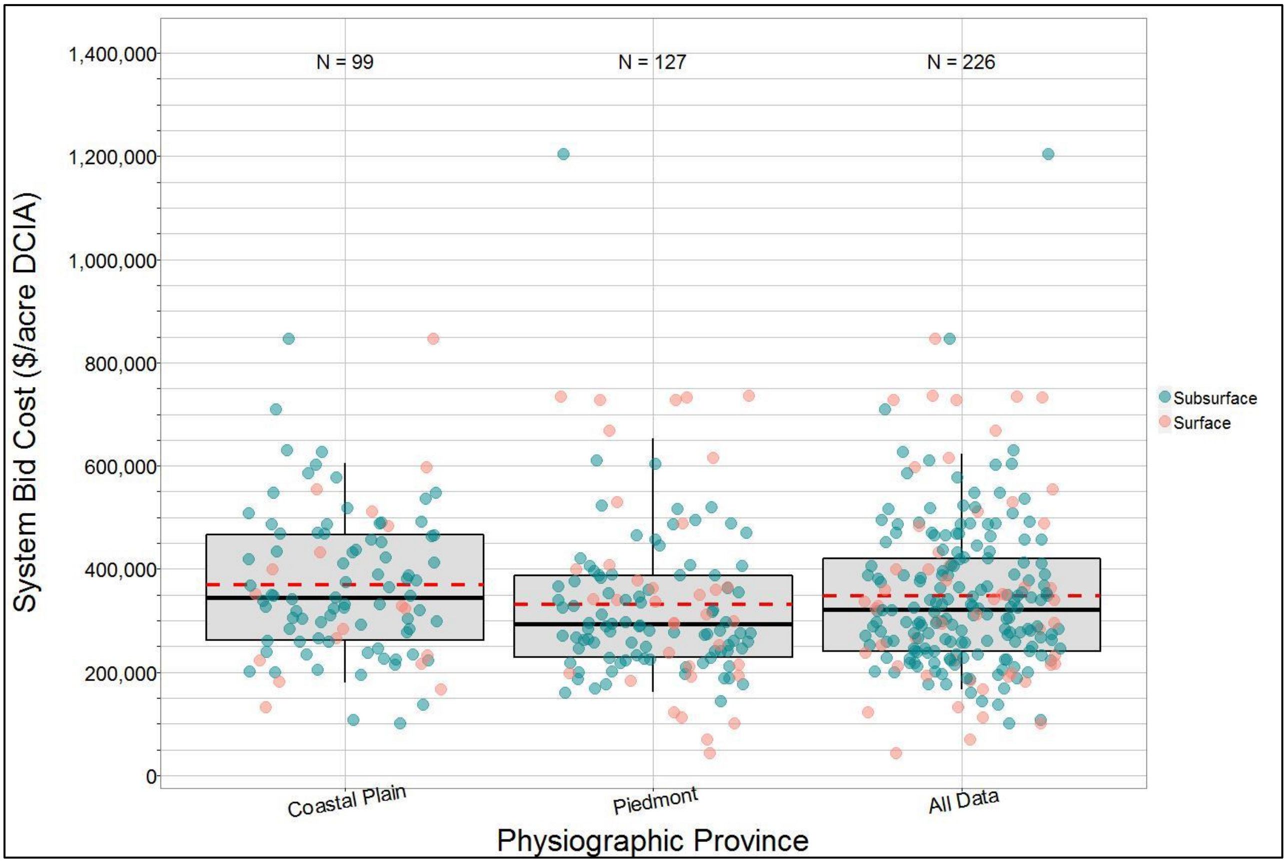


Figure 4-11: Bid Price per Managed Impervious Area (2015 USD) by Physiographic Province

4.3.5 Street Crossing

Street Crossing refers to whether or not runoff is conveyed across a street to a GSI system and how it is conveyed.

Systems where runoff is conveyed across the street have lower unit costs than systems without the additional conveyance.

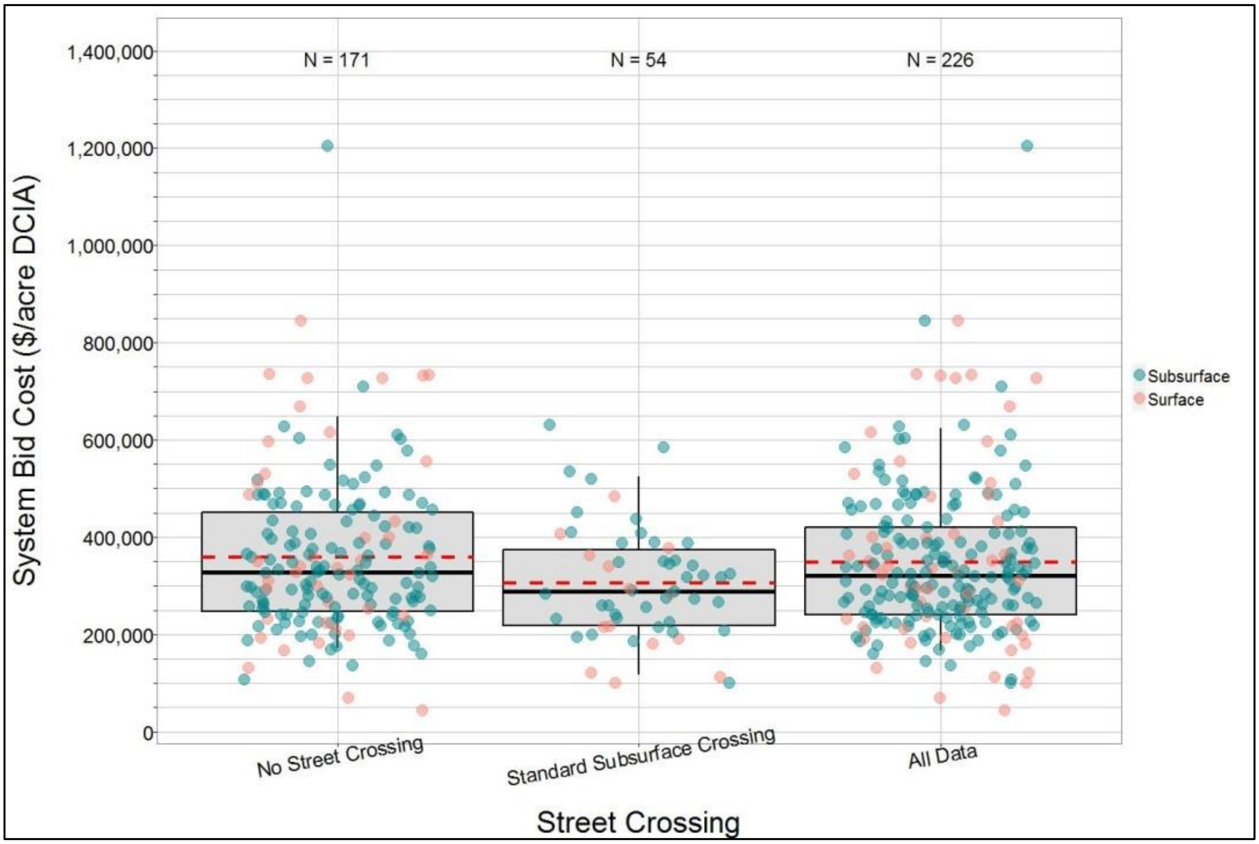


Figure 4-12: Bid Price per Managed Impervious Area (2015 USD), with and without Street Crossing

4.3.6 Static Storage Volume

This Variable is defined as the available static storage volume of the system, expressed in inches of runoff over the DCIA. The Levels of this Variable include: Low (< 1.0 inch), Medium (1.0 – 1.5 inches), and High (> 1.5 inches).

The box plots for unit cost broken down by static storage volume showed that total storage volume does not have much of an impact on cost. The median unit costs for all three categories are within a very small range.

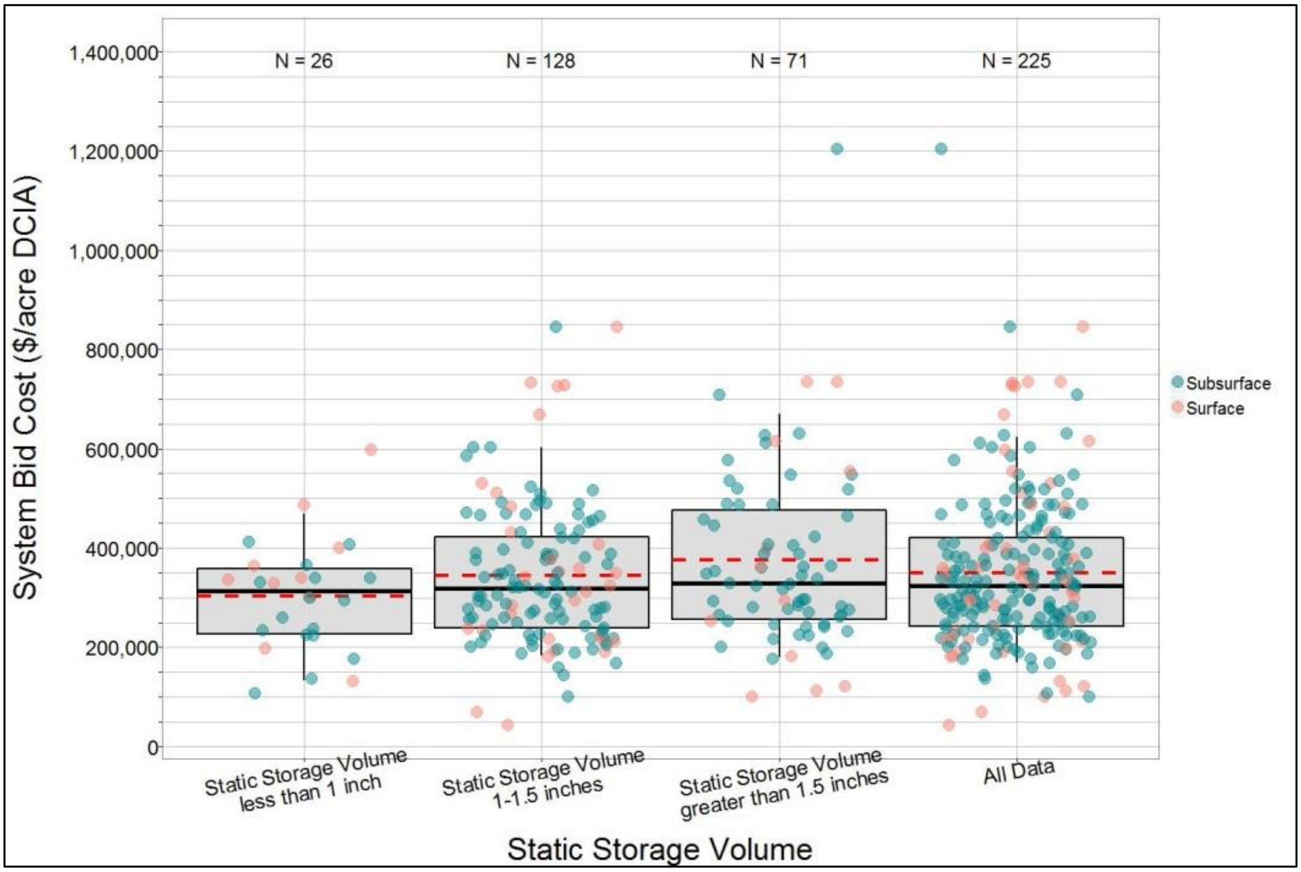


Figure 4-13: Bid Price per Managed Impervious Area (2015 USD) by Static Storage Volume

4.3.7 Land Use Type

This Variable is defined as the type of land use on which the footprint of the GSI system is located. Levels of this Variable include the following: School Yard or School Perimeter, Recreation Center, Open Space Park Site, Traffic Triangle, Streets, High Density Residential Street, Median, Alley – Private, Alley – Public, Athletic Field, Commercial Corridor, Parking Lot – Private, Parking Lot – Public, Vacant Land – Private, and Vacant Land – Public. Definitions of these Variables can be found in Appendix A (Pilot Variable Framework).

Land use did not appear to have a significant impact on construction cost.

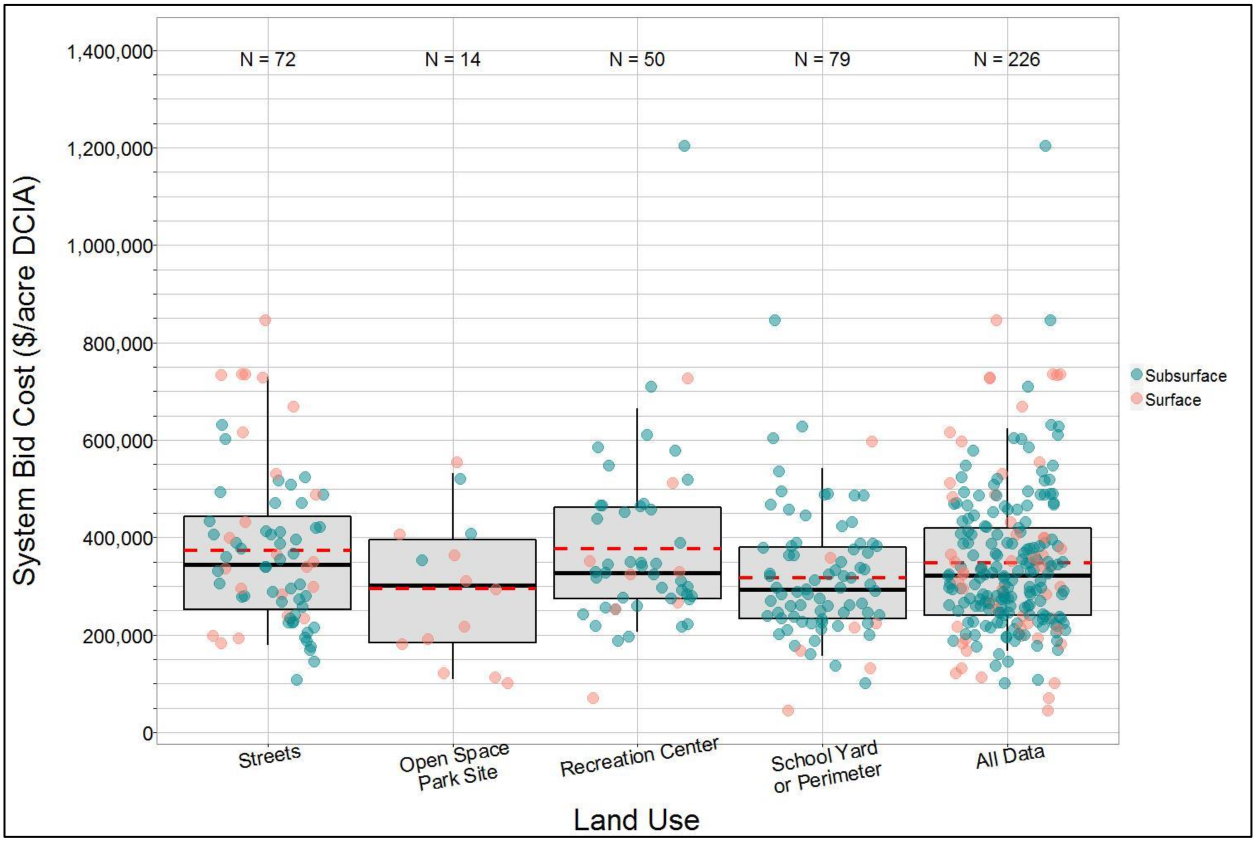


Figure 4-14: Bid Price per Managed Impervious Area (2015 USD) by Land Use

4.4 Discussion

A large driver of construction cost of GSI seems to be the amount of concrete work that is needed. This is apparent in the trend of cost per acre for the various GSI system types, where systems with the most concrete work–planters, infiltration/storage trenches–have the highest median cost. In addition to repaving costs, planters also typically have concrete walls that are formed in place within the footprint of the storage media, which tends to be costly. The two system types with the lowest median costs contain both surface vegetated features (bumpouts, rain gardens) and subsurface storage. The additional storage provided by the open surface area and the reduction of repaving requirements could be a factor in this trend. It is also interesting to note that while tree trenches and infiltration/storage trenches are very similar in design, they have significantly different median construction costs per acre of drainage area.

Loading ratio, or the impervious drainage area divided by the system footprint, also showed a significant trend in construction cost, where the systems with loading ratios less than 10 had a much higher unit cost. This is likely due to the fact that a greater area of earth disturbance is required for construction per unit drainage area, meaning more depaving and repaving costs. It is typically cheaper to add storage volume by increasing depth over a smaller area (within practical limits to not require sheathing and shoring) than to increase footprint.

Following a similar trend, systems that capture larger drainage areas by conveying runoff across the street tend to have lower unit costs. This is likely due to the fact that it is relatively inexpensive to increase storage volume for a system already being constructed, so increasing the drainage area for one system will be cheaper than constructing a completely separate system to capture that additional area.

Physiographic province showed a significant trend in cost, with systems in the Piedmont costing about $50,000/acre less than systems in the Coastal Plain. It is unlikely that the underlying geology has much of a causal relationship with higher or lower costs. However, it could be a coincidental correlation due to the relative urban density in different parts of Philadelphia. Much of the Coastal Plain is comprised of south Philadelphia, Center City, and neighborhoods along the Delaware River like Northern Liberties, Kensington, Port Richmond, and Frankford. These areas are all very dense urban environments, with row homes, narrow streets and sidewalks, and limited space. This could be a factor that increases construction complications, effort, and cost. On the other hand, much of the Piedmont area is more spread out, including the northern part of west Philadelphia in neighborhoods like Overbrook and northwest Philadelphia. These areas seem to have more space and larger open parks that could make construction less costly. It is unknown if this is a true driver of cost, but it will be an interesting trend to continue to follow, especially considering that systems in the Piedmont tend to also have much better infiltration performance, as discussed in Section 3 (Performance).

Two variable groups where a significant trend could have been expected, but was not observed, were static storage volume and land use. It would make intuitive sense to think that adding storage volume, increasing excavation and material volumes, would result in an increased unit cost, but that trend was not seen in the data. For land use, although streets projects had a slightly greater median cost than systems in open space parks or around recreation centers and schools, it was not a statistically significant result.

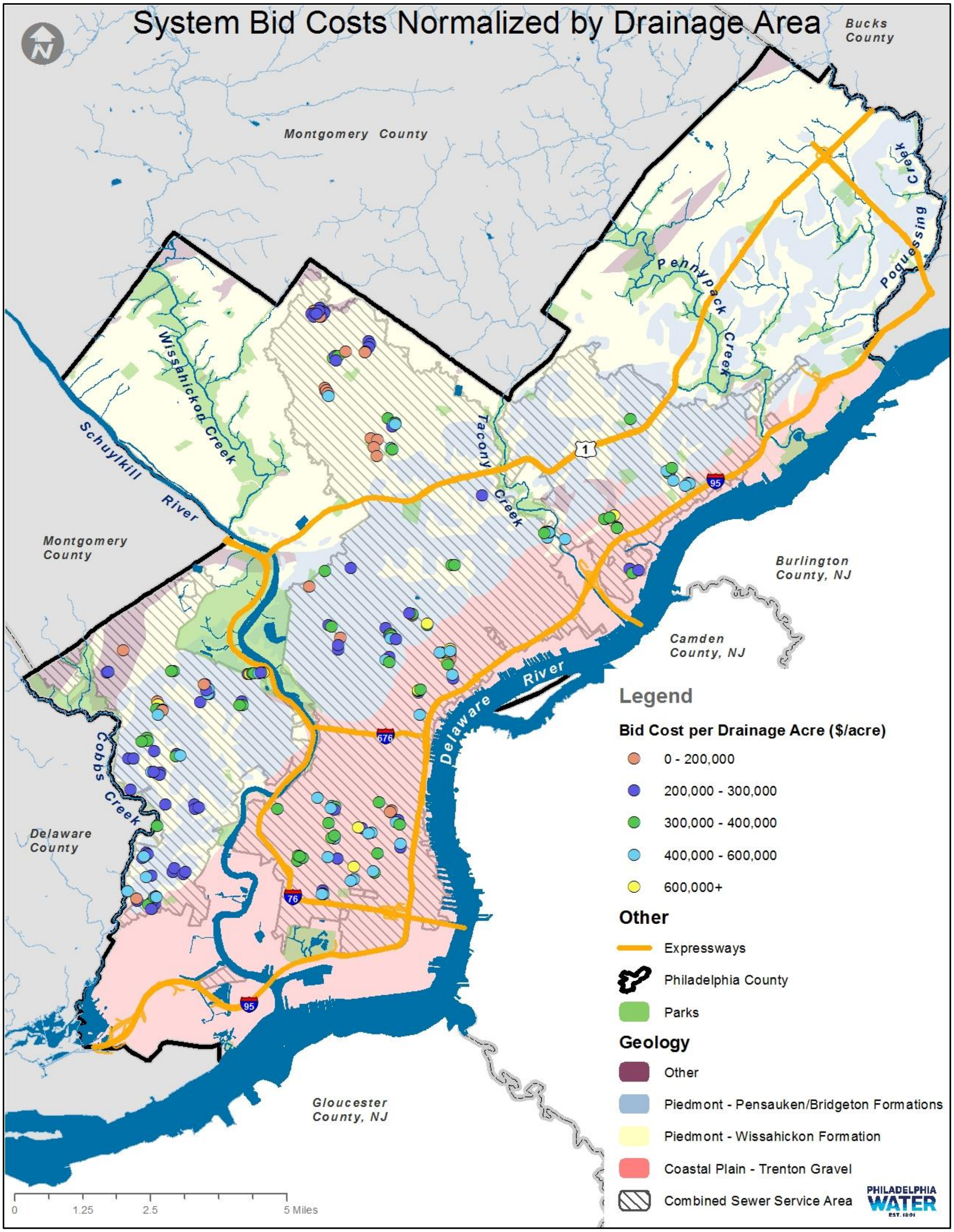


Figure 4-15: Cost per Managed Impervious Area by Physiographic Province

5.0 Maintenance

This section describes the data acquisition methods and analysis techniques for evaluating the relationship between the Pilot Variables and maintenance performance metrics. It also discusses findings for significant relationships identified during the analysis.

5.1 Data Collection

Data related to Green Stormwater Infrastructure (GSI) maintenance are tracked in a database, called CityWorks, populated by work orders and reports generated from field activities. The data tracked for each work order include, but are not limited to, subsurface maintenance cost, surface maintenance cost, and volume of material removed (sediment, debris, and organic material). These data were aggregated by month for each GSI system being maintained. The available data were collected from November 2014 through December 2015. While many systems were being maintained since the beginning of the *Green City, Clean Waters* program in 2011, the CityWorks database first came into full utilization for GSI maintenance in November 2014, and is considered to contain the most reliable data for analysis. Any conclusions from this analysis should take into account that this is a very limited dataset, and data will continue to be collected and analyzed in the future. Table 5-1 summarizes the GSI Maintenance dataset collected for this analysis.

Table 5-1: GSI Maintenance Data Collected

Metric	Units	Number of Systems	Data Collection Frequency	Data Start	Data Finish	Total Data Points
Subsurface Cost	$	271	Year	Oct-14	Dec-15	330
Surface Cost	$	305	Month	Nov-14	Dec-15	3,732
Material Removed	CF	304	Month	Nov-14	Dec-15	3,715

5.2 Analysis Methods and Tools

The key GSI maintenance metrics analyzed were total maintenance cost and total volume of material removed. Other available data included maintenance labor hours, but it was found that these data closely aligned with the total maintenance cost data, and would not yield different results or trends. Total maintenance cost includes subsurface labor cost, surface labor cost, and surface material cost. Total volume of material removed includes sediment, debris, and organic material. Performance metrics were developed from these data which were run through the Pilot Framework statistical analysis to determine if any of the Pilot Variables showed trends that could be a potential driver of maintenance cost or material deposition.

5.2.1 Maintenance Cost

Subsurface maintenance typically occurs once per year, and involves flushing out subsurface distribution pipes and underdrains into inlets, and then vacuuming the material out of the inlets so that all subsurface infrastructure is clear of debris. Each subsurface maintenance event has a cost that is tracked, which includes labor and equipment cost. Each maintenance event occurs once per year, so this cost is considered the annual subsurface maintenance cost. Since data was tracked in FY15 and FY16, if two years of data was available, the average was calculated to represent the annual cost for that system. This cost has a relatively small range, between $500 and $2,000 per year (top and bottom 10% of systems removed), as seen in Figure 5-1.

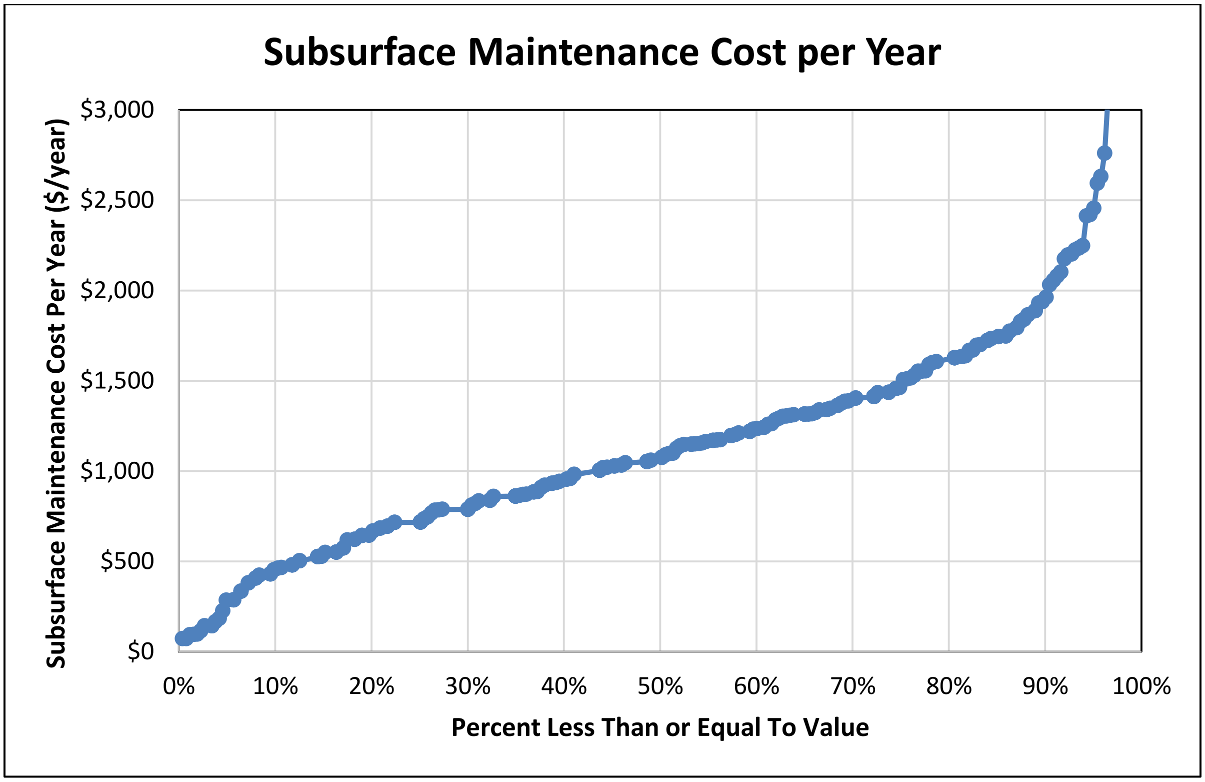


Figure 5-1: Cumulative Distribution Function (CDF) of Annual Average Subsurface Maintenance Cost for 263 GSI Systems between October 2014 and December 2015

Surface maintenance typically occurs once per month, which involves cleaning inlet filter bags, collecting deposited materials, weeding, pruning, and other reparative measures as needed. Most of these activities are expected to consistently occur in a typical year. However, there are some activities that occur on an as-needed basis that increase the total cost and are not expected to occur each year. These additional tasks may include plant watering, structural repairs, painting, graffiti removal, erosion repair, tree replacement, inlet frame replacement, soil replacement, etc. To account for this, surface maintenance costs were categorized as either “base maintenance” or “additional tasks,” and annual average costs were summed by the base maintenance costs and the total observed costs (including additional tasks).

To identify costs associated with as-needed tasks, monthly costs for each GSI system were flagged if they were either greater than $1,000 or showed a relatively high cost compared to other monthly costs for that system. Flagged costs were further investigated by reviewing the work orders submitted during that month, which typically list the specific activities in a comments section. If the activities were considered additional as-needed tasks, the costs associated with those activities were removed from the annual average base maintenance cost. Typical surface maintenance activities include:

- Base maintenance tasks (monthly, semi-annual, or annual)
  - Remove trash, sediment, and organic debris from Stormwater Management Practice (SMP) and all inlets
  - Pruning overgrown, dead, damaged, or diseased plants
  - Structural pruning
  - Cutting back of vegetation
  - Removing non-target/invasive vegetation
  - Mulching
  - SMP winterization
  - Herbicide application
- Additional tasks (as needed)
  - Plant watering
  - Settling repairs
  - Painting
  - Graffiti removal
  - Concrete repair
  - Erosion repair
  - Plant or tree replacement
  - Damaged inlet frame replacement
  - Soil replacement
  - Structural repairs
  - Additional maintenance of the surrounding area outside of the SMP on certain sites (aesthetic maintenance)

After all as-needed costs were separated, annual average base maintenance costs and total costs were calculated. Since the dataset for each GSI system ranged in total months of data, this was done by multiplying the average of all monthly costs by twelve. Annual averages were only calculated if a system had six or more months of data.

The annual average surface and subsurface costs were summed to calculate the total maintenance cost for each GSI system. Because the systems vary in size and configuration, the costs were normalized by drainage area and footprint to create the performance metrics to be run through the Pilot Framework statistical analysis.

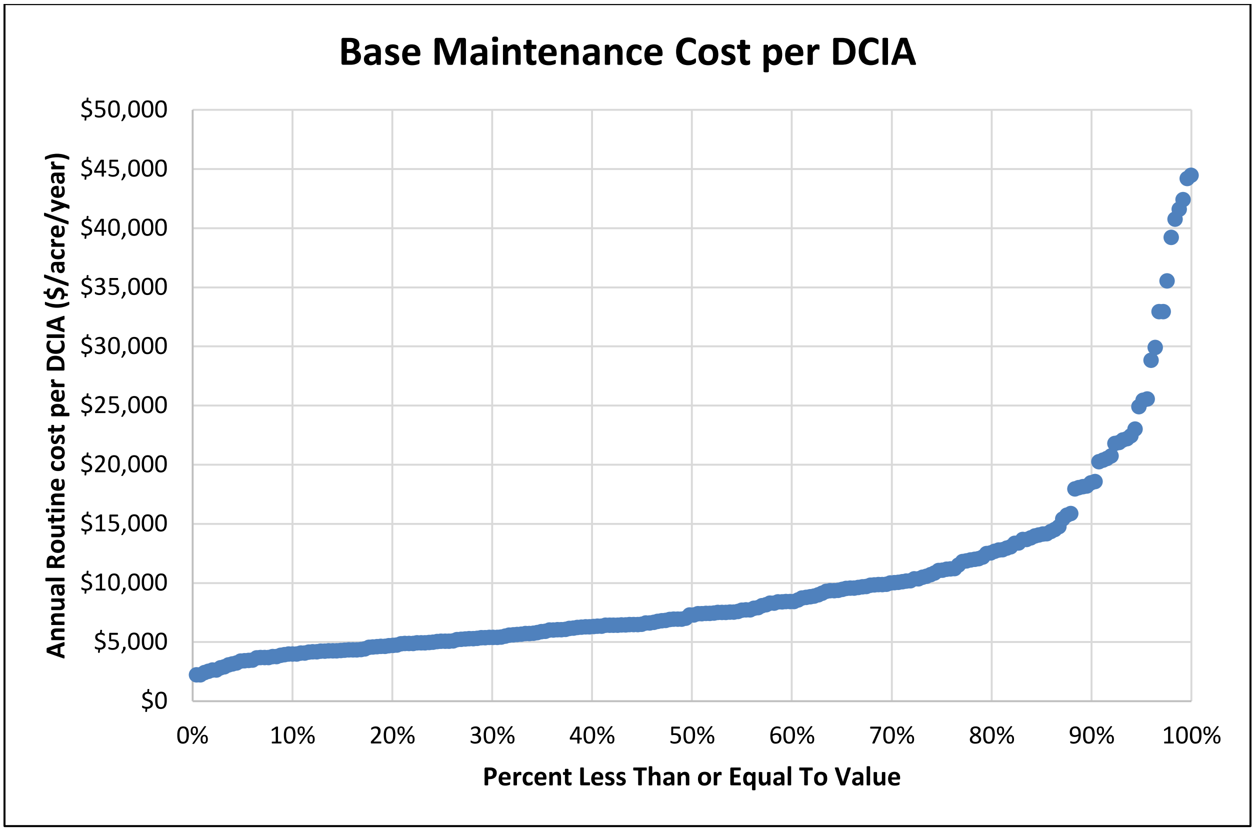


Figure 5-2: CDF of Base Maintenance Cost per Acre of Directly Connected Impervious Area (DCIA) per Year

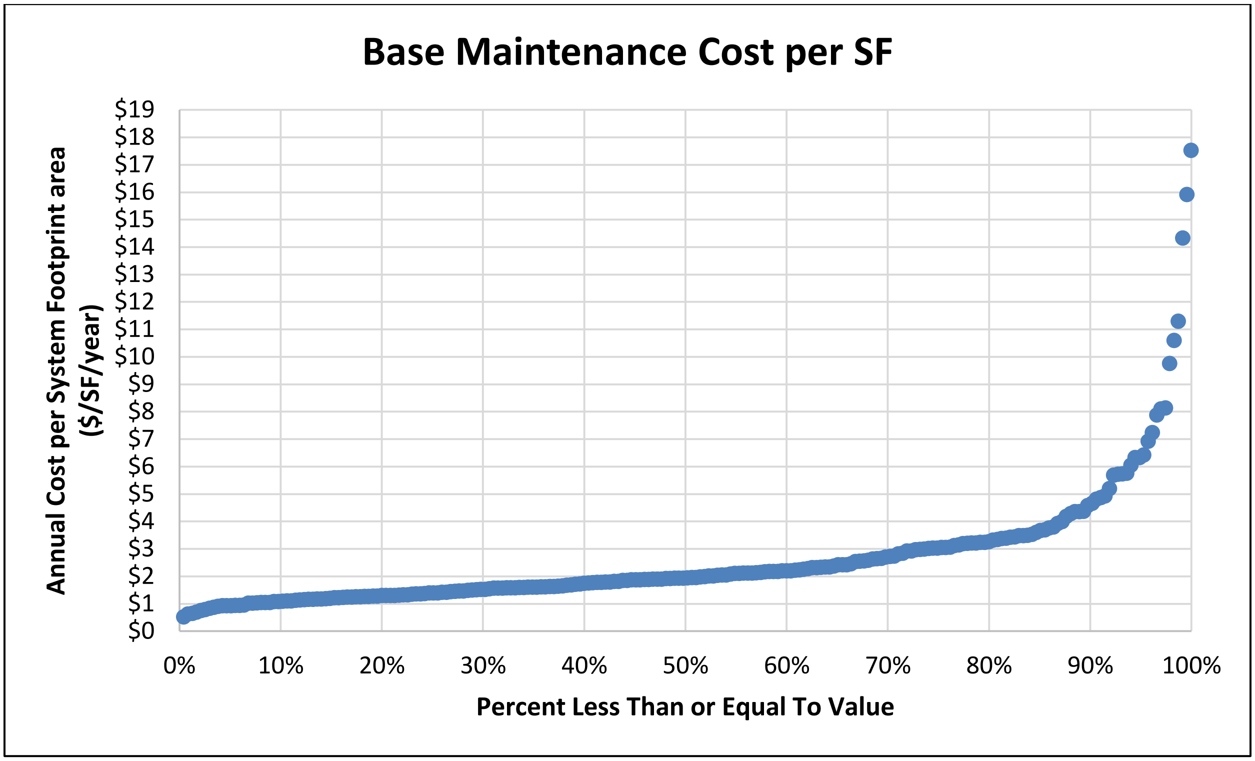


Figure 5-3: CDF of Base Maintenance Cost per Footprint Area per Year

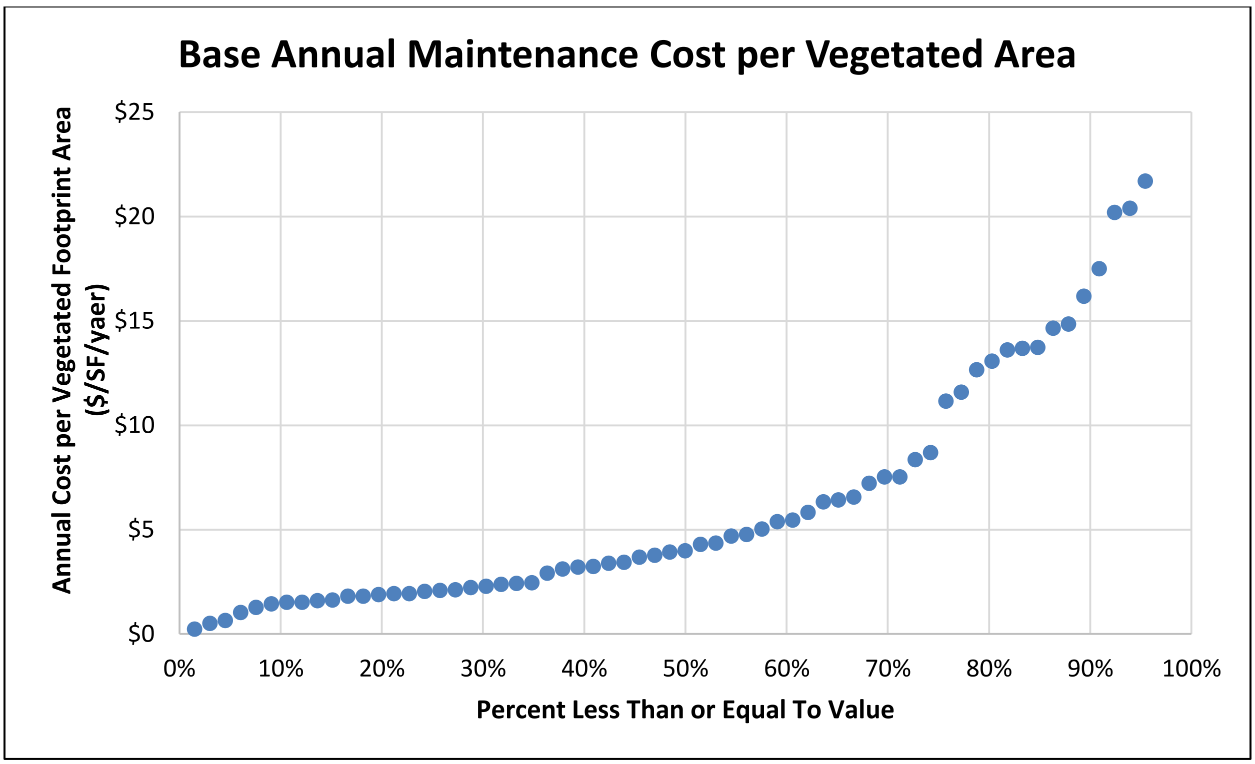


Figure 5-4: CDF of Base Maintenance Cost per Vegetated Footprint Area per Year

Some of the smallest sites resulted in very high normalized costs, likely due to some fixed costs such as mobilization and transportation. These sites would skew the results in the statistical analysis, so they were removed as follows:

- DCIA - remove sites less than 0.10 acres
- Footprint - remove sites less than 300 square feet
- Vegetated area - remove sites less than 300 square feet

These metrics were run through the Framework analysis to create box plots of the data broken down by the Levels of each Pilot Variable. The box plots were reviewed to see if there were any noticeable trends among the levels within each Variable. If a trend was identified, a possible causal link was investigated to determine if the variable was a likely driver of maintenance costs.

5.2.2 Total Material Removed

During monthly maintenance activities, any deposited material is removed from the vegetated surface and all inlet pretreatment devices accessible from the surface of the GSI system, as seen in Figure 5-5. This material is typically composed of trash, sediment, organic material, and other debris. The material is collected in standardized waste disposal bags with a known volume, and a total approximate volume of material, in cubic feet, is calculated and reported with each work order.

Figure 5-5: Tree trench inlet pretreatment device cleaning (left) and resulting volume of material removed from a rain garden (right) during example surface maintenance activities (source: The PWD)

The material removed data was aggregated by system for each month. The annual average material removed was calculated by multiplying the average of all monthly volumes by twelve. Because the systems vary in size and configuration, the costs were normalized by drainage area and footprint to create the performance metrics to be run through the Pilot Framework statistical analysis:

- Volume removed per DCIA per year (cf/acre/yr)
- Volume removed per system footprint area per year (cf/sf/yr)
- Volume removed per vegetated footprint per year (cf/sf/yr)

These metrics were run through the Framework analysis to create box plots of the data broken down by the levels of each Pilot Variable. The box plots were reviewed to see if there was any noticeable trend among the levels within each Variable. If a trend was identified, a possible causal link was investigated to determine if the Variable was a likely driver of unwanted material deposition.

5.3 Quality Control

In order to ensure the accuracy of the calculations and generated tables, all materials were checked for quality assurance. All spreadsheets, formulas, and assumptions were checked. In addition, several systems were spot checked by following the raw data through the analysis and eventually to the final box plots in order to assure the values are accounted for throughout the analysis.

5.4 Findings

5.4.1 Maintenance Cost

Box plots were generated to compare the maintenance data for every Variable. Although most Variables yielded results that did not indicate a clear relationship between the different Levels and either maintenance cost or material deposition, one clear trend did emerge. The greatest driver of maintenance cost appears to be whether or not there are vegetated surface features associated with the system (Figure 5-6, Figure 5-7).

Several Variables showed this trend, but the higher costs were always for Levels associated with surface vegetated surface features. For example, in the GSI System Type Variable, the Levels with the higher costs were bumpouts and rain gardens, while the Levels with the lower costs were subsurface basins, tree trenches, and infiltration/storage trenches (Figure 5-8, Figure 5-9).

This same trend appeared for the Inlet Type Variable, where systems with curb cut inlets, typically part of surface vegetated systems, had a higher cost than inlets typically part of subsurface systems such as highway grate inlets (Figure 5-10, Figure 5-11). The inlet type on its own does not appear to be a driver of cost.

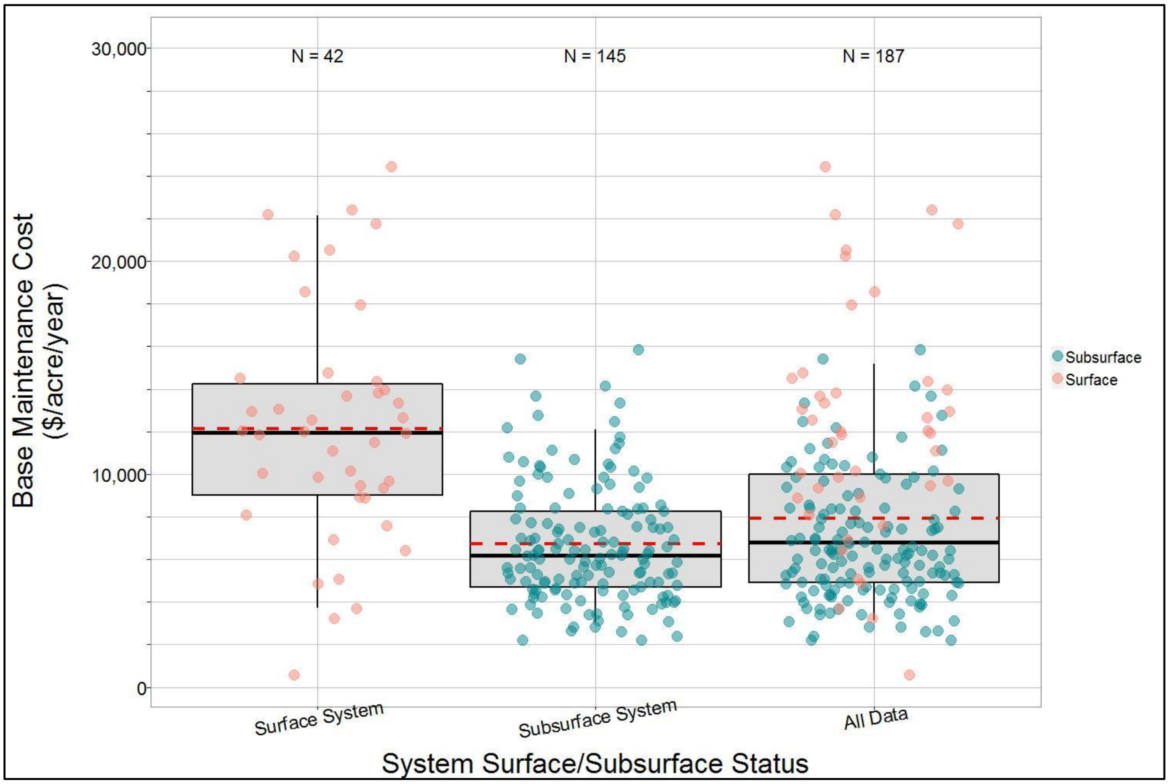


Figure 5-6: Base Maintenance Cost per DCIA per Year, Surface v. Subsurface

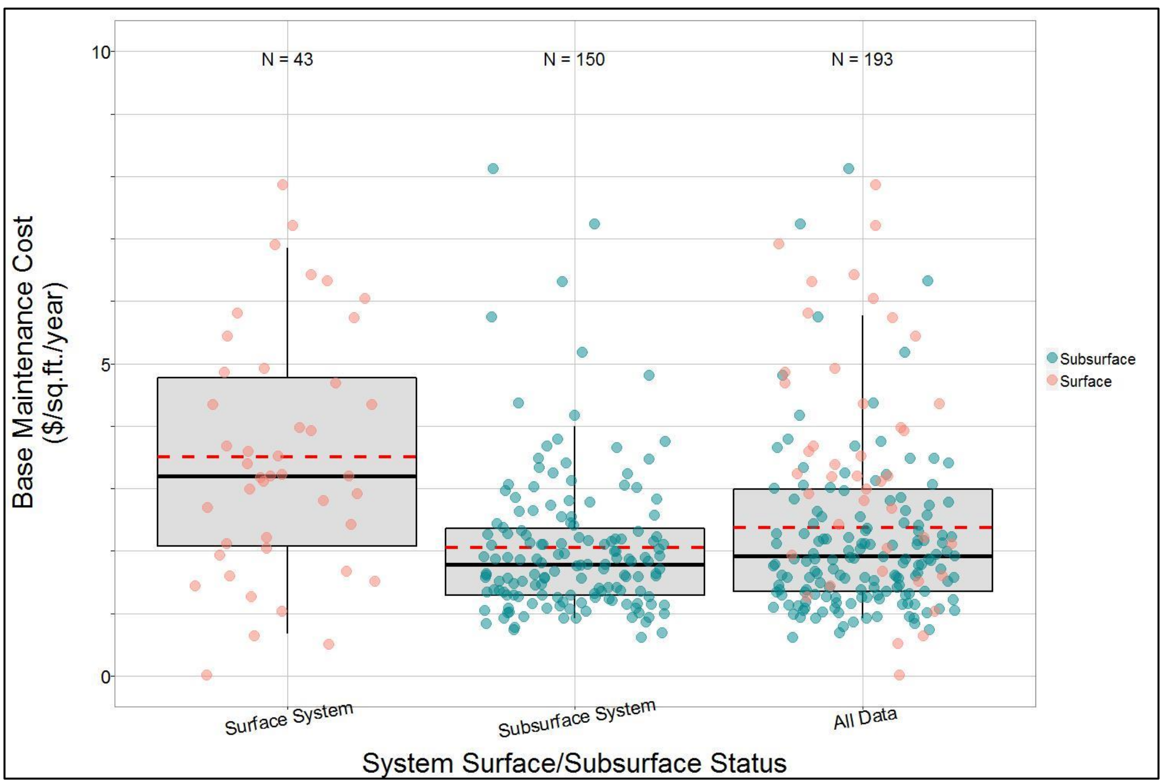


Figure 5-7: Base Maintenance Cost per System Footprint per Year, Surface v. Subsurface

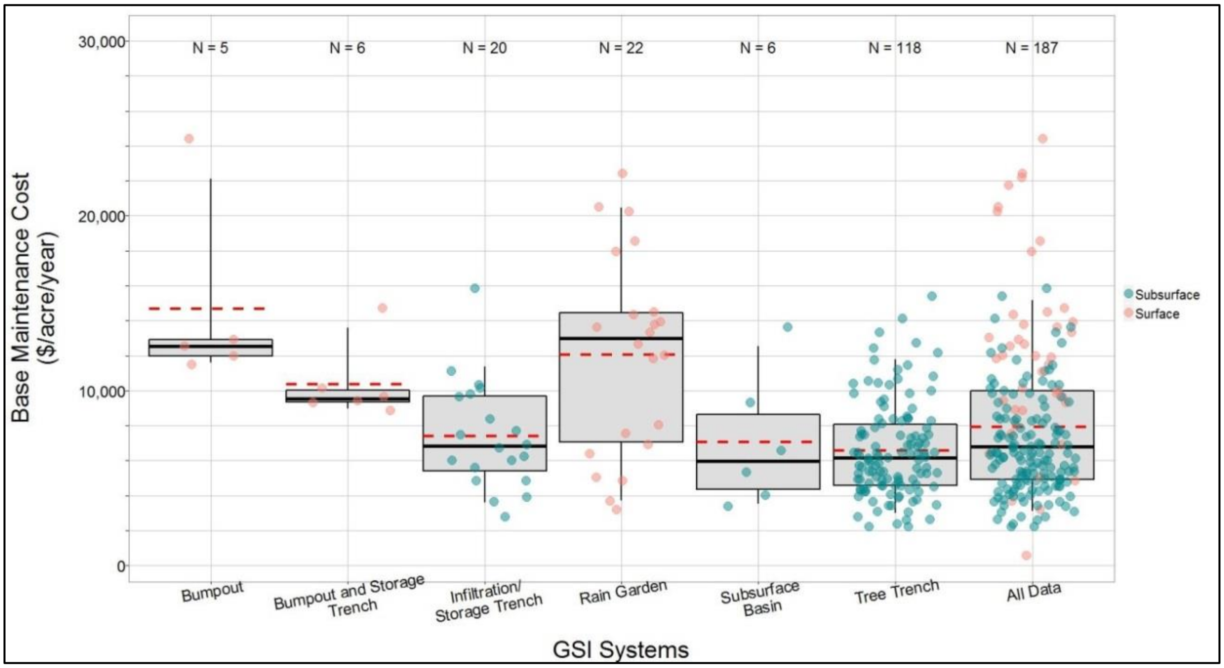


Figure 5-8: Base Maintenance Cost per DCIA per Year by GSI System Type

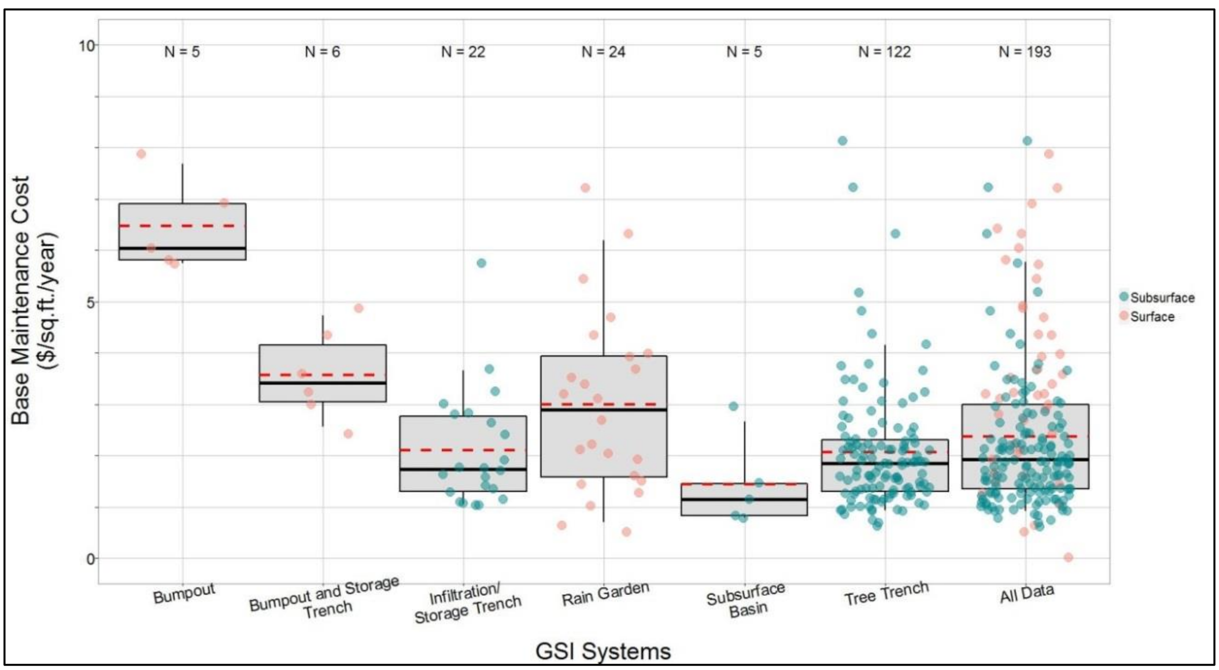


Figure 5-9: Base Maintenance Cost per System Footprint per Year by GSI System Type

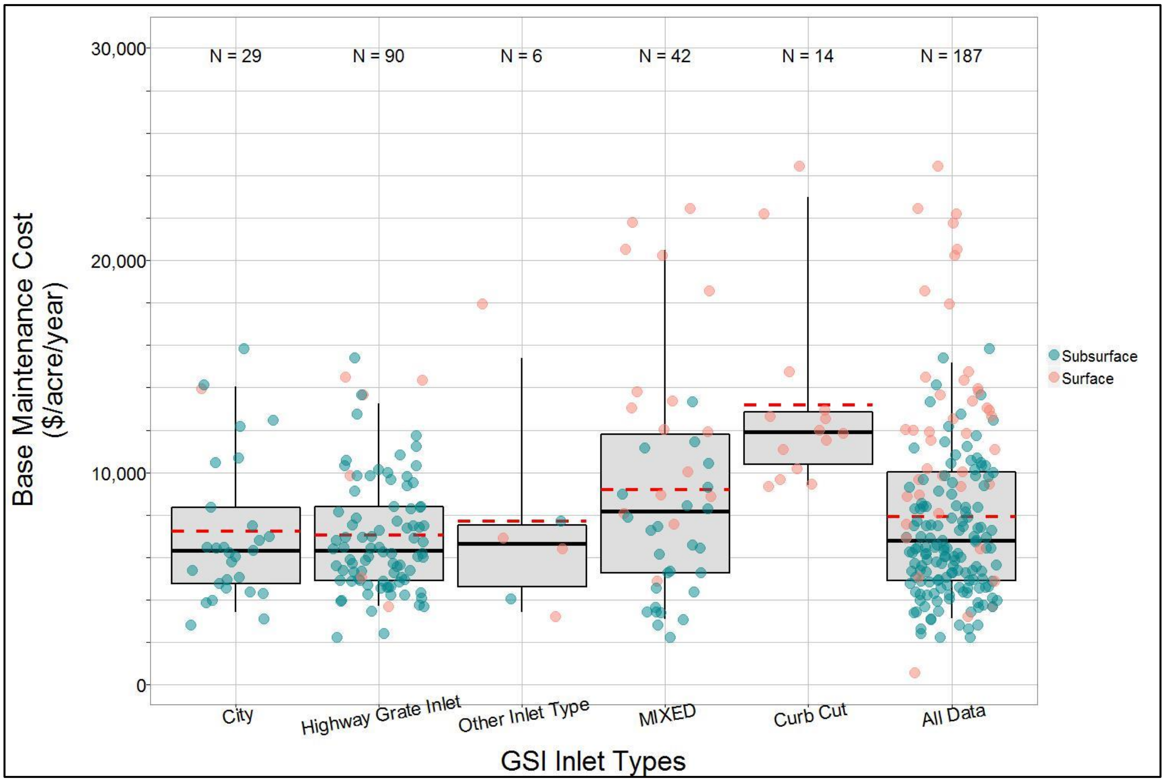


Figure 5-10: Base Maintenance Cost per DCIA per Year by Inlet Type

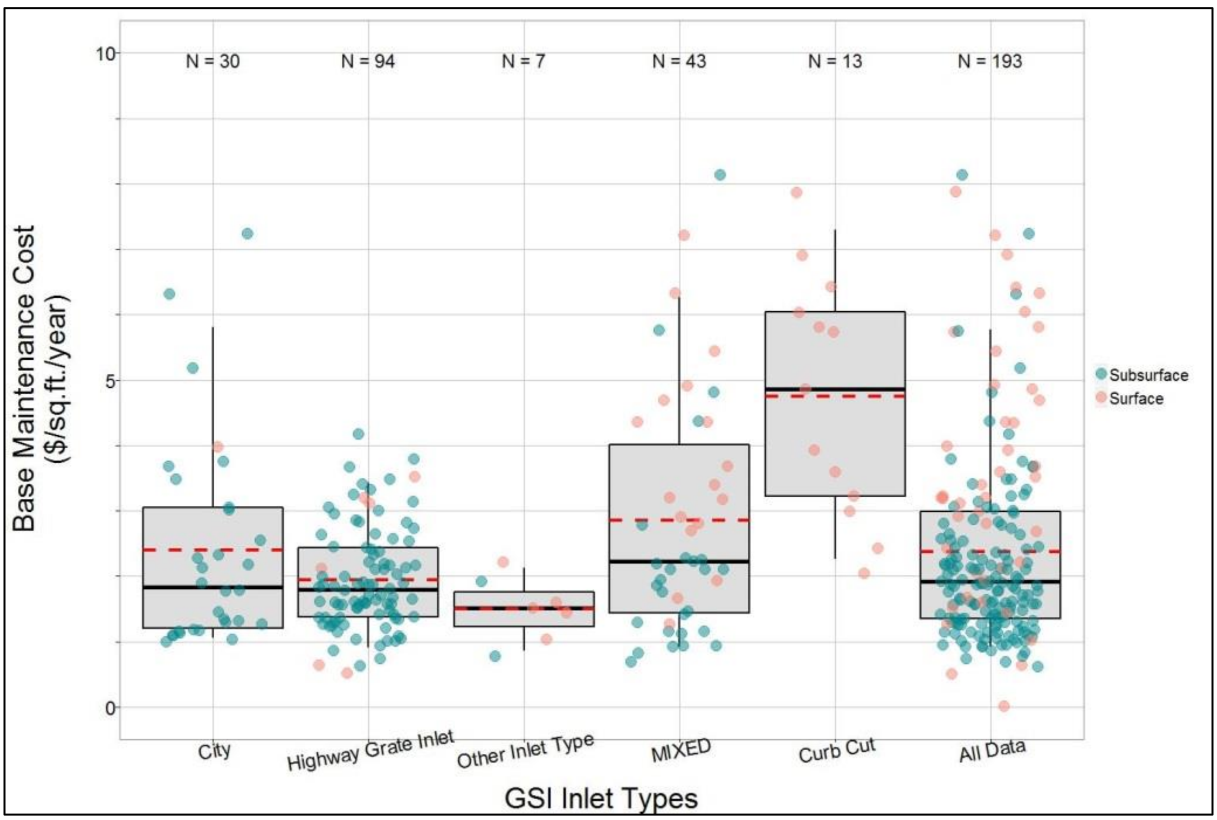


Figure 5-11: Base Maintenance Cost per System Footprint per Year by Inlet Type

Another trend that was found in the results was the height of the domed riser from the soil surface in vegetated systems. Shallower domed riser heights, less than three inches, had higher costs than greater domed riser heights (Figure 5-12, Figure 5-13). Shallow domed risers result in less capacity for surface ponding storage. The risers are utilized more often during smaller storms, depositing more material in the risers and subsurface piping. Also, since the system has little ponding, runoff flowing into the system does not enter a pool of standing water, but rather continuously moves across the surface directly to the riser, potentially increasing erosion and requiring grade stabilization or re-grading.

Several Variables were identified as having potential to have an impact on maintenance cost prior to the statistical analysis, but no noticeable trend was found in the results of the analysis. These include: Land Use, GSI Visibility, Loading Ratio, Static Storage, and Street Slope.

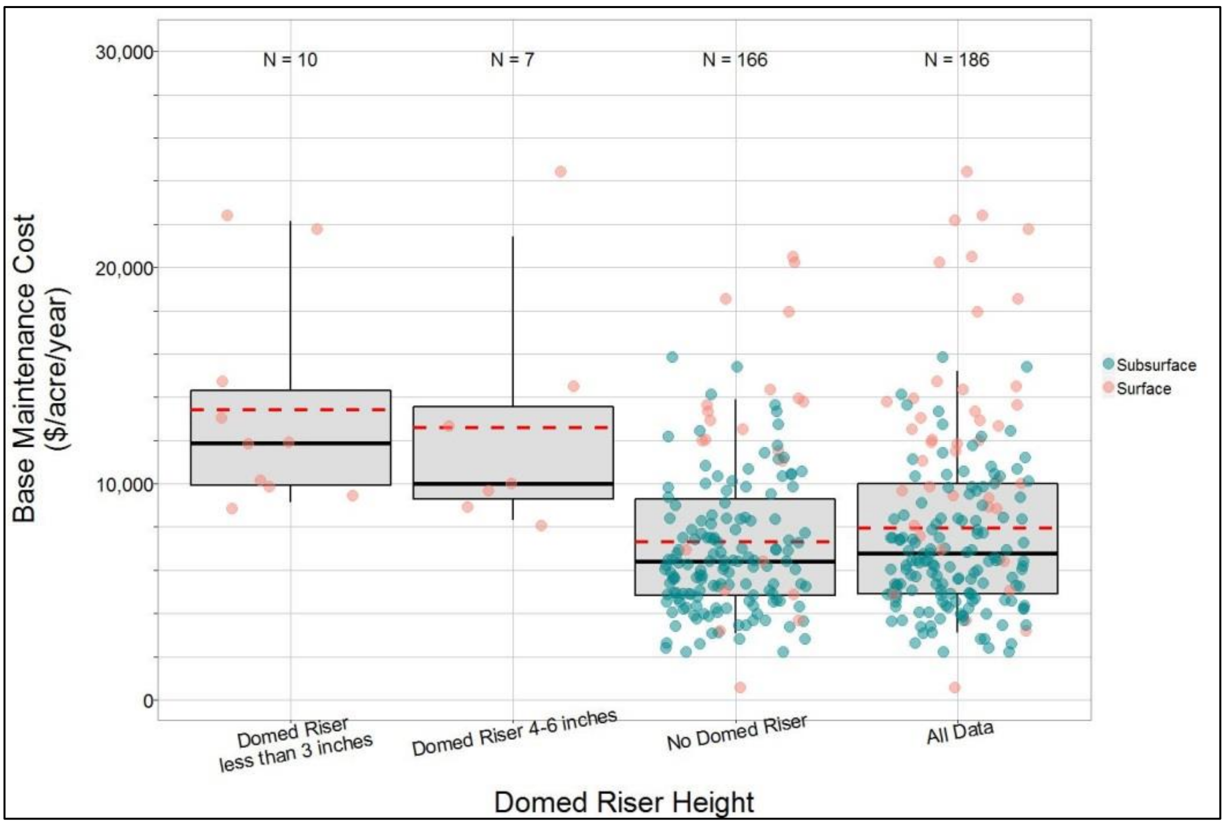


Figure 5-12: Base Maintenance Cost per DCIA per Year by Domed Riser Depth

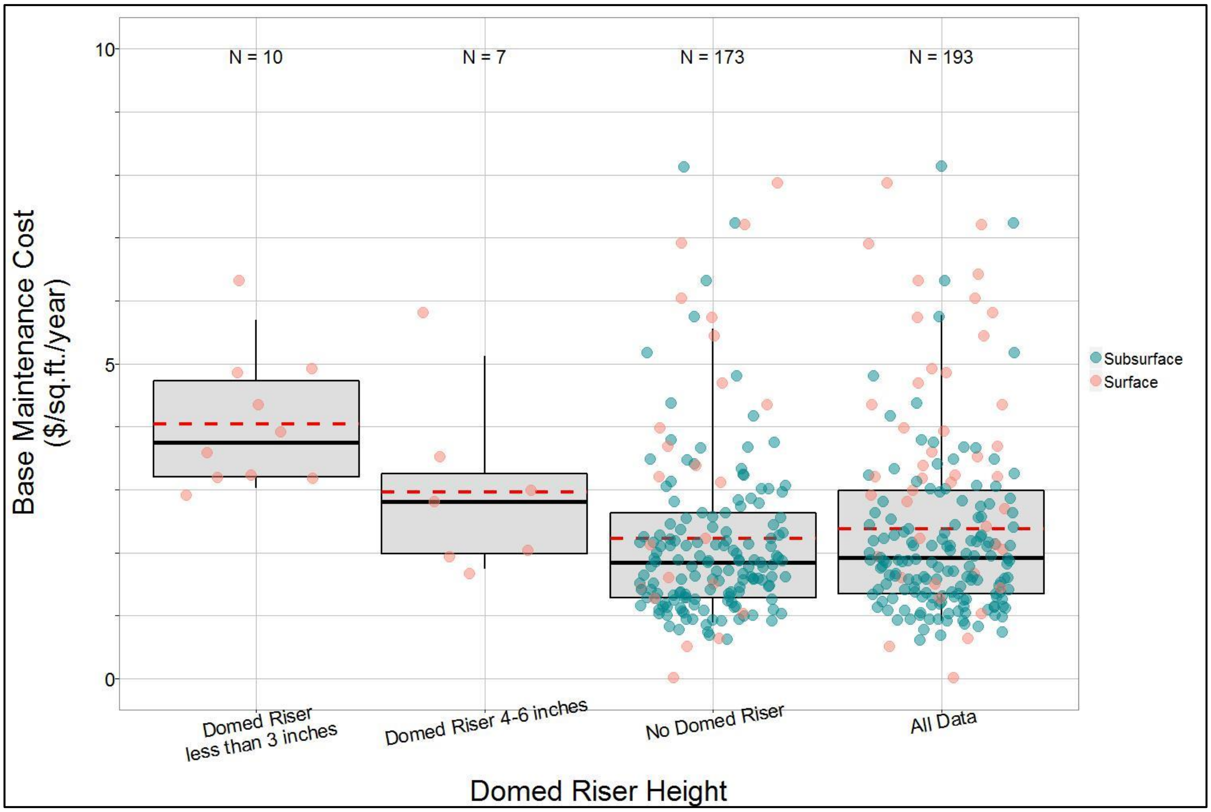


Figure 5-13: Base Maintenance Cost per System Footprint per Year by Domed Riser Depth

5.4.2 Material Removed

The results from the total material removed data analysis followed similar trends as the total cost. Surface systems, and other Variables associated with surface systems, had a greater volume of material removed (Figure 5-14, Figure 5-15). This is likely due to the fact that surface systems have more available space to store unwanted materials, are more susceptible to litter and short dumping, and require more material to be removed after routine pruning and weeding.

When broken down by GSI system type, the surface vegetated systems (planters, rain gardens, bumpouts) tend to have greater volumes of material removed than subsurface systems (tree trenches, infiltration/storage trenches), as seen in Figure 5-16 and Figure 5-17.

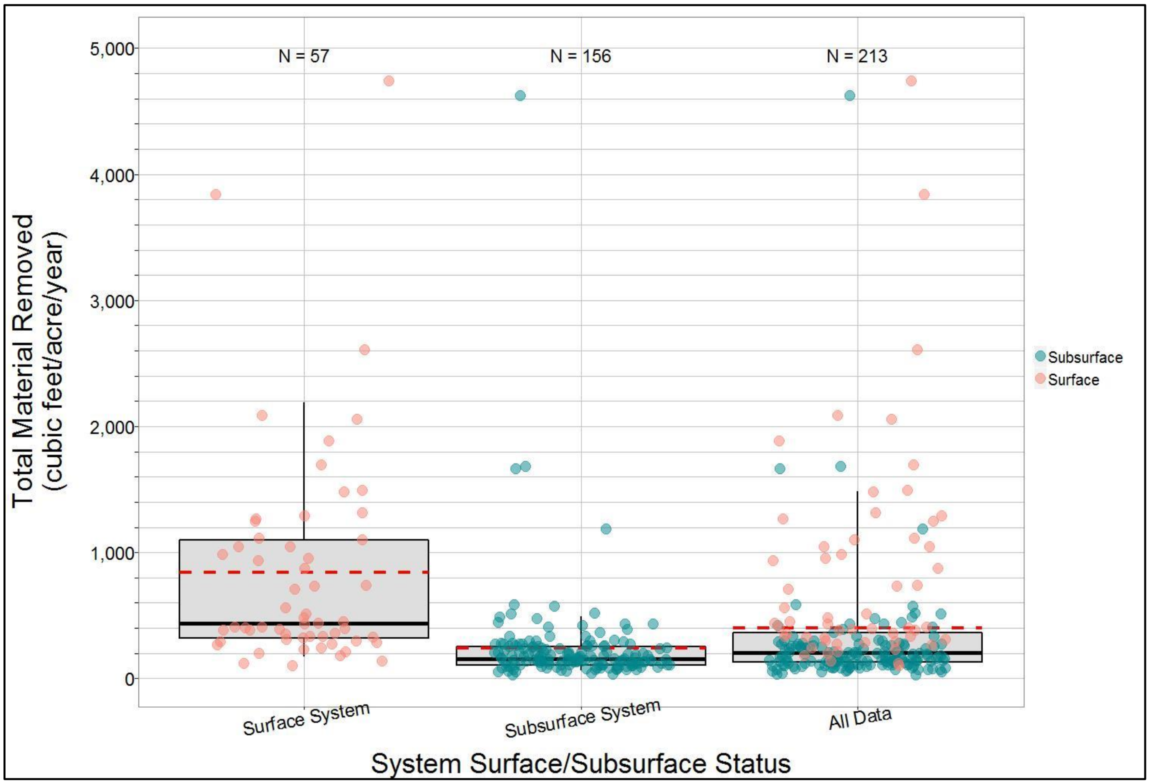


Figure 5-14: Volume of Materials Removed per acre of DCIA per Year, Surface v. Subsurface

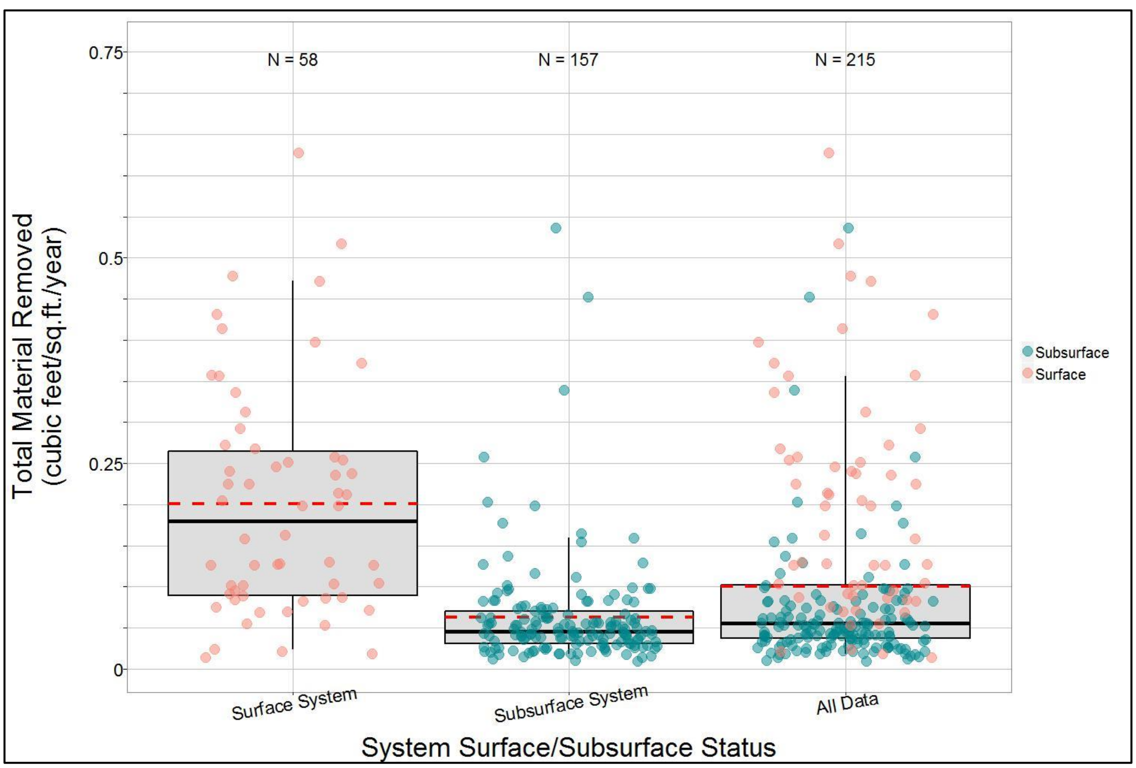


Figure 5-15: Volume of Materials Removed per System Footprint per Year, Surface v. Subsurface

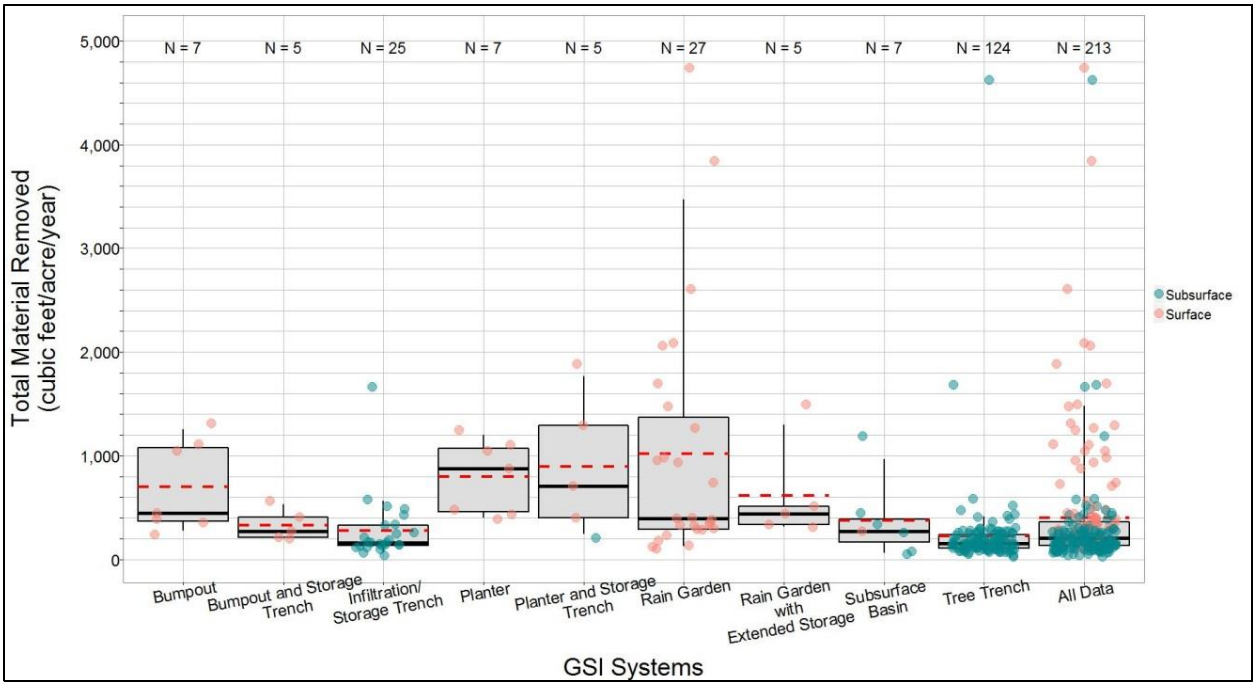


Figure 5-16: Volume of Materials Removed per Acre of DCIA per Year by System Type

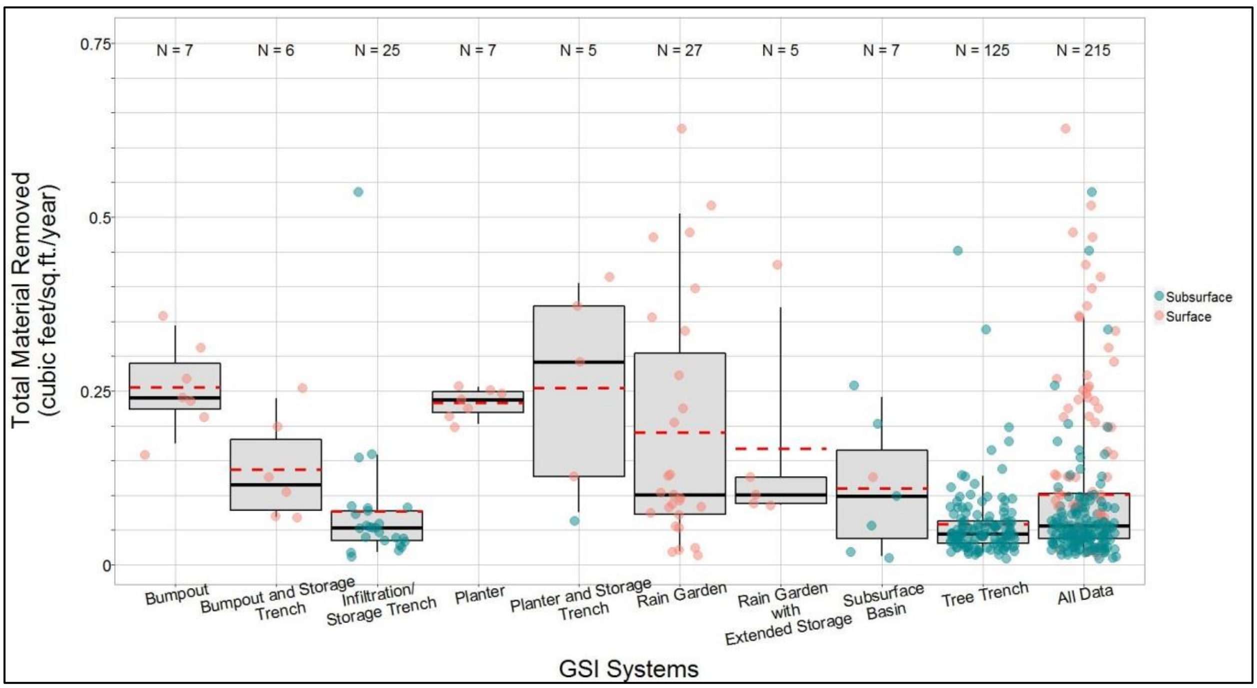


Figure 5-17: Volume of Materials Removed per System Footprint per Year by System Type

5.5 Discussion

In the first five years of the *Green City, Clean Waters* program, PWD has maintained its surface GSI systems to a high aesthetic standard rather than only to meet more limited stormwater performance objectives. As a result, maintenance cost data show that surface vegetated systems require more maintenance, both in terms of total cost and material removal. This result makes sense given that surface maintenance occurs more frequently, and greater surface area will require more maintenance effort. In some cases, additional maintenance cost is a result of littering and dumping in surface vegetated features, which may not affect stormwater performance directly, but results in undesirable aesthetic conditions. While subsurface systems do have monthly surface maintenance, it typically only includes cleaning inlet filter bags and other light cleanup, whereas surface systems like rain gardens and bumpouts require additional activities like pruning, weeding, watering, etc.

It should be noted, however, that the available dataset was very limited, only spanning one year. In addition, most of the vegetated surface systems being maintained are still young, meaning the plants have yet to become fully established. Surface systems will require greater resources for maintenance during the plant establishment period, which can last up to two growing seasons after planting. Costs are expected to decrease over time as established vegetated systems require less intensive maintenance.

Although some clear trends were observed in the available data, results should be considered preliminary. Maintenance data will continue to be tracked and analyzed in order to determine long-term trends that can help inform future design and maintenance practices.

6.0 Ease of Implementation

This section describes the data acquisition methods and analysis techniques for evaluating how Pilot Variables affect the ease of implementation of Green Stormwater Infrastructure (GSI). It also discusses findings for significant relationships identified during the analysis.

6.1 Data Collection and Analysis Method

"Ease of implementation" is a broad question which is difficult to directly measure. There is no quantitative dataset available to analyze, as there is with cost, performance, or maintenance. "Ease of implementation" was defined as a wide variety of factors that may affect the implementation process of GSI, by either making it easier or more difficult in planning, design, and/or construction completion. To measure this, a questionnaire was designed to document the knowledge and experience of key PWD staff responsible for the implementation of GSI, including planners, who are tasked with finding locations for GSI projects, and design engineers, who manage projects from concept design through final design construction documents. The questions were designed to assign a rating on a scale of 1 to 5 for each Pilot Variable and Level and its effect on ease of implementation. The ratings are defined in Table 6-1. In addition to the ratings, planning and design engineering staff were asked to give explanations for how each Variable impacts ease of implementation to document specific reasons that could explain the results.

Interviews were conducted during the period 2/17/2016-4/14/2016 with a total of 10 staff members, including four GSI planners and six GSI design engineers.

Table 6-1: Ease of Implementation Question Rating Scale Definitions

Rating	Definition
1	Most challenging - very difficult: very high cost, duration, complexity, or effort; high risk of project failure/cancellation
2	Somewhat challenging
3	Neutral - typical cost, duration, complexity, effort, or no noticeable trend
4	Somewhat easy
5	Easiest - very easy: low cost, duration, complexity, or effort; projects almost always are implemented as planned/expected
Don't Know/No Experience	No personal experience with projects associated with the variable

Due to their different roles in the implementation process, the questionnaires for the planning and design staff were designed slightly differently, with only Variables relevant to each group's responsibilities included. The definitions of the Variables can be found in Appendix A (Pilot Variable Framework).

The Variables included in the questionnaire for the design phase of implementation were:

- Land Use Type
- Drainage Area Characteristics
- GSI System Type
- Inlet Type
- System Surface/Subsurface Status
- Vegetation Status
- Pretreatment Type
- Inflow Type
- Street Crossing
- Rooftop Disconnection
- Domed Riser Depth
- Primary Storage Type
- Permeable Pavement Type
- Street Slope
- Partnership Types
- GSI Visibility

The Variables included in the questionnaire for planning phase of implementation were:

- Land Use Type
- Drainage Area Characteristics
- GSI System Type
- System Surface/Subsurface Status
- Street Crossing
- Rooftop Disconnection
- Street Slope
- Partnership Types
- Implementation Strategy
- GSI Visibility
- GSI Location Ownership

When all of the interview results and explanations were collected, the data were compiled and analyzed to compare the different Levels within each Variable. Several explanations were consistent among different staff members, which helped provide descriptions for the key findings, documented in Section 6.2 (Findings).

6.2 Findings

Key findings from the Ease of Implementation interviews are presented in this section for selected Variables.

6.2.1 Policy/Partnership Type

This Variable is defined as a project with one or more partners, either contributing financially, providing locations for GSI implementation, or simply having some role in design decision making. Levels of this Variable include Civic Groups, Non-Government Organizations, Public/Private Partnerships, and Public Agencies. Definitions of these Variables and Levels can be found in the Appendix A (Pilot Variable Framework).

Implementation of GSI tends to be easier with the involvement of partners such as neighborhood civic groups and non-government organizations. Feedback from staff interviews show that the involvement of these partners facilitates early buy-in to projects, site identification, and a sense of project ownership. Respondents noted, however, that projects involving multiple partners may require more coordination among a variety of stakeholders with differing priorities and interests. The degree to which a partnership and/or process is established has an impact on the ease of implementation from both the planning and design perspective as well. For example, Philadelphia Parks and Recreation established a Stormwater Review Team to facilitate project selection and to establish workflows with PWD. This has helped facilitate more efficient planning and design. Partners with whom PWD has a less established relationship and fewer defined processes can lead to projects which are more time intensive.

Policy constraints that primarily affect implementation are mainly permitting processes which are especially time intensive. These include “right-of-entry” permits on public school property and project reviews and approvals that are required by other agencies.

Certain partners have been found to impact different parts of the implementation process in different ways, where project planning and site selection are made difficult while design is somewhat easier, or vice versa.

6.2.2 Implementation Strategy

This Variable is defined as the strategy utilized for the implementation of GSI, which includes the following Levels: Complete Streets Concept, Storm Flood Relief, Standard Detail, Area Wide Disconnection, Following Public Works, Low-Budget Retrofit, Green Campus, Stormwater Management Incentives Program (SMIP) Grant, Greened Acre Retrofit Program (GARP) Grant, Pilot Program Managed, and Typical Implementation. Definitions of these Variables and Levels can be found in Appendix A (Pilot Variable Framework). This question was only given to GSI Planning staff, who utilize these strategies to find and initiate projects. The questionnaire results are found in Figure 6-1.

Coordination with other programs can be difficult due to different time tables, objectives, and constraints. More established processes and guidance continue to be evaluated to ease implementation for these types of projects. Complete Streets are viewed as difficult for the implementation of GSI due to the presence of utility constraints that are often found on streets that would be considered for a complete streets project. Furthermore, coordinating design and construction schedules can be challenging.

An implementation strategy in which PWD provides grants to private properties or third party GSI implementers (SMIP and GARP) has been a relatively easy source of GSI implementation.

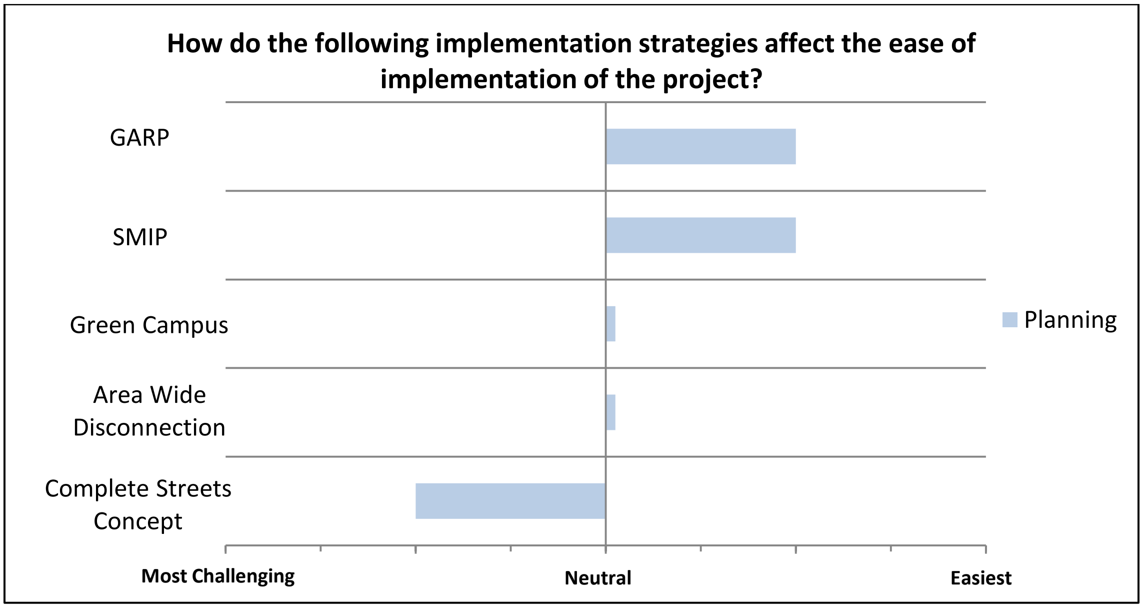


Figure 6-1: Implementation Strategy Questionnaire Average Response: Planning (n=4)

6.2.3 Land Use Type

This Variable is defined as the type of land use on which the footprint of the GSI system is located, which includes the following Levels: School Yard or School Perimeter, Recreation Center, Open Space Park Site, Traffic Triangle, Streets, High Density Residential Street, Median, Alley – Private, Alley – Public, Athletic Field, Commercial Corridor, Parking Lot – Private, Parking Lot – Public, Vacant Land – Private, and Vacant Land – Public. Definitions of these Variables and Levels can be found in the Appendix A (Pilot Variable Framework). The questionnaire results are found in Figure 6-2.

The main factors affecting implementation due to land use type can be categorized in the following:

Programming Issues
The involvement of multiple stakeholders and multiple uses of the site makes implementation more difficult. This applies especially to schools, athletic fields, recreation centers, and vacant lands.

Legal/Policy Constraints
This is an issue on all projects, but feedback from Planning and Design staff indicated that this is a particularly difficult challenge on parking lots, alleys, schools, and vacant lands.

Financial Barriers
Financial constraints are the main complication for direct PWD implementation on school yards. Schools are considered private property, and, absent an easement, PWD is prohibited from spending capital dollars on private property. To date, direct implementation of school projects by PWD has been challenging. Implementation of GSI on athletic fields is perceived as being more expensive as it may require playing surface replacement, equipment replacement, and other special requirements.

Technical Constraints
High density residential streets, commercial corridors, traffic triangles, and medians complicate the design process due to a higher presence of utilities and laterals.

Land use types that tend to have easier implementation from the planning and design perspective are the rights of way around school perimeters and other streets due to fewer space constraints, as well as open space park sites because of their high potential for larger disconnections.

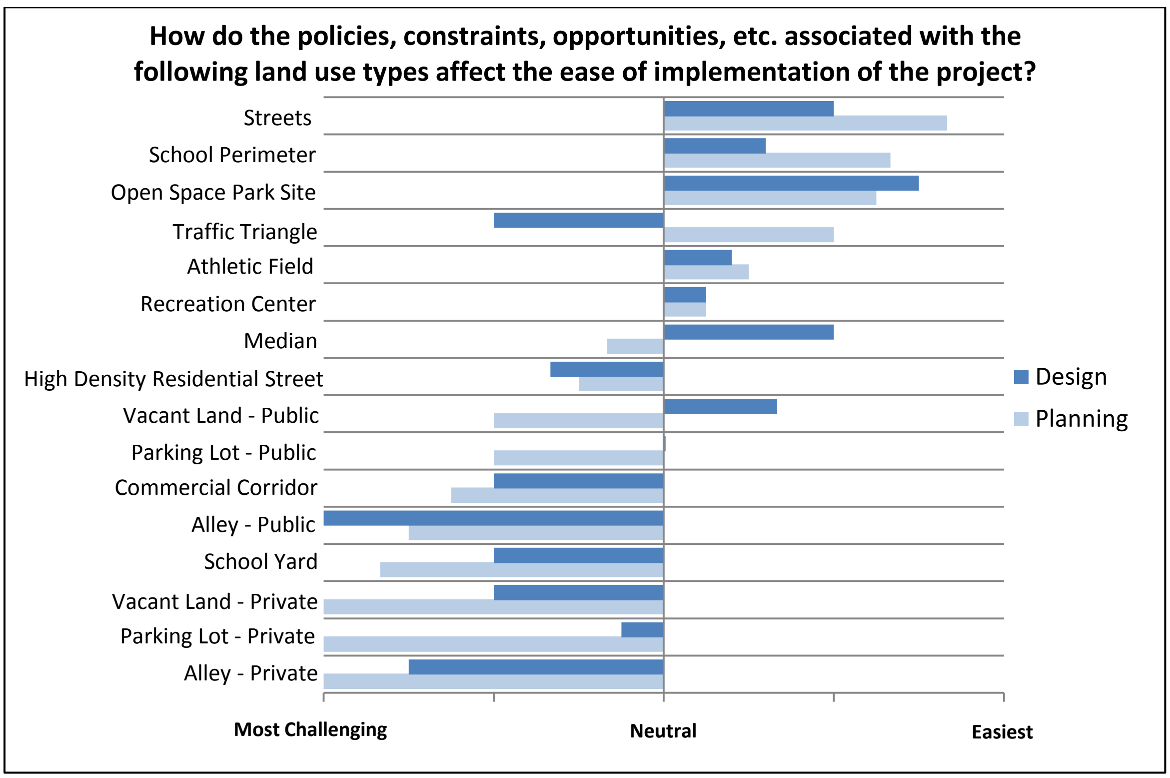


Figure 6- 2: Land Use Type Questionnaire Average Response: Planning (n=4) and Design (n=6)

6.2.4 Drainage Area Characteristics

This Variable is defined as the types of impervious cover that make up the GSI system's drainage area, which includes the following Levels: Street, Sidewalk, Street Crossing, Parking Lot, School Yard/Playground, Rooftop, Bridge, Park, and Alley. Definitions of these Variables and Levels can be found in Appendix A (Pilot Variable Framework). The questionnaire results are found in Figure 6-3.

Drainage area characteristics that promote easier implementation from the planning and design perspectives are streets, parks, and sidewalks. Many projects are located within the right of way, and capturing runoff from these areas is easy to plan and implement. They have favorable drainage area properties, such as higher runoff coefficients, consistent slopes, and low depression storage.

During the planning process, policy constraints are the main causes of difficulty in capturing certain types of drainage areas. There are no processes in place as of yet for accessing runoff from parking lots as liability and ownership issues complicate implementation.

Technical factors related to Drainage Area Characteristics affecting ease of implementation include:

- Existing topography and drainage network of potential Stormwater Management Practice (SMP) sites. This applies especially to parking lots, school yards, and parks where localized low points often require additional surveys. Poor condition of existing pavement often results in required repaving for the whole drainage area, which can increase construction costs. Additionally, integrating multiple inlets into existing drainage networks can be complicated.
- Rooftops with internal drainage systems make management of roof runoff challenging
- High velocity runoff from bridges requires significant energy dissipation

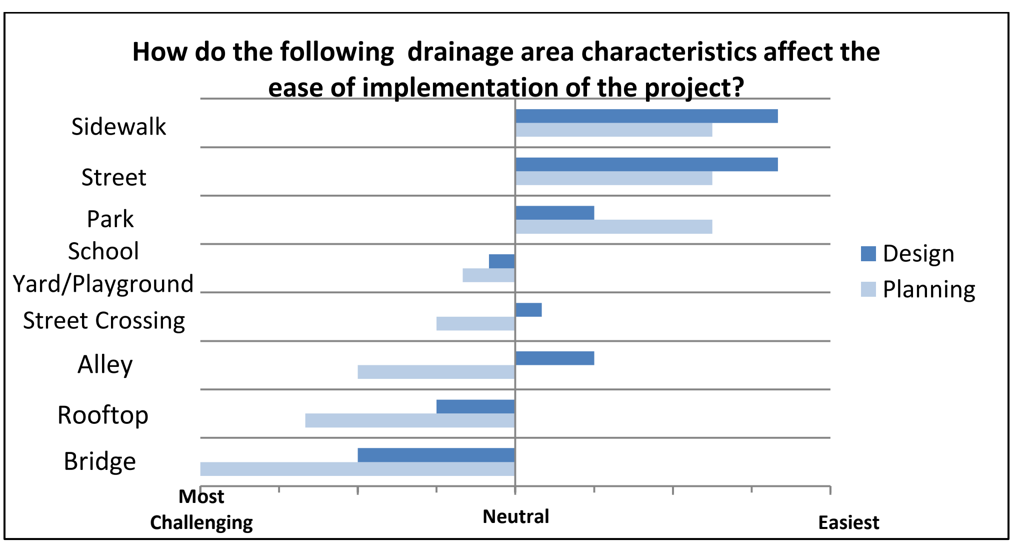


Figure 6-3: Drainage Area Characteristics Questionnaire Average Response: Planning (n=4) and Design (n=6)

6.2.5 GSI Visibility

This Variable is defined as the visibility of the GSI to residents, which includes the following Levels: None – Subsurface, No Trees; Moderate – Subsurface, with Trees; High – Surface Vegetated System; and Highest – Surface Vegetated System, Community Anchor Site. Definitions of these Variables and Levels can be found in Appendix A (Pilot Variable Framework). The questionnaire results are found in Figure 6-4.

Subsurface systems that have low visibility are typically less complex from a design perspective. Sometimes subsurface, non-visible SMPs will lead to new structures, such as sidewalks, that are viewed by the community as adding value. This helps facilitate implementation.

Generally, higher visibility of GSI helps support implementation from a planning perspective because the GSI is viewed by stakeholders as adding value, increasing green space, and improving aesthetics. However, systems with the most surface vegetated systems require more coordination effort with project stakeholders in the planning phase.

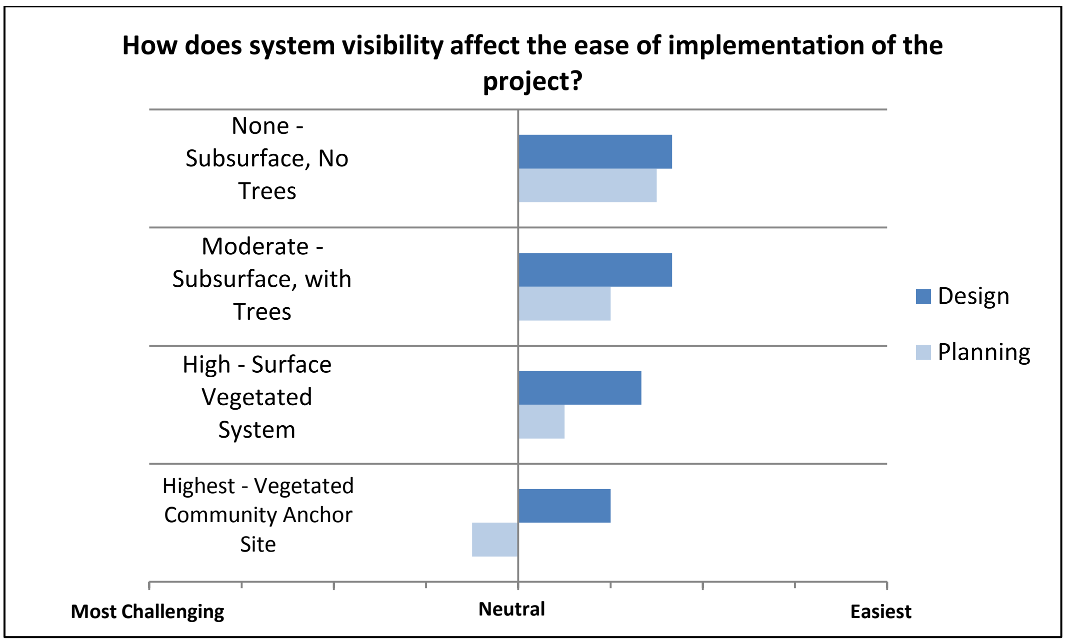


Figure 6-4: System Visibility Questionnaire Average Response: Planning (n=4) and Design (n=6)

6.2.6 GSI Location Ownership

This Variable is defined as public or private ownership of the location of the GSI system, which includes the following Levels: Public Right-of-Way, Public Parcel, and Private Parcel. Definitions of these Variables and Levels can be found in Appendix A (Pilot Variable Framework). The questionnaire results are found in Figure 6-5.

Projects located in the public right-of-way have established standard procedures, processes, and guidance, which favor the planning process. Policy constraints can affect implementation on public parcels, since there are sometimes no standard procedures established for working with certain stakeholders of the project site.

Direct implementation on private property is generally very difficult in the planning process due to lack of financial incentives, complications in acquiring easements, and the fact that projects typically need to be initiated by the parcel owner.

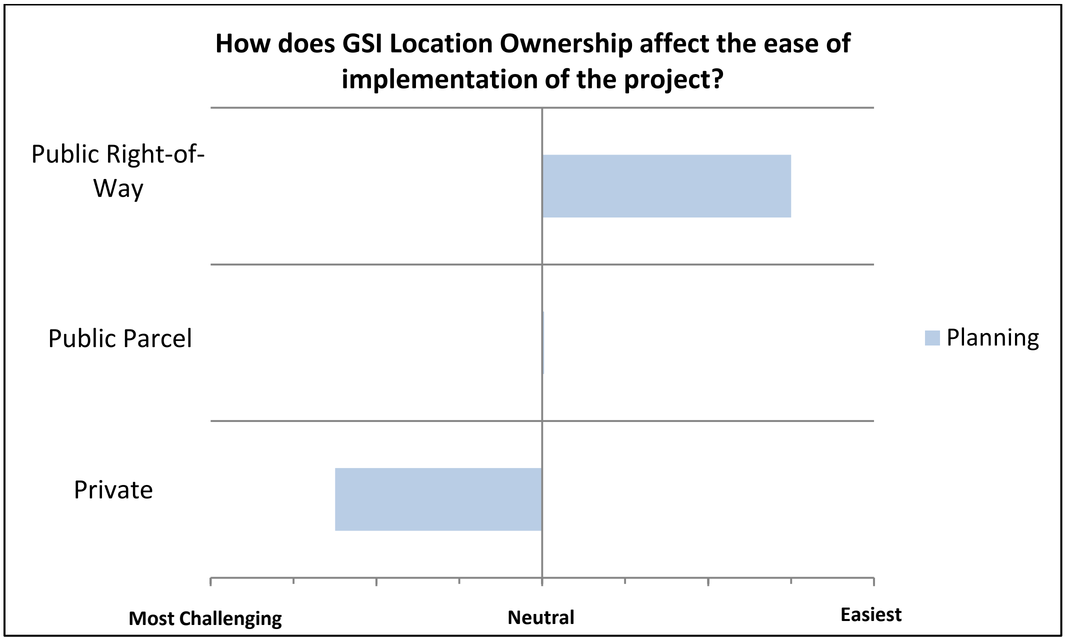


Figure 6-5: GSI Location Ownership Questionnaire Average Response: Planning (n=4)

6.2.7 GSI System Type

This Variable is defined as the type of GSI system design, which includes the following Levels: Bumpout, Bumpout and Storage Trench, Planter, Planter and Storage Trench, Tree Trench, Infiltration/Storage Trench, Subsurface Basin, Permeable Pavement, Rain Garden, Rain Garden with Extended Storage, Swale, Green Roof, Blue Roof, and Drainage Well. Definitions of these Variables and Levels can be found in Appendix A (Pilot Variable Framework). The questionnaire results are found in Figure 6-6.

Generally, from the planning perspective, GSI that adds green elements to the neighborhood and improves the aesthetics of a site are perceived as positive by the community and make the planning process easier. These GSI systems primarily include planters, tree trenches, and rain gardens. Innovative approaches such as green roofs and permeable pavement draw attention and interest of the community and therefore can make implementation easier.

From the design perspective, certain system types require more coordination with City agencies and the community. For example, bumpouts require a traffic analysis to evaluate turning and parking prior to acceptance. GSI System Types that affect parking are also a community issue and require more coordination with local residents.

From a technical perspective, bumpouts and planters with storage trenches are particularly affected by space and utility constraints. Creating enough space for surface ponding as well as adequate energy dissipation can be difficult, since the new system will have to comply with

Americans with Disabilities Act (ADA) requirements, turning radius requirements, parking demands, and other space constraints. Permeable pavement can be difficult to implement due to high construction costs. Lastly, few projects to date have included green roofs, blue roofs, or drainage wells.

Certain GSI System types have the following positive effects on ease of implementation:

- Easy design (e.g. planters without storage trenches, infiltration trenches, tree trenches, rain gardens)
- Better cost efficiency and site location flexibility (e.g. tree trenches, swales)
- High potential for managing large drainage areas (e.g. subsurface basin)

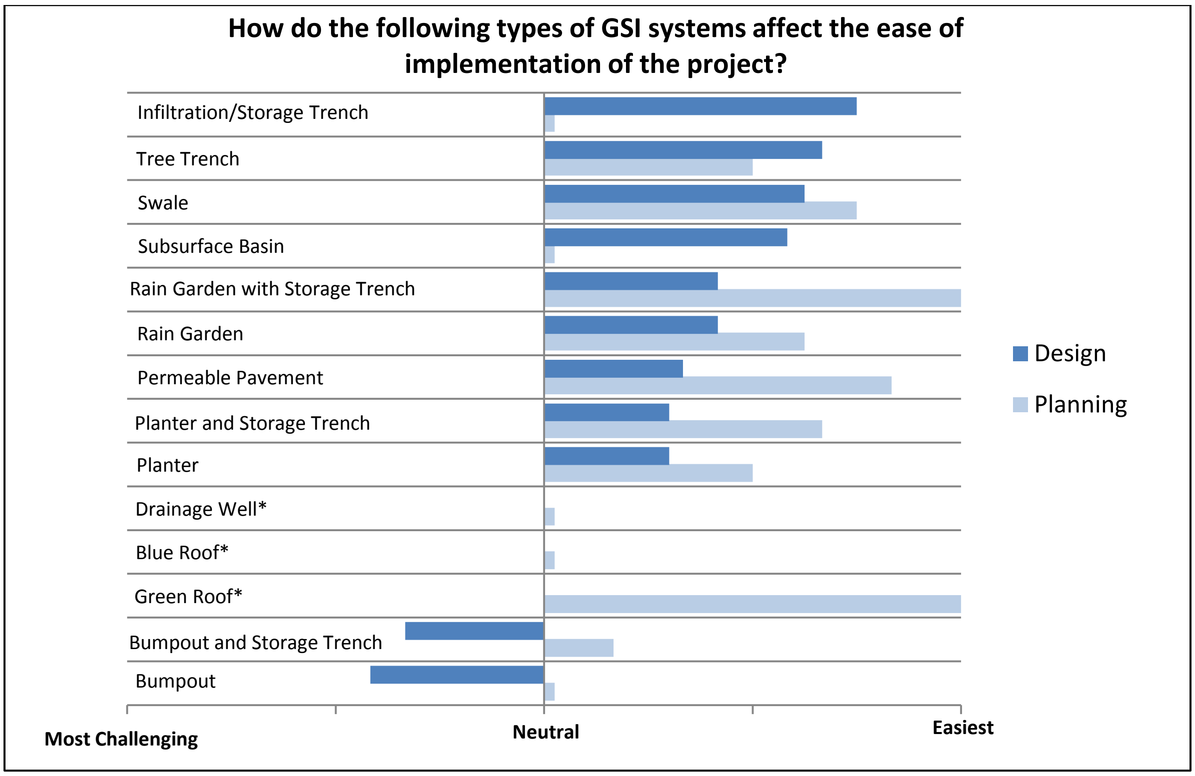


Figure 6-6: GSI System Type Questionnaire Average Response: Planning (n=4) and Design (n=6)

6.2.8 GSI Design Elements

This section includes findings for how several Variables that fall under GSI Design Elements impact ease of implementation.

System Surface/Subsurface Status

System Surface/Subsurface Status describes whether the GSI elements implemented are on the surface or subsurface. Subsurface systems compared to surface systems tend to be easier to implement because they are often less complex. It is easier in the planning phase since there are typically fewer space constraints. Surface systems are harder to implement in the public right of way and require more design effort, but usually provide a better chance for involving communities.

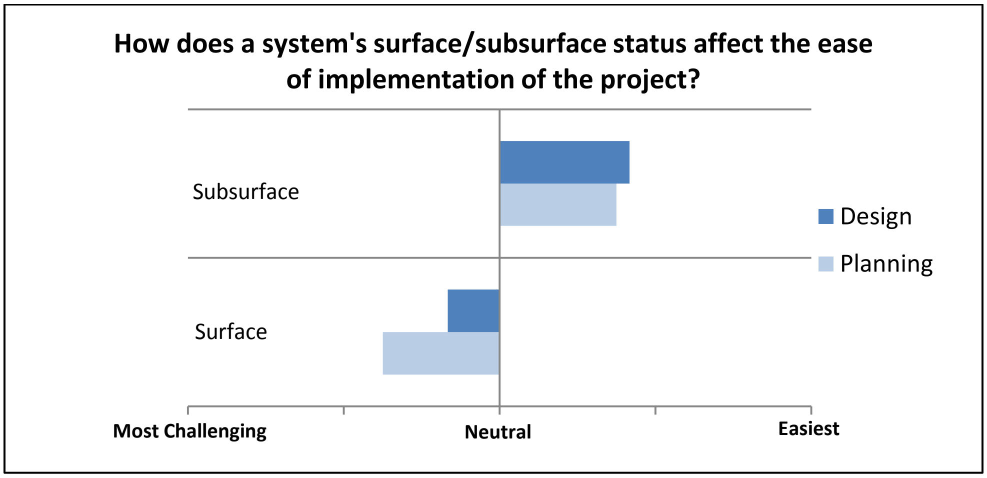


Figure 6-7: Surface/Subsurface Status Questionnaire Average Response: Planning (n=4) and Design (n=6)

Street Crossing

Street Crossing refers to whether or not runoff is conveyed across a street to a GSI system and how it is conveyed. The main factor affecting implementation of street crossings is the presence of utilities. Street crossing conveyance on the surface or shallow subsurface are more challenging to implement than typical subsurface crossings, which are often several feet underground and can more easily avoid utilities. It is easier in design if no street crossing is included, but less drainage area is able to be managed.

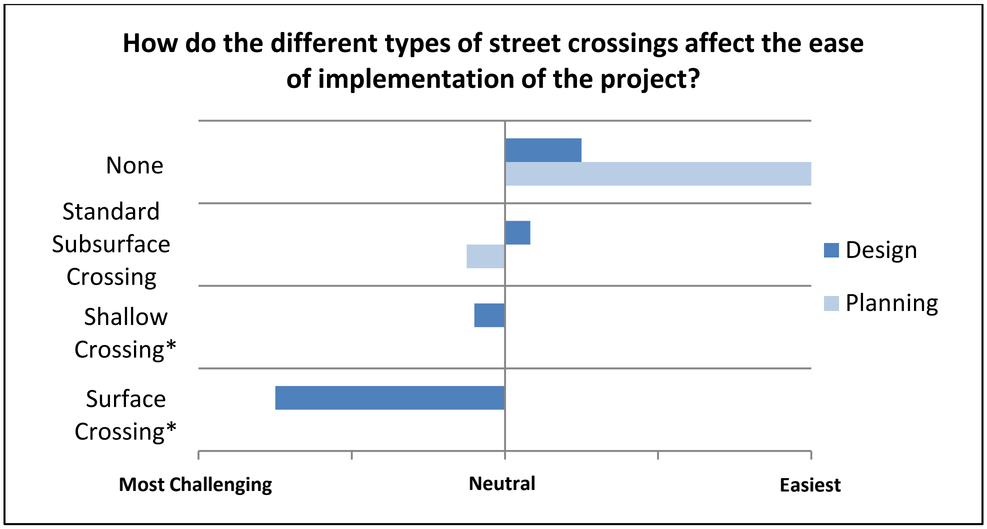


Figure 6-8: Street Crossing Questionnaire Average Response: Planning (n=4) and Design (n=6)

Street Slope

Street Slope describes the slope of the street on which the GSI element is located. In general, the steeper the slope of the street, the more difficult the planning and design process. Steeper streets result in higher flow velocities, requiring more substantial inlet and energy dissipator design. In addition, since systems need to have a flat bottom to maximize storage, steeper streets require deeper excavation on the upstream end of the system, which can complicate construction. Flat slopes might require additional topographical surveys as localized low points might exist, but it is easier to maximize drainage area and create bigger systems.

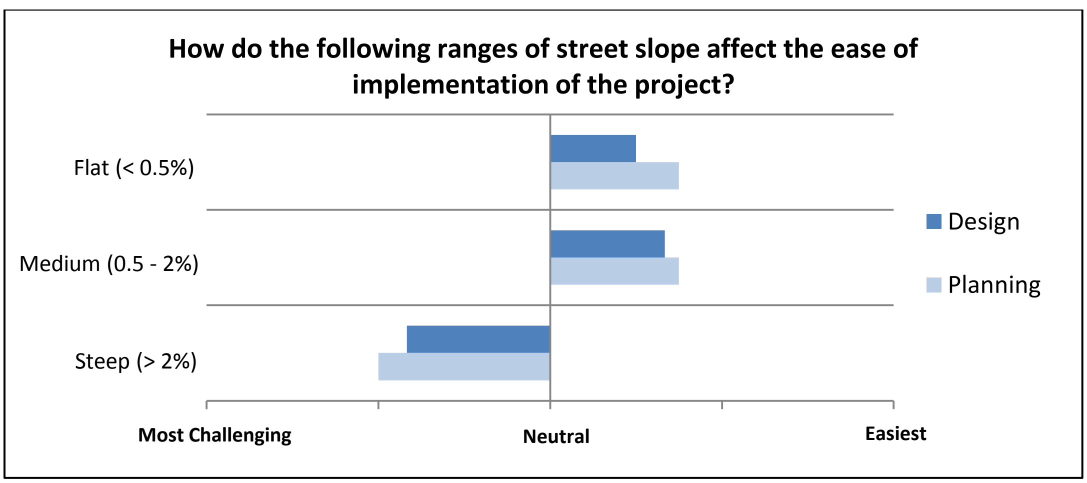


Figure 6-9: Street Slope Questionnaire Average Response: Planning (n=4) and Design (n=6)

Rooftop Disconnection

Rooftop Disconnection describes flow being redirected from a rooftop downspout to a GSI system.

The design process is difficult as no citywide policies currently exist for rooftop disconnections. Runoff may need to be conveyed across a sidewalk to drain to a GSI system, which causes concerns regarding freezing in winter. Issues with acquiring easements also add complications. Avoiding rooftop disconnection is currently easier, but reduces the total drainage area able to be managed. Solutions to capture more rooftop drainage area are under evaluation.

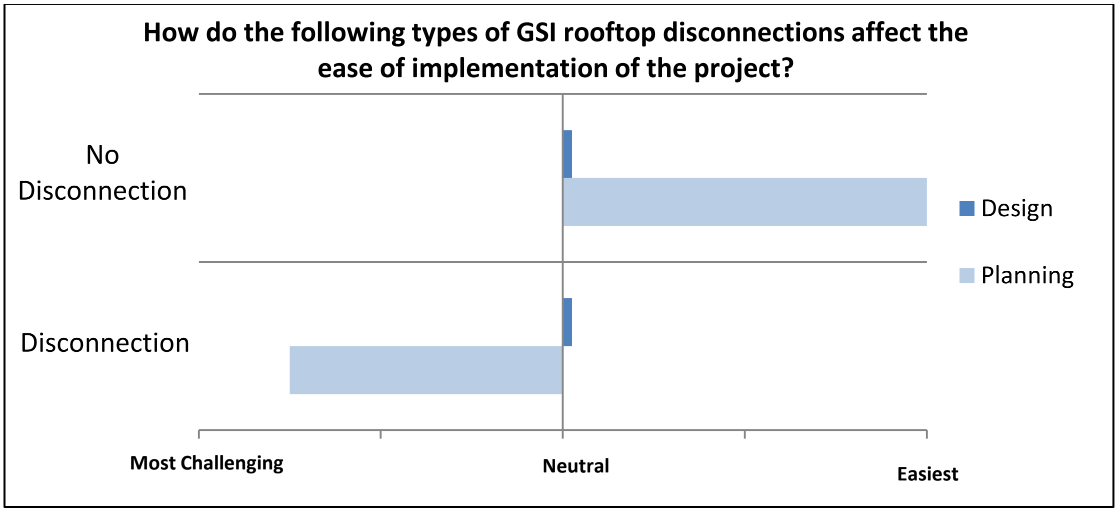


Figure 6-10: Rooftop Disconnection Questionnaire Average Response: Planning (n=4) and Design (n=6)

Vegetation Status

Vegetation Status describes whether the GSI elements implemented contain vegetation. GSI systems with no vegetation are easier to design since they are simpler and do not require landscaping designs.

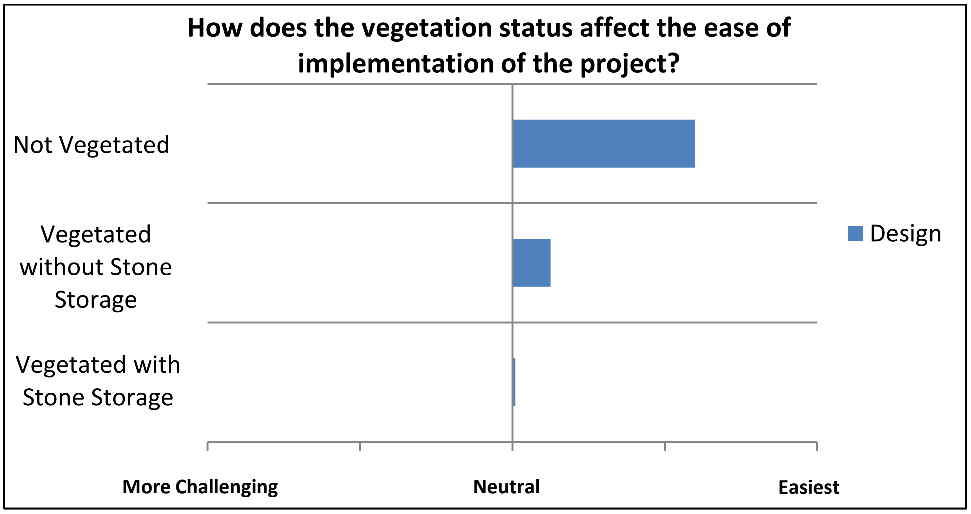


Figure 6-11: Vegetation Status Questionnaire Average Response: Design (n=6)

Inflow Type

Inflow Type describes whether inflow to the GSI system is at the surface or subsurface. Subsurface inflow systems typically have less design complexity than surface inflow types. Systems with surface inflow types can be shallower but topography and conveyance can make the design process more challenging.

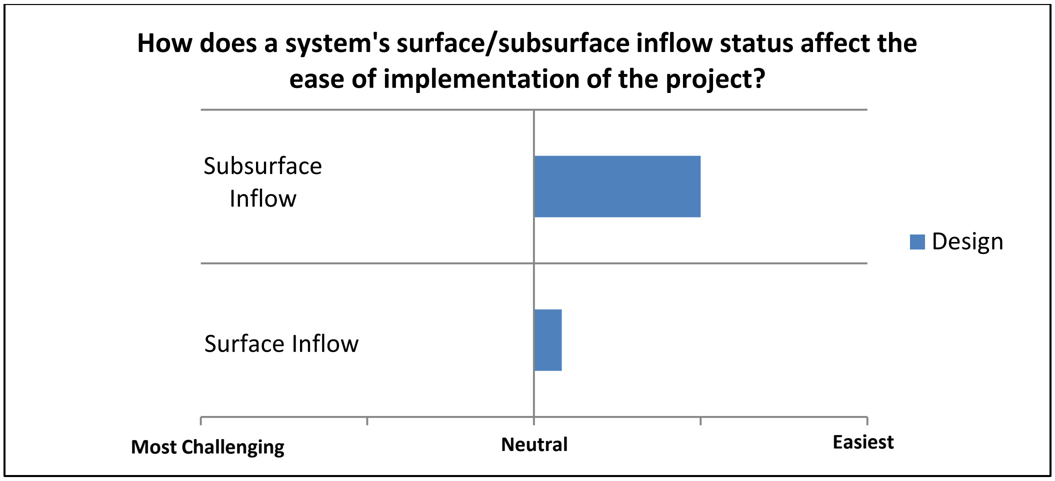


Figure 6-12: Inflow Status Questionnaire Average Response: Design (n=6)

Inlet Type

Inlet Type describes the type of structure used to convey runoff from the drainage area to the GSI system. Certain inlet types can complicate or ease the implementation process. Permeable pavement and inlets that require changing the existing curb line require Streets Department involvement, which lengthens the process. Highway grates, city inlets, curb cuts, and trench drains are typically easy to design and are included in most projects. More design effort is necessary for dual trap inlets, which are catch basin structures with two chambers–one as the inlet chamber, the other as the outlet chamber–separated by a weir wall. This impacts the design by lowering the maximum storage elevation, which is controlled by the weir wall as opposed to the top of grate elevation in more typical designs.

Dual trap inlets and curb cuts in combination with trench drains are perceived as being more cost intensive in some situations, which can be a constraint making implementation and design more challenging.

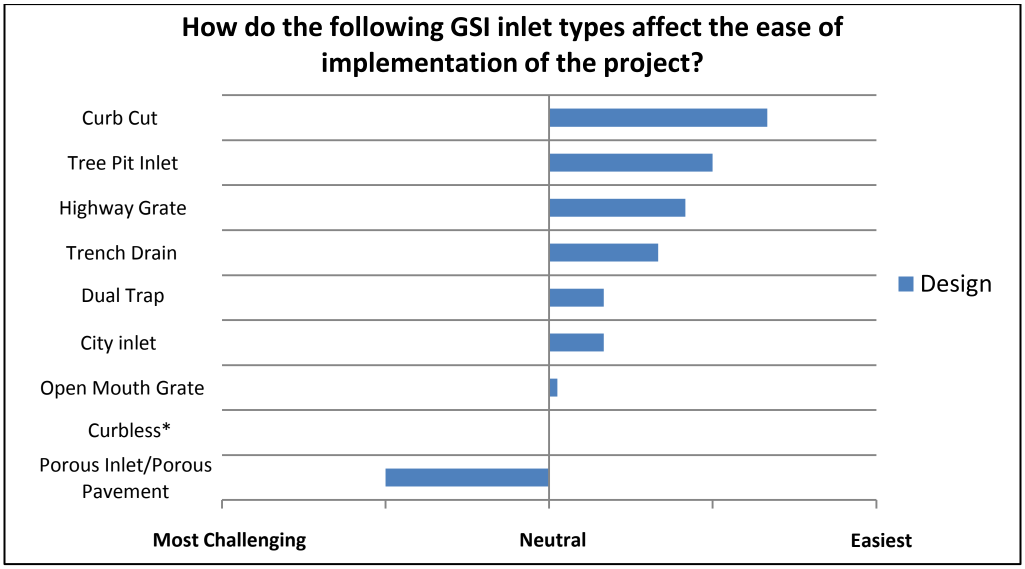


Figure 6-13: Inlet Type Questionnaire Average Response: Design (n=6)

Pretreatment Type

Pretreatment Type describes what type of GSI pretreatment, if any, is implemented. The different technical specifications and characteristics of the pretreatment type determine ease of implementation. Standard pretreatment types are either sump and trap configurations, inlet filter bags, or a combination of both. These do not require complex designs. Space constraints can make designs more difficult for swales and forebays. Forebays also require a more detailed design. Energy dissipators and splash blocks are typically easy to design and construct.

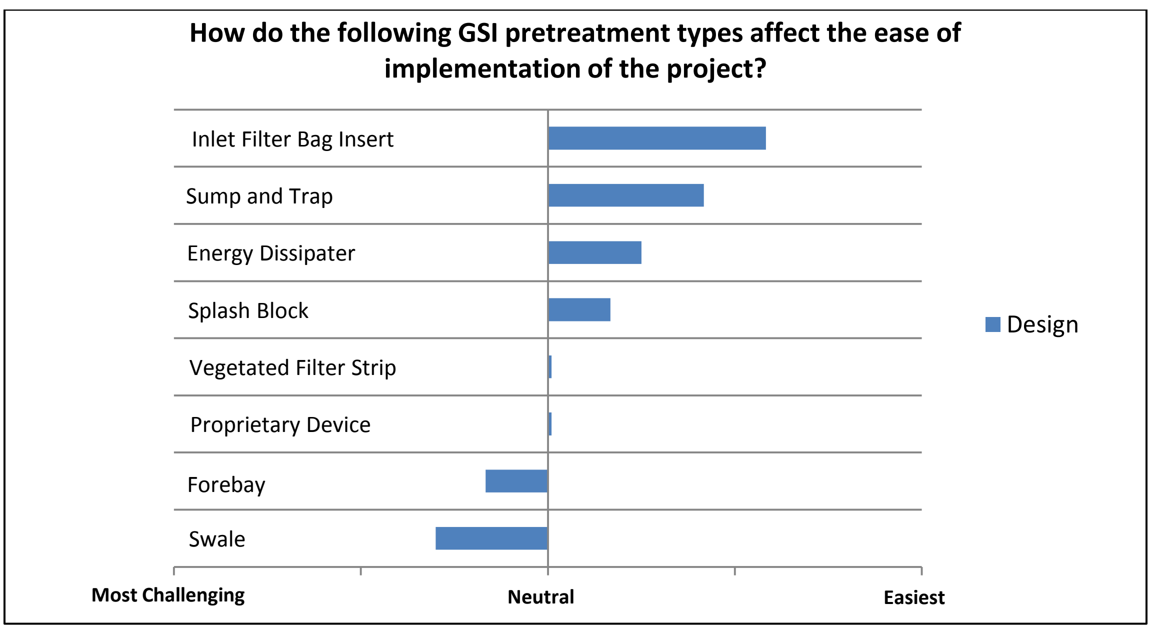


Figure 6-14: Pretreatment Type Questionnaire Average Response: Design (n=6)

Domed Riser Depth

Domed Riser Depth refers to the height of the domed riser grate opening from the vegetated surface. The greater the height of the domed riser above the soil surface (thus a deeper ponding depth), the more difficult it is to design and implement due to topographical constraints. Deeper ponding depths at some sites are less accepted by stakeholders and partners due to perceived safety concerns.

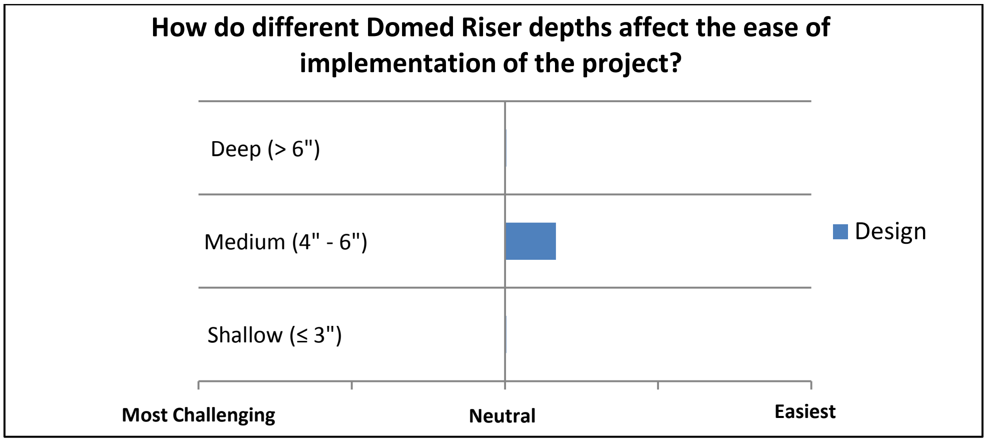


Figure 6-15: Domed Riser Depth Questionnaire Average Response: Design (n=6)

6.2.9 Materials

This section includes findings for how several Variables that fall under Materials impact ease of implementation.

Primary Storage Type

Primary Storage Type describes the GSI materials primarily used to store stormwater, including stone, bioretention soil, arched chambers, structural vault, plastic crates, suspended pavement cells, and structural soil.

Standard storage materials, such as stone and bioretention soil, are easy to acquire and easy to incorporate in designs. Cost is the main factor that makes implementing some materials more challenging. Arched chambers, structural vaults, and structural soil are relatively expensive. Certain storage types, such as plastic crates and arched chambers require materials that are only appropriate for footways. Suspended pavement cells are often opposed by partners.

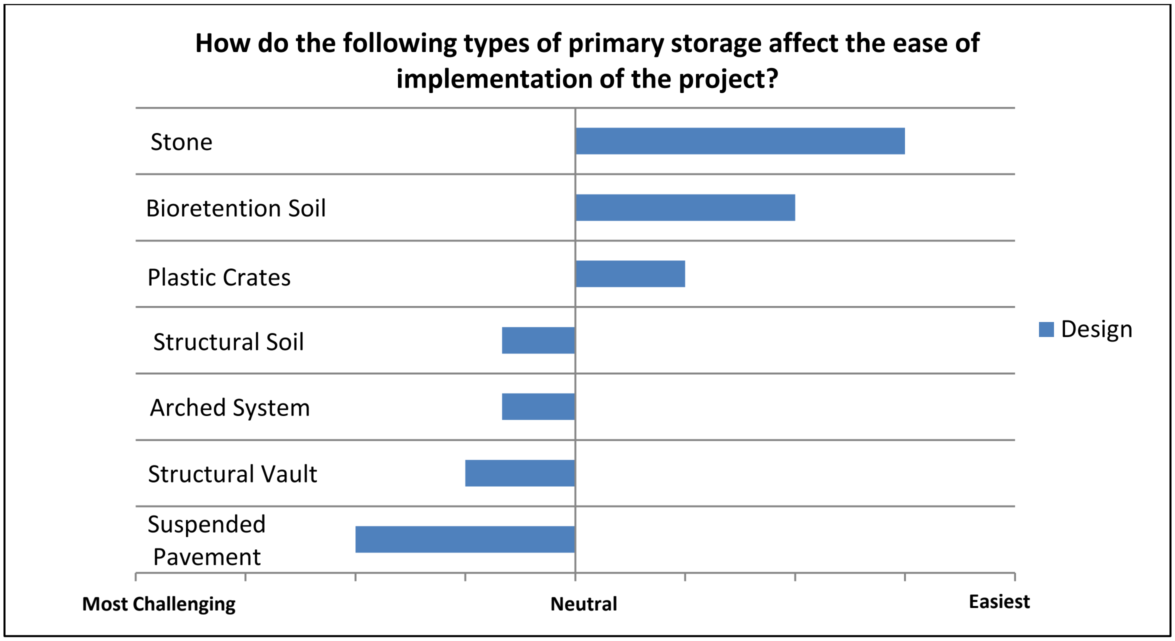


Figure 6-16: Primary Storage Type Questionnaire Average Response: Design (n=6)

Permeable Pavement Type

Permeable Pavement Type describes the paving surface materials used as part of a permeable pavement system, including asphalt, concrete, pavers, and rubber playground surface. Most permeable pavement types are easy and simple to design, but expensive to construct. Permeable play surfaces are typically more expensive and are less durable than other permeable pavement types.

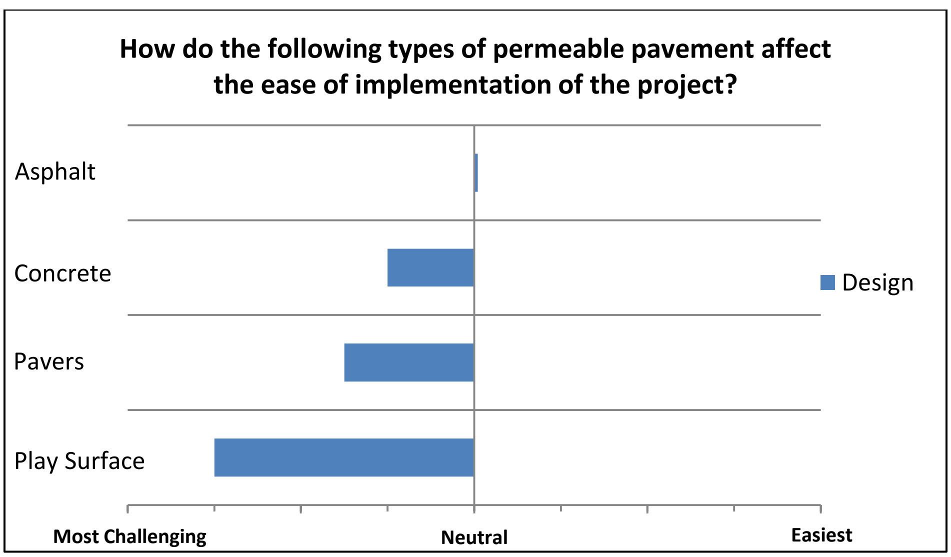


Figure 6-17: Permeable Pavement Type Questionnaire Average Response: Design (n=6)

6.3 Discussion

The results from staff interviews reflect the ease of implementation given the current practices, procedures, and design methods at this stage of Long Term Control Plan Update (LTCPU) implementation. The program is in the early period, having completed the fifth year of the 25-year implementation plan. In general, results showed that projects are easiest to implement when there are established processes, procedures, and policies or the design is relatively straightforward and lacking complexity. Implementation may become more difficult due to legal, financial, space, and technical constraints. The current conditions where results indicated difficulty in implementation highlight needs to establish more standardized approaches and policies. Implementation of GSI may become easier as both the program and the technical designs of GSI evolve to address the current constraints.

7.0 Community Perception

PWD's Public Affairs Division conducted a public survey to gage community perception of Green Stormwater Infrastructure (GSI). This section describes the questionnaire design, analysis techniques, and main findings. General questions about GSI and the Long Term Control Plan Update (LTCPU) as well as questions directly related to selected Pilot Framework Variables were included. Results related to these Variables are presented in the Section 7.3 (Findings). The general findings which are not directly related to the Variables but are still important for GSI implementation in residential areas are presented in Section 7.4 (Discussion).

7.1 Questionnaire Design

The questionnaire distributed to the general public asked 10 questions about familiarity with GSI and the LTCPU (*Green City, Clean Waters* was the term used), as well as preference for the tools used to capture stormwater, preferable locations of infrastructure, and perceived effects of GSI in the respondent's community. In addition, Public Affairs collected participants' demographics and allowed for open ended responses.

The following four questions were asked and are directly related to Pilot Framework Variables:

- GSI Land Use Type: *Where would you like to see GSI in your community? (Select all that apply)*
  - Schools, recreation centers, parks, streets and sidewalks, alleys, commercial/shopping districts, private residential, parking lots, vacant land
- GSI System Type: *Which kind of GSI would you like to see in your community? (Select all that apply)*
  - Stormwater bumpouts, stormwater planters, rain gardens and swales, stormwater tree trenches, underground storage trenches, permeable pavement, green roofs
- GSI Visibility: *What kind of GSI would you like to see in your neighborhood? (Select all that apply)*
  - Below ground without trees or vegetation, above ground with stormwater trees, above ground with low vegetation (shrubs, grasses, flowers)
- Rooftop Disconnection: *Would you be willing to work with PWD to disconnect the downspout on your home or business so that stormwater runoff can flow into public GSI?*
  - Yes, no, not sure

The following questions are not directly related to Pilot Framework Variables:

- Are you familiar with *Green City, Clean Waters*?
  - I have never heard of it before; I've heard of it in passing, but don't really know what it's about; I've learned about it in the news and/or other sources and understand what it is about

- How familiar are you with Green Stormwater Infrastructure?
    - Extremely, very, moderately, slightly, not at all
- How likely are you to support public investment in Green Stormwater Infrastructure if it resulted in improvements to the health of local rivers and watersheds?
    - Very likely, likely, neutral, unlikely, very unlikely
- In your opinion, what kind of effect does Green Stormwater Infrastructure have on the following?
    - Neighborhood beauty, property values, crime reduction, waterway health, local economy, ease of transportation, traffic safety, pedestrian safety
    - Very positive, positive, neutral, negative, very negative
- Would you be willing to deal with temporary inconveniences of construction in your neighborhood if it resulted in improvements?
    - Yes, no, not sure
- Which of the following stormwater tools in your neighborhood are you aware of?
    - Rain barrels, downspout planters, GSI on the street, GSI in an off-street location, none

7.2 Analysis Methods and Tools

The survey was conducted through the QuestionPro online survey software. PWD asked members of the *Green City, Clean Waters* Advisory Committee to distribute the link to the online questionnaire to their organization's mailing list, members, and partners. In addition, PWD publicized the link on Facebook, Twitter, and the phillywatersheds.org blog.

The sampled individuals were those likely exposed to *Green City, Clean Waters* previously, as a random sample of Philadelphia wasn't attainable in the limited time period. It is likely that most Philadelphians have not been exposed to the concept of GSI and *Green City, Clean Waters*. While the online questionnaire was open, the Public Affairs team monitored and conducted outreach in zip codes and among demographic groups that had few responses. In addition, PWD is currently conducting a more comprehensive customer service survey of all customers, which includes questions about GSI and field surveys of residents whose streets have undergone construction of GSI. These survey results will provide a more complete picture of public awareness and attitude towards GSI.

By distributing this questionnaire through PWD's civic partner organizations, which include environmental groups, neighborhood civic associations, community development corporations, and partner agencies, Public Affairs acknowledges that the resulting sample is more likely to be composed of engaged citizens who are familiar with Philadelphia's *Green City, Clean Waters* program.

The analysis excluded respondents who identified as living outside of the City of Philadelphia.

7.3 Findings

This section presents only those results for questions which are related to Framework Variables. Details on results not directly related to the Variables can be found in Section 7.4 (Discussion).

7.3.1 GSI Land Use Type

This section includes the findings for the question: "Where would you like to see Green Stormwater Infrastructure in your community?" This question is related to the Variable GSI Land Use Type. Eligible answers are: Streets and Sidewalks, Schools, Parks, Recreation Centers, Parking Lots, Vacant Land, Commercial/ Shopping Districts, Private Residential, and Alleys. Definitions of GSI Land Use Type Variables and Levels can be found in Appendix A (Pilot Variable Framework).

Results indicate that there is wide support for GSI across various land use types. Seventy-one percent of respondents would like to see GSI constructed at schools and on streets and sidewalks. In addition, parks, recreation centers, parking lots, vacant land, commercial/shopping districts, and private residential all were places respondents wanted to see GSI in their community. Alleys were the only offered site that most respondents did not want to see GSI constructed.

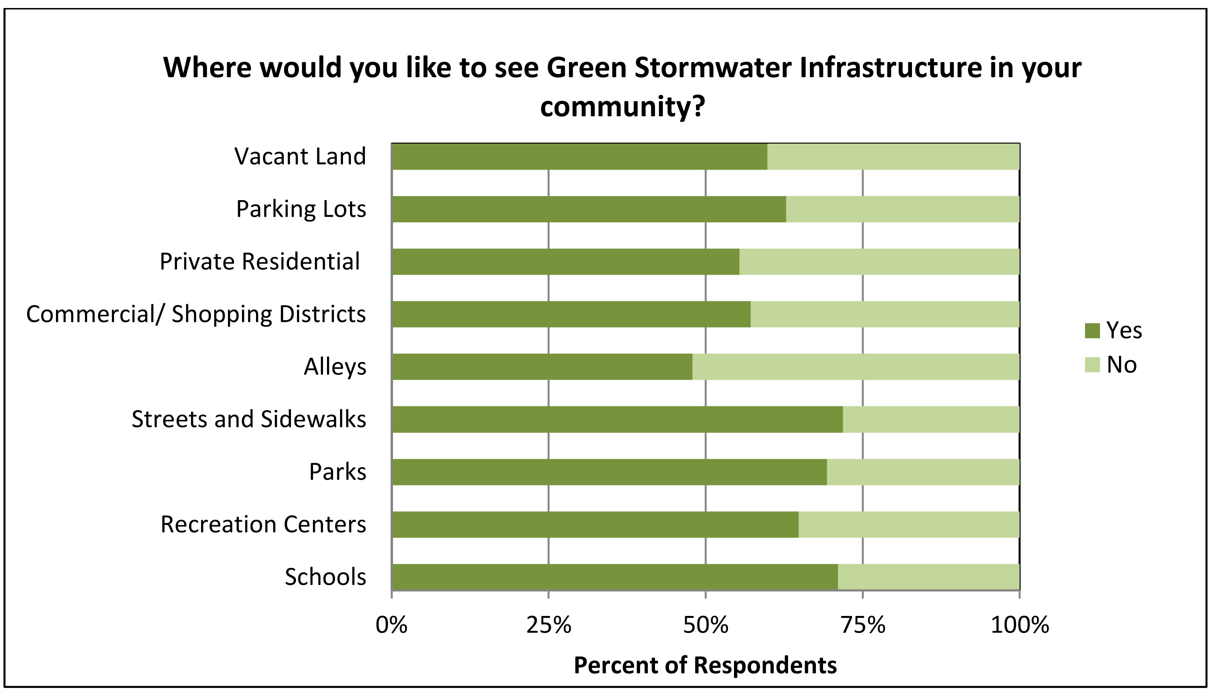


Figure 7-1: Response to a Question about the Placement of Green Infrastructure (n = 1,665)

7.3.2 GSI System Type

This section includes the findings for the question: "Which kind of Green Stormwater Infrastructure would you like to see in your community?" This question is related to the Variable GSI System Type.

Eligible answers are: Underground Storage Trenches, Permeable Pavement, Green Roofs, Stormwater Bumpouts, Stormwater Planters, Stormwater Tree Trenches, and Rain Gardens and Swales. Definitions of the GSI System Type Variable and Levels can be found in Appendix A (Pilot Variable Framework).

As shown in Figure 7-2, the most popular GSI system types included rain gardens and swales, stormwater planters, stormwater tree trenches, green roofs, and permeable pavement. Fifty-two percent of respondents would like to see stormwater bumpouts in their community, and only 38% of respondents were interested in underground storage trenches.

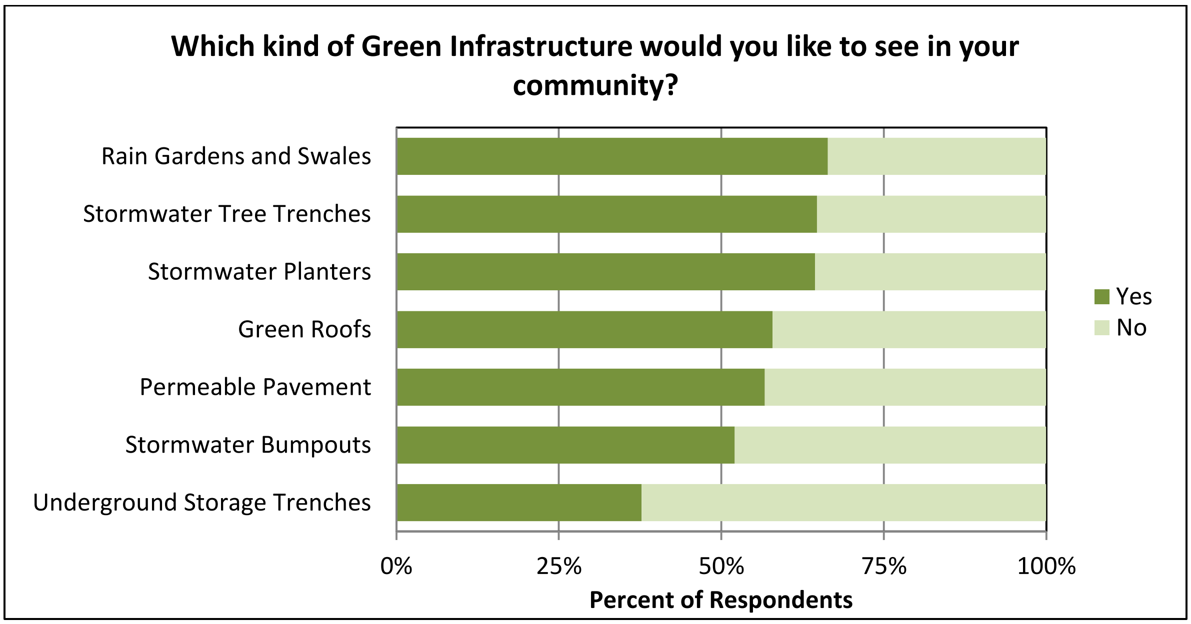


Figure 7-2: Response to a Question about the Type of Green Infrastructure in a Community (n = 1,664)

7.3.3 GSI Visibility

This section includes the findings for the question: "Which kind of Green Stormwater Infrastructure would you like to see in your neighborhood?" This question is related to the Variable group GSI Visibility. Eligible answers are: Below ground without trees or vegetation, above ground with stormwater trees, and above round with low vegetation (shrubs, grasses, flowers). Definitions of GSI Visibility Variable and Levels can be found in Appendix A (Pilot Variable Framework).

Generally, above ground systems are preferred by the community as they are more desirable aesthetically, as shown in Figure 7-3. Seventy-three percent of respondents want to see GSI above ground with low vegetation, and 69% of respondents want to see GSI above ground with stormwater trees. Only 23% were interested in having GSI below ground in their community.

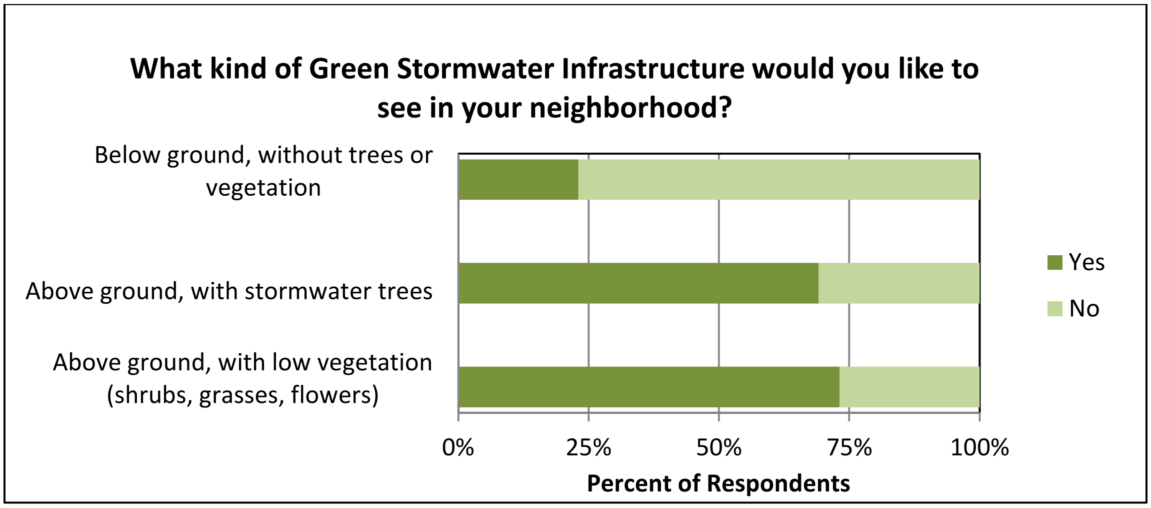


Figure 7-3: Response to a Question about the Type of Green Infrastructure Visibility in a Community (n = 1,664)

7.3.4 Rooftop Disconnection

This section includes the findings for the question: "Would you be willing to work with PWD to disconnect the downspout on your home or business so that stormwater runoff can flow into public Green Stormwater Infrastructure?" This question is related to the Variable Rooftop Disconnection, which refers to runoff from a rooftop which is disconnected from the sewer and drains to a GSI system. Definitions of the Levels for this Variable can be found in Appendix A (Pilot Variable Framework).

Seventy-two percent of respondents are willing to work with PWD to disconnect the downspout on their home or business so that stormwater runoff can flow into public GSI.

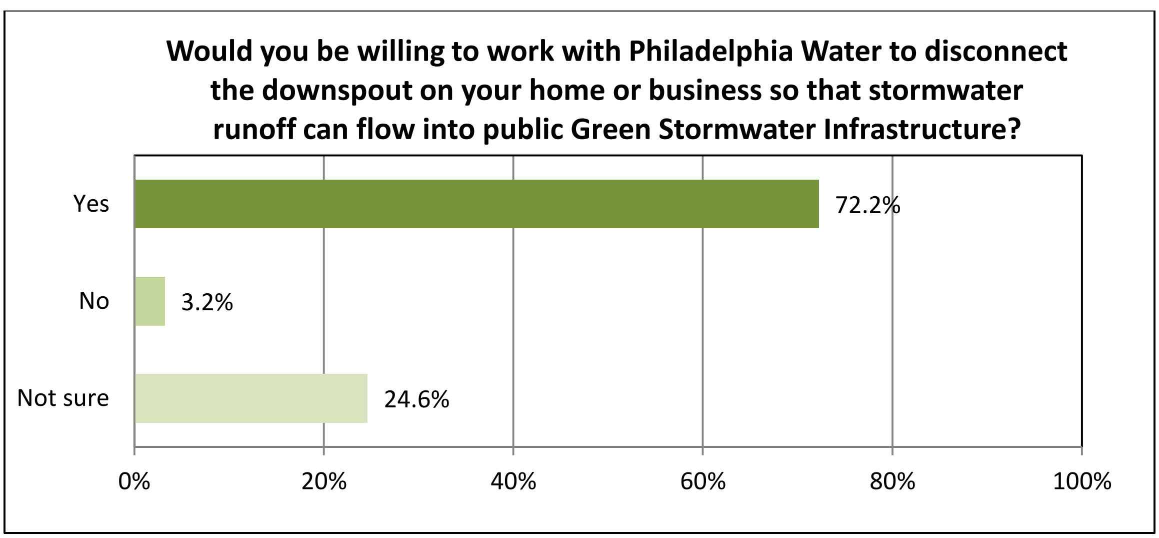


Figure 7-4: Response to a Question about Rooftop Disconnection (n = 1,664)

7.4 Discussion

This section contains results which were not directly related to Framework Variables but still of importance for future work and improvements of the implementation of the program, in particular with relation to community involvement and GSI in residential areas.

Public Affairs evaluated respondents' perceptions of what effect GSI has on a number of criteria, including neighborhood beauty, property values, crime reduction, waterway health, local economy, ease of transportation, traffic safety, and pedestrian safety. Most respondents viewed that GSI had positive or very positive effects on neighborhood beauty, property values, and waterway health. Respondents were neutral about GSI's effects on crime reduction, local economy, ease of transportation, traffic safety, and pedestrian safety. GSI is not perceived as having negative or very negative effects on any of these variables. When asked how likely respondents are to support public investment in GSI if it resulted in improvements to the health of local rivers and watersheds, only 8% were unlikely or very unlikely to support those investments. Most people are likely or very likely to support this public investment. These results show a very strong public support for PWD's LTCPU. This is important as community perception can impact the ease of implementation as shown in Section 6 (Ease of Implementation) of this report.

People were also asked about their awareness of GSI systems in their neighborhood. Fifty-seven percent of respondents reported that there were rain barrels in their neighborhood. Between 34% and 41% of respondents reported having downspout planters, GSI on the street, and GSI in an off-street location. Only 17% of respondents reported having no GSI in their neighborhood. Also, an overwhelming majority of respondents, 91%, are willing to deal with temporary inconveniences of construction in their neighborhood if it resulted in improvements.

Results from Section 6 (Ease of Implementation) also show that high density residential streets or rooftop disconnection affects the ease of implementation rather negatively due to policy and technical constraints. However, removing these obstacles could be beneficial. Feedback from the public indicates already existing awareness of stormwater management practices and a strong support for downspout disconnections in particular.

8.0 Pilot Program Summary and Conclusions

The Pilot Program was created by PWD to evaluate the first five years of the green stormwater infrastructure (GSI) program, a period of growth, evolution, and experimentation. Lessons learned from the Pilot Program have improved designs; informed understanding of stormwater management potential; enhanced design, construction, and maintenance procedures; and refined program cost estimates.

Because a GSI-centered approach to Combined Sewer Overflow (CSO) control is relatively new at the scale planned by PWD, the Pilot Program was designed to test the feasibility and measure the effectiveness of GSI under a range of potential conditions. To accomplish these goals, the Pilot Program executed the following steps:

Step 1: Developed a Set of "Pilot Projects"

Pilot projects are defined as GSI projects designed, constructed, and monitored to provide information for improved design and program implementation. One or more of the following were tracked on a total of 244 GSI systems: long-term continuous water level (46), water level response to a synthetic runoff test event (46), porous pavement surface infiltration rate (5), maintenance records (215), and construction cost (226). Of the 46 systems selected for long-term continuous water level monitoring, 40 have produced data of sufficient quality for detailed, quantitative hydrologic and hydraulic analyses.

Step 2: Identified Relevant Project Variables

GSI projects take many forms, are located in a variety of settings, and consist of different technologies and materials. This complex mix of characteristics contributes to differences in performance, cost, ease of implementation, maintenance needs, and community perception among projects. It was hypothesized at the beginning of the program that there might be a subset of these characteristics that is most important in explaining the outcome of a given project. A key mission of the Pilot Program has been to attempt to identify this subset of variables and to use it to inform future choices on how projects are sited, designed, implemented, and maintained. In order to make this objective assessment, it was necessary to develop a standardized description of the complex variables present in each project, thereby enabling comparisons of these variables across projects. To assess these characteristics contributing to the outcome of GSI projects, 24 descriptive variables (e.g., Land Use Type) were identified, each with a set of levels to be evaluated for the relative importance of their contributions (e.g., schools, parks, streets). Variables are conditions that could affect the ability of GSI to be implemented, its ability to function as designed, or its ability to maintain its functionality over time. These variables include:

- Land Use Type
- Drainage Area Characteristics
- GSI System Type
- GSI Design Elements
    - Inlet Type

  - System Surface/Subsurface Status
  - Loading Ratio
  - Static Storage Volume
  - Vegetation Status
  - Pretreatment Type
  - Inflow Type
  - Street Crossing Type
  - Rooftop Disconnection
  - Domed Riser Depth
  - Energy Dissipator Type
- Materials
  - Primary Storage Materials
  - Permeable Pavement Type
  - Soil Type
- Physical Conditions
  - Physiographic Province
  - Tested Soil Infiltration Rate
  - Street Slope
- Policy/Partnerships
- Implementation Strategy
- GSI Visibility
- GSI Location Ownership

Each item in this list was labeled as a "Variable" consisting of several "Levels." For example, the Land Use Type Variable consists of Levels including schools, streets, parks, etc. The full list of Pilot Variables, Levels, and descriptions of each are located in Appendix A (Pilot Variable Framework). Applicable Levels of the Variables were assigned to each pilot project. It was the intent to select projects to evaluate as many of the Variables and Levels as possible, and each pilot project is useful in testing multiple Variables.

Step 3: Evaluated the Impact of the Project Variables

Project Variables were evaluated for their effect on the following five categories:

- Hydrologic performance
- Construction cost
- Ease of implementation
- Ease of maintenance
- Community perception

The program is continuously producing a large, and growing, volume of data on GSI. It is challenging to find ways to analyze all of these data using traditional engineering methods. The Pilot Program has developed a two-step process for managing these data. The first step uses statistical algorithms to identify significant relationships and trends in the data. This step eliminates a large amount of data that do not contain significant trends. Some of the relationships and trends identified as potentially significant by the automated algorithms turn out to be significant in an engineering sense, while others are not. Statistical screening does not replace engineering analysis, but it reduces the effort required to perform engineering analysis. Once the statistical analysis identifies Variables of interest, the second step involves the engineering team analyzing the results to try to identify physical explanations for the behavior that can be translated into conclusions and actionable recommendations.

A total of ten datasets of performance metrics were run through the statistical analysis for each of the 24 Variables, resulting in a total of 240 potential correlations. These performance metrics were used to evaluate three of the five categories, including hydrologic performance, construction cost, and ease of maintenance. Ease of implementation and community perception did not have quantitative data appropriate for this statistical analysis, and were evaluated through staff interviews and community questionnaires. Of the 240 Variable/performance metric tests, 215 were eliminated for lack of trend or significance. The remaining 25 Variables were further analyzed to assess their impact on the three categories mentioned above.

Results demonstrating the program's effectiveness of meeting each of the five categories are summarized in this section.

8.1 Conclusions about Hydrologic Performance of GSI

The performance monitoring of GSI has shown that overall, systems are performing better than predicted by PWD's current engineering design assumptions. The systems overflow less often than predicted, experience higher infiltration rates and faster draindown times than predicted, and have more excess storage capacity available than predicted over a range of events. The performance monitoring period providing data for Pilot Program analyses covers parts of four calendar years (2012-2015). The years 2013 and 2015 had more rainfall than the long-term average, while 2012 and 2014 had less rainfall than the long-term average. Therefore, stormwater management performance of GSI systems during this monitoring period can be considered reasonably representative of performance over a range of conditions.

Results provide strong evidence that these systems are capturing stormwater effectively and keeping it out of the combined sewers, with many fewer system overflows than predicted using conservative design assumptions. After analyzing data from all events at all systems during this monitoring period, there were 22 system-events where a system filled to design capacity and only 18 system-events where capacity was exceeded and a system overflowed into the downstream combined sewer. These events represented only 3.6% of the 497 exceedances predicted using current engineering design assumptions, thus showing that the designs are relatively conservative. Only 0.36% of all 5,027 system-events over the monitoring period overflowed into the downstream combined sewer.

Comparison of pre-construction and post-construction infiltration rates provides further evidence that field performance is consistently exceeding expectations. Infiltration rates under post-construction field conditions are estimated by observing the rate of water level recession following runoff in systems where infiltration is the only significant outflow process (i.e., without controlled releases to the combined sewer system). The small number of observed storage capacity exceedances (compared to exceedances predicted by engineering design assumptions) is most likely due to higher than expected infiltration rates under post-construction field conditions, influenced by both vertical infiltration into native soil and fill, horizontal movement through the sides of systems, and movement through preferential pathways. Observed infiltration rates under post-construction conditions for the 22 monitored infiltration-only systems range from 0.49 to 13.2 inches per hour, with an average of 5 inches per hour. Compared to results of the pre-construction infiltration tests which form the basis for system design, these observed post-construction rates are consistently higher for most sites and events, as shown in Figure 8-1. Analysis of these rates indicates that a single pre-construction infiltration test is a conservative indicator of expected post-construction infiltration over the footprint of the system. Although results of unlined borehole percolation tests (accounting for vertical and horizontal infiltration) lie closer to the line of agreement, they also conservatively predict performance.

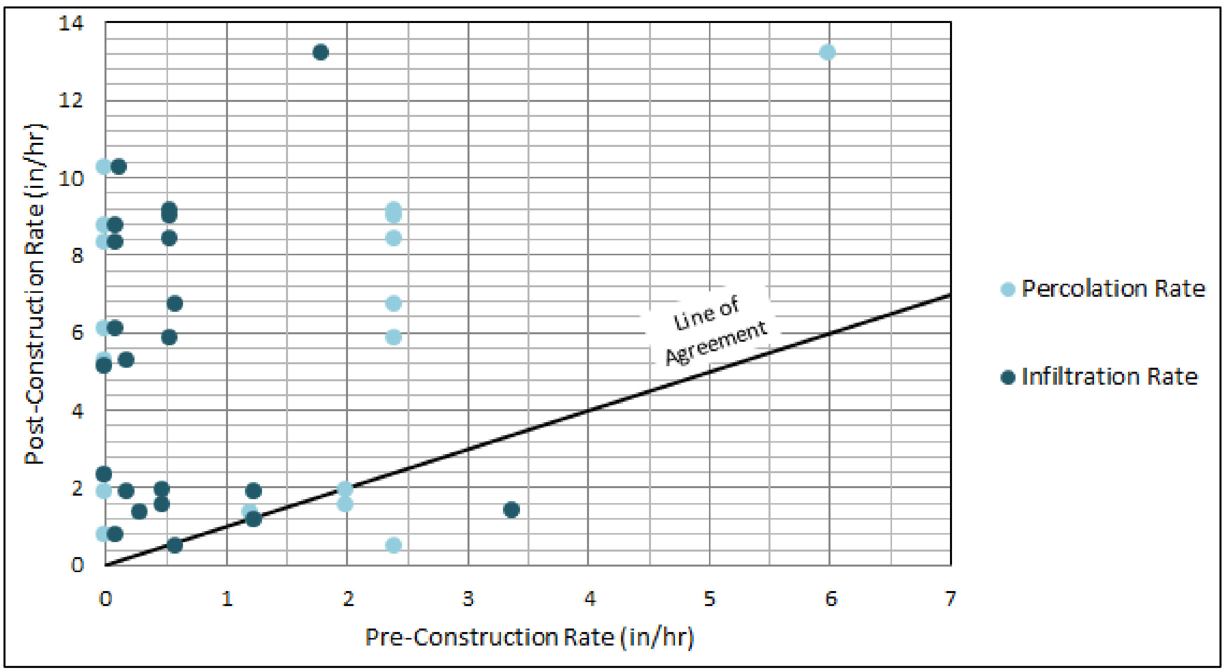


Figure 8-1: Pre and Post-Construction Infiltration and Percolation Rate Comparisons (Percolation rates are the observed drop in water in a pre-construction infiltration test, while infiltration rates are adjusted with a reduction factor to account for estimated radial flow.)

The evidence of higher than expected infiltration rates is consistent with data showing the portion of storage volume occupied during each storm. Over a range of wet weather event sizes, the fraction of storage capacity utilized is consistently less than predicted by design assumptions, providing further evidence of over-performance. Figure 8-2 shows that for the 15 systems where this data was analyzed, the average maximum portion of available storage used is less than 53% during storms less than 3.0 inches of rainfall depth, and approximately 60% for storms greater than 3.0 inches of rainfall depth. Approximately 95% of storms from 2012 to 2015 (and PWD's "typical year" used in wet weather planning) were 2.0 inches depth or less

(Figure 8-3), with 12 storms in the monitoring period above 2.0 inches depth. These results indicate that systems are regularly managing storms in excess of 3.0 inches with significant storage capacity remaining unutilized.

These results suggest it may be possible to design systems less conservatively and still meet design performance objectives. On the other hand, short-term over-performance, if it comes at a relatively low cost, may be desirable if it indicates a resilient system, that is a system able to meet design objectives reliably over a range of local conditions (for example, partial clogging) and external drivers (for example, short-term hydrologic variability and long-term climate change). Oversizing a system initially also leaves open the possibility of diverting additional drainage area to that storage element in a future phase. For example, oversizing a system on a residential street, initially designed to receive runoff only from the street and sidewalk, leaves open a possibility of diverting rooftop runoff to the storage element in a future phase.

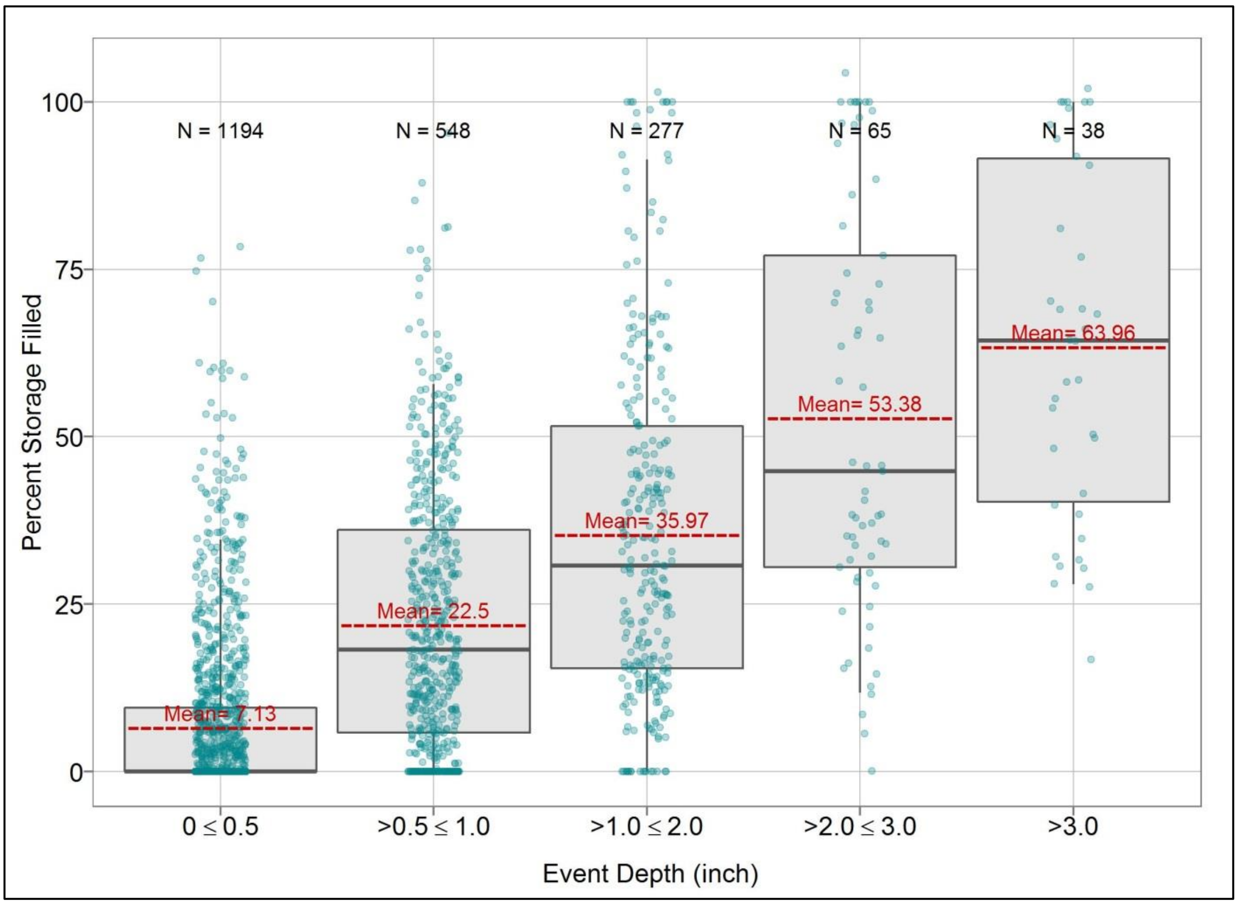


Figure 8-2: Percentage of Storage Filled for 16 Systems (2,120 events)

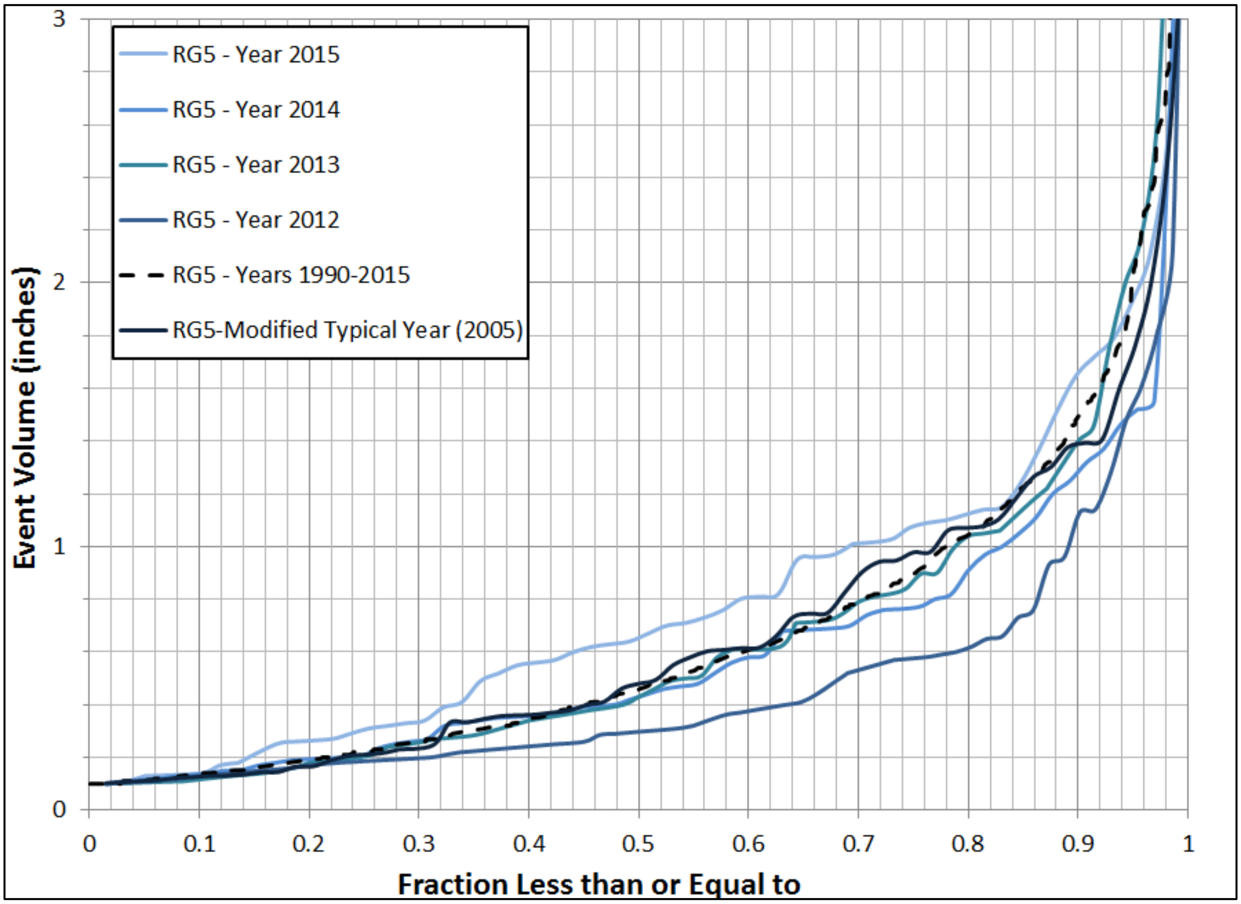


Figure 8-3: Cumulative Distribution Function (CDF) for Years 2012-2015 with Long Term (1990-2015) and typical year (modified 2005) Rain Gage 5

Additional evidence that Philadelphia's GSI systems are over-performing compared to design assumptions is provided by analysis of the time required for systems to drain following runoff events. The systems are designed to drain within 72 hours. Analysis of the continuous water level data indicated that only six of the 40 monitored systems had recession durations longer than 72 hours, and only two of these systems took longer than 72 hours to drain following simulated runoff tests. These relatively few instances of longer than expected draindown times may be influenced by soil conditions and storm shape; a long duration, large volume storm can fully saturate the soil and cause a longer draindown period, while an intense, 1 inch storm (typical of summer convective events and the synthetic runoff tests), will less fully saturate soils and drain down more quickly. Figure 8-4 is an example of differing draindown responses of three nearby systems to the same rainfall event.

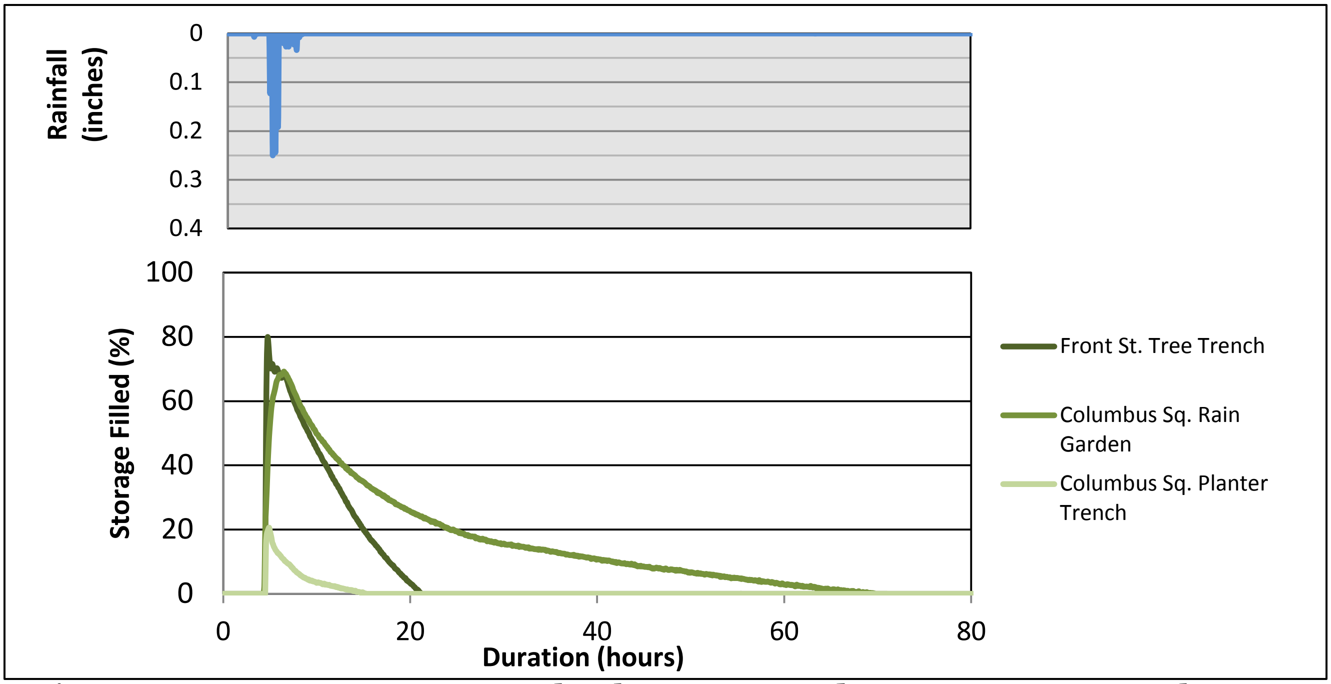


Figure 8-4: System Response at Columbus Square and Front Street to a 1 Inch Event on June 27, 2014

Long draindown times cause undesirable combined sewer system performance only if they cause storage capacity to be exceeded when it otherwise would not be during a subsequent event. During the monitoring period, only one instance was observed where a slow draining system caused a subsequent event to exceed storage capacity. In this case, the excess volume was diverted into another GSI system rather than directly to a combined sewer, and therefore was unlikely to contribute to combined sewer overflow.

The results of infiltration rate, storage utilization, and draindown duration analyses together make a strong case that PWD's GSI systems are performing better than predicted using current engineering design assumptions. A further initiative of the program was to try to create accurate water budgets for each system, showing the breakdown between the amount of water leaving the system through infiltration and slow release. Several factors make it difficult to create these water budgets without significant uncertainty. This is an area where further research may be useful in the future.

Key Design and Siting Variables that affect Performance

Analysis of monitoring data within the Pilot Variable Framework yielded limited information on siting and design decisions with significant effects on variation on performance among sites. A possible reason for this finding is that PWD's systems are all designed with the same performance criteria, limiting performance variation among sites. Another possibility is that differences in performance among sites are explained by factors, or combinations of factors, not captured in the Pilot Variable Framework.

There was one location-related finding of interest identified in the analysis. An early analysis of pre-construction infiltration rates indicated better performance within the Piedmont physiographic province than in the Coastal Plain, which is supported by the post-construction infiltration data. A possible explanation is the presence of fractured bedrock in this area.

8.2 Conclusions about GSI Construction Cost

Construction bid costs were analyzed to identify factors affecting construction cost. The purpose of analyzing system construction cost was not to develop an average cost for the program as a whole, but to relate the cost of constructing individual systems to key Pilot Variables. A few interesting conclusions can be drawn from the results:

- Several economy of scale effects are evident in the data. Construction cost per unit of drainage area exhibits economies of scale with respect to both contract size (measured by total impervious drainage area; Figure 8-5), and with respect to drainage area per individual system. The economy of scale effect is weaker but still visible with respect to cost per unit storage volume.

Figure 8-5: Bid Price (2015 USD) per Managed Impervious Area by Managed Impervious Area by System

- Some clear trends are seen with respect to GSI system type, with higher unit costs for infiltration/storage trenches and systems with planters (Figure 8-6). In both cases, the more expensive systems were smaller in footprint and located within the right-of-way (ROW).
- Land use type, as defined in this study, did not appear to have a significant impact on variation in unit area construction cost among sites.
- Systems with lower loading ratios had higher construction costs per unit drainage area than systems with loading ratios above 10:1 (Figure 8-7).

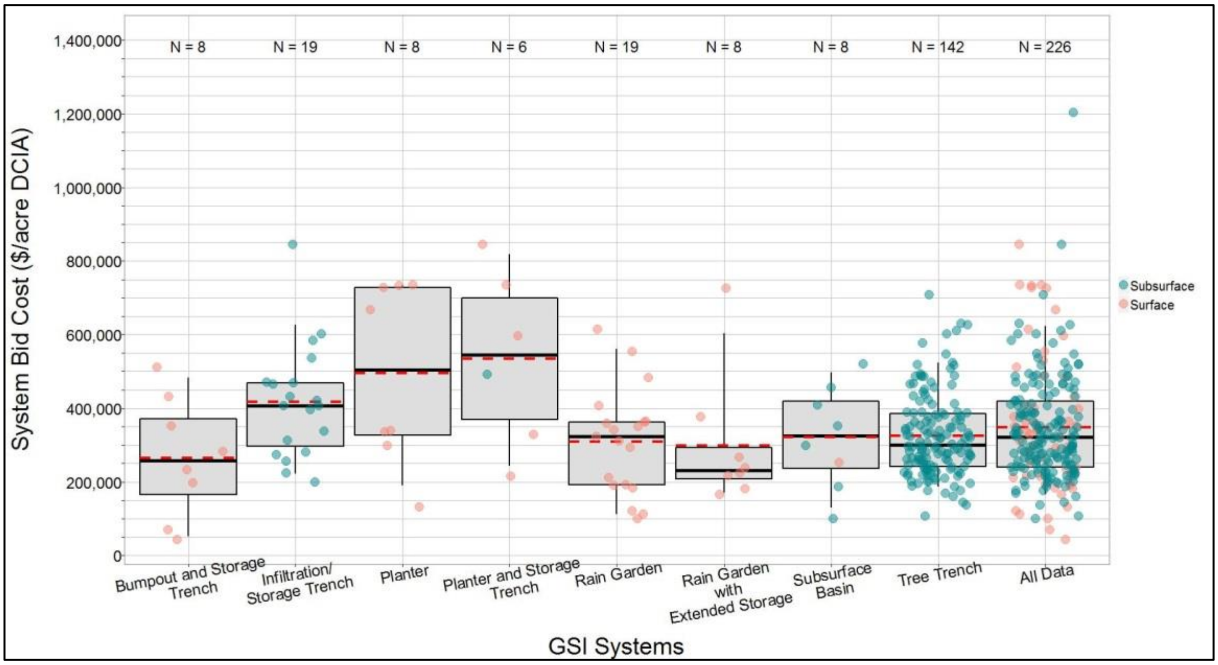


Figure 8-6: Bid Price per Managed Area (2015 USD) by GSI System Type

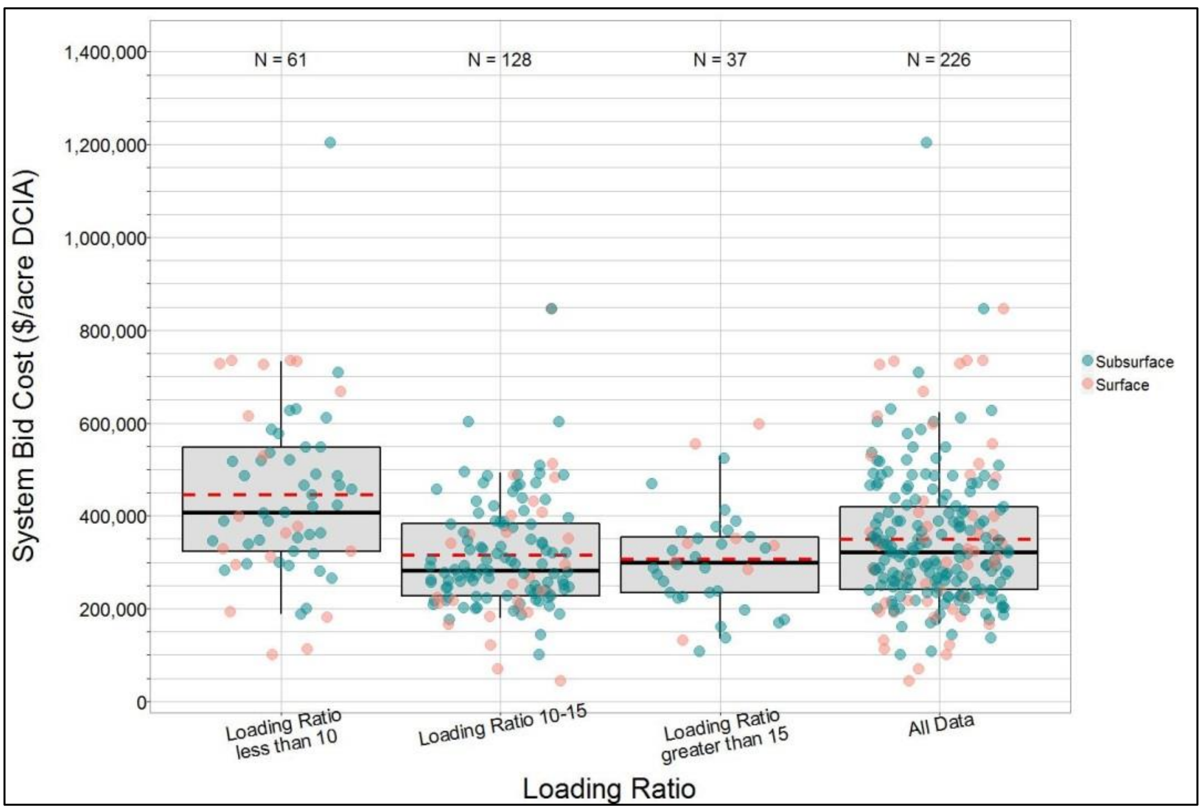


Figure 8-7: Bid Price per Managed Impervious Area (2015 USD) by Loading Ratio

- Systems where runoff is conveyed across the street have lower costs per unit drainage area than systems without the additional conveyance, because adding the additional drainage area outweighs the cost of additional piping.
- At the beginning of the program, it was hypothesized that unit cost might decrease over time and with construction of more sites over time, as designers and contractors “learn by doing,” becoming more efficient and less risk-adverse. This hypothesis was not confirmed based on data from the first five years of the program. PWD plans to continue monitoring cost to determine if a trend can be observed over longer periods of time.
- Prior to data collection, it was hypothesized that increasing design storage volume on any given site would increase construction cost. This hypothesis was not confirmed following analysis of data from a large number of sites. In other words, sites with more storage volume per unit of drainage area do not have higher construction costs, on average, than sites with less storage volume. This result suggests that factors other than storage volume are important drivers of variation in cost between sites. One implication of this result is that using less conservative design assumptions (e.g., reduced storage volume) may not be an efficient approach to bringing down unit costs.

8.3 Conclusions about Ease of GSI Implementation

“Ease of implementation” was defined as a wide variety of factors that may affect the implementation process of GSI, by either making it easier or more difficult in planning, design, and/or construction completion. PWD staff professionals were consulted and have provided some key points for consideration. Staff consulted included those responsible for the implementation of GSI, such urban planners, who are tasked with finding locations for GSI projects, and design engineers, who manage projects from concept design through preparation of construction bid documents.

A number of factors were identified by planning professionals as affecting ease of implementation.

- Involvement of civic groups and non-government organizations was viewed as easing implementation. These can increase early buy-in and acceptance of projects, although they do require time and effort to coordinate. However, the involvement of multiple stakeholders and multiple uses of the site can add difficulty to implementation. This applies especially to schools, athletic fields, recreation centers, and vacant lands.
- Permitting and review processes required by various public agencies such as education and transportation agencies can add time and difficulty to project planning and design. On the other hand, projects located in the public right-of-way tend to have clearly established standard procedures, processes, and guidance, which can help streamline the planning process. Some standard procedures for working with stakeholders on other types of public sites are still in development.
- Implementation on private land was most successful through incentive programs involving public funding for implementation on the private parcel by the private landowner.

- Capturing runoff from private parking lots and roofs for management in GSI systems on the street or other public land was identified by planning professionals as encountering significant legal and policy constraints.

Engineering design staff identified a number of conditions that affect ease of implementation.

- High density residential streets, commercial corridors, traffic triangles, and medians complicate the design process due to concentrated presence of utilities and laterals.
- Rooftops with internal drainage systems that mix sanitary sewage and stormwater make management of roof runoff very difficult.
- Rights of way around school perimeters and other streets without a significant presence of utilities and laterals have greater ease of implementation due to fewer space constraints. Open space park sites have higher potential for capture of large drainage areas in a single GSI footprint.
- Bumpout (curb extension) designs were perceived as causing vehicular traffic, turning, and parking concerns, and therefore being difficult to coordinate with transportation agencies.
- Conveying runoff across a crowned street is sometimes difficult when there is a presence of underground utilities.
- Steeper streets result in higher flow velocities, affecting inlet design. Since storage elements require flat bottoms to maximize storage, steeper streets require either deeper excavation on the upstream end of the system, or stepped systems, increasing design and construction complexity.
- Standard available storage materials, such as stone and bioretention soil, are easy to acquire and incorporate in designs. Less common materials such as arched chambers, structural vaults, and structural soil are perceived as relatively expensive. Engineering staff and partners express structural concerns about storage technologies containing plastic elements, and about suspended pavement cells.

8.4 Conclusions about Ease of GSI Maintenance

The key GSI maintenance metrics analyzed were base maintenance cost, defined as the cost of maintenance activities expected to regularly occur in a given year minus occasional as-needed costs such as structural repairs, and total volume of material removed during maintenance activities. Performance metrics were developed from this data that were run through the Pilot Framework statistical analysis to determine if any of the Pilot Variables showed trends that could be a potential driver of maintenance cost or material deposition.

- Data from the first five years reflect the choice PWD has made to maintain its surface GSI systems to a high aesthetic standard rather than only to meet more limited stormwater performance objectives. Maintenance cost data show that these high-value systems also have somewhat higher maintenance costs than subsurface systems (Figure 8-8). The most likely explanation is simply that these sites have been visited more often during the growing season to perform aesthetic landscape maintenance. In some cases, they have experienced littering and dumping which does not affect stormwater performance directly, but results in an unacceptable condition for members of the community. This dataset provides valuable information for future decisions about how to balance maintenance cost with aesthetics and engage partners to help ensure community benefits while allowing PWD to focus on its core stormwater management mission.

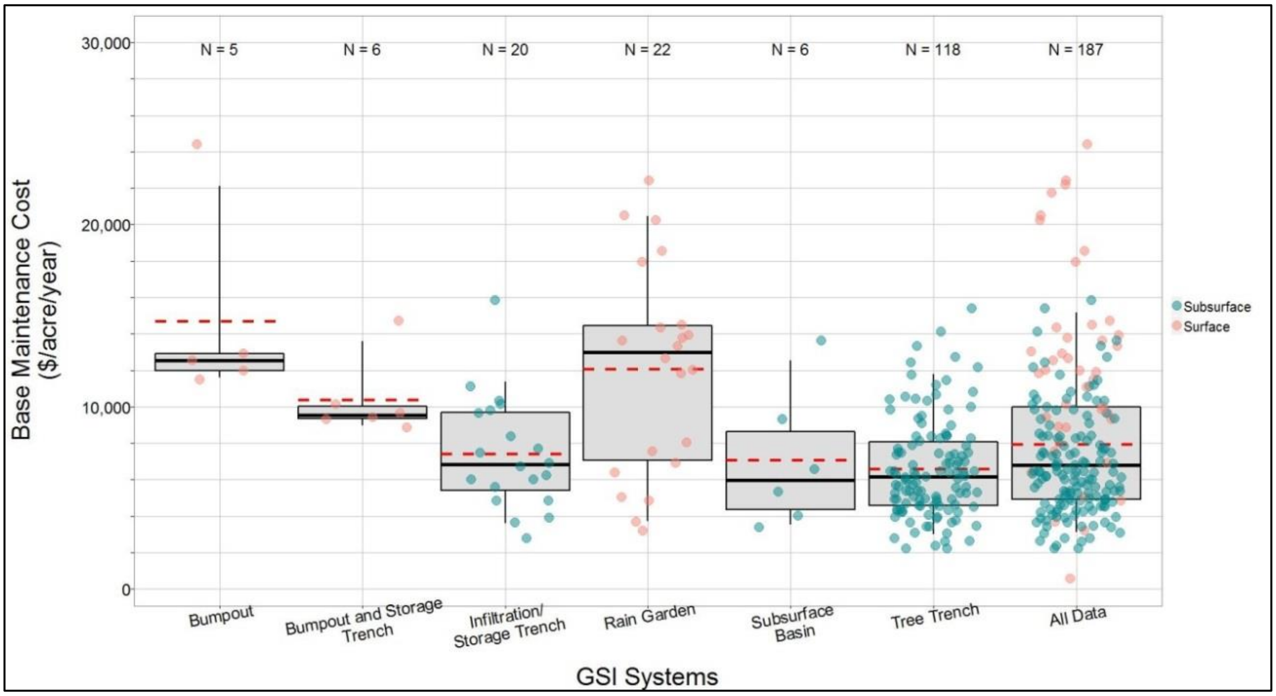


Figure 8-8: Base Maintenance Cost per Directly Connected Impervious Area per Year by GSI System Type

- Maintenance cost per unit of GSI footprint is higher for systems where risers have been installed with rims less than 3 inches above the surface of the soil. In smaller storms where subsurface storage is not filled to capacity, this design limits surface ponding to the height of the riser rim. In systems with lower riser rims and relatively impermeable planting soils, filter bags installed in the risers may be more likely to clog with sediment and inundate the surface of the system with water for periods of time that exceed design guidelines, requiring maintenance.
- An early hypothesis of the Pilot Program was that systems with higher ratios of drainage area to GSI footprint area would have more concentrated loads of solids and trash to GSI systems, and therefore might have higher maintenance costs per unit of drainage area. This hypothesis was not proven. Data show that systems with loading ratios less than 10 have slightly higher maintenance costs per unit drainage area (Figure 8-9). This result suggests that loading ratio alone may not be a good predictor of maintenance cost.

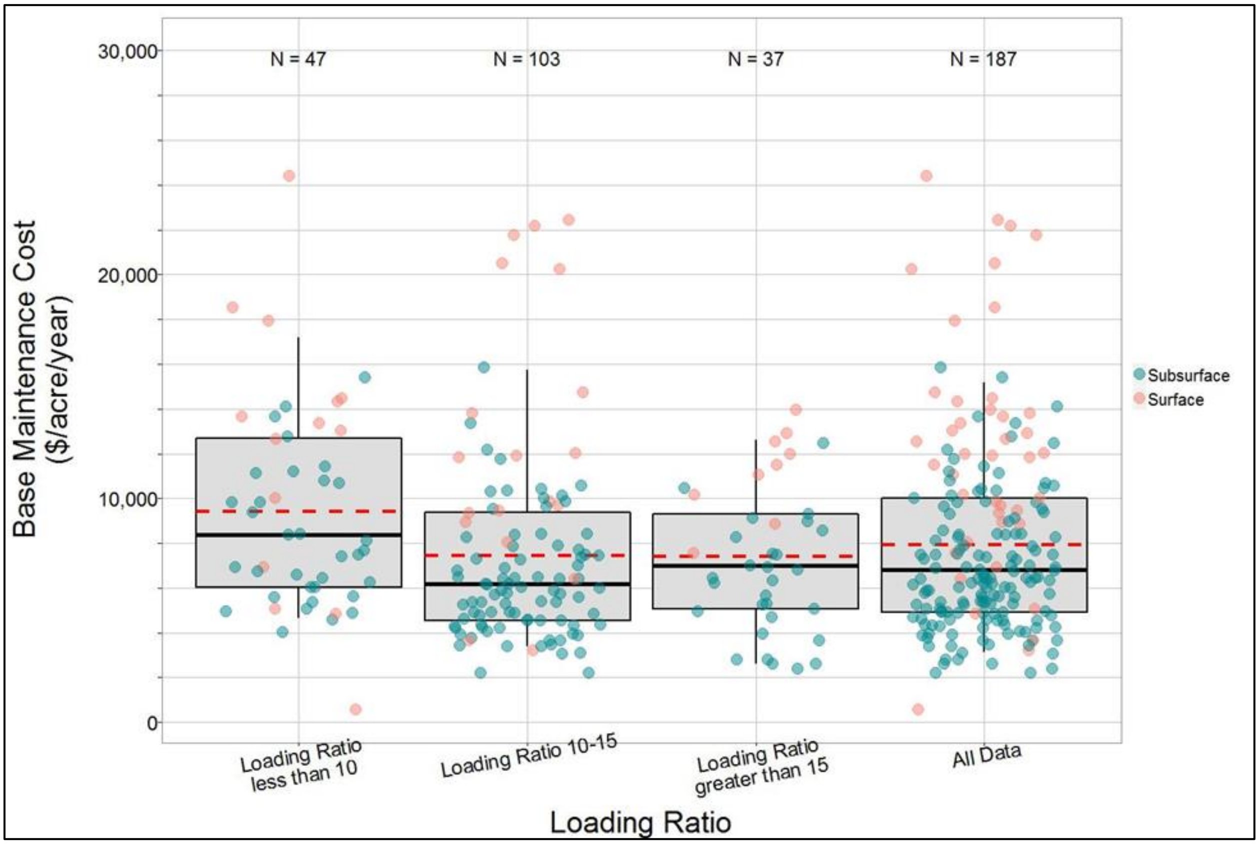


Figure 8-9: Base Maintenance Cost per Directly Connected Impervious Area per Year by Loading Ratio

8.5 Conclusions about Community Perception of GSI

Members of the public provided information about familiarity with GSI and the *Green City, Clean Waters* program, as well as preference for the tools used to capture stormwater, preferable locations of infrastructure, and perceived effects of GSI in the community. While this information may not meet the standards of a scientific survey, it provides some initial insights into how the program is being received by people who live and work in Philadelphia.

- Members of the public who chose to comment generally confirmed the perception of the professional planning staff that they see value in visible, surface vegetated systems. The most popular tools included rain gardens and swales, stormwater planters, stormwater tree trenches, green roofs, and permeable pavements.
- There is wide support for GSI across various land use types.
- Residents would be willing to work with PWD to disconnect the downspout on their home or business if stormwater runoff could flow into public GSI.