Disclaimer

How can cities establish sub-watershed scale approaches to monitor and evaluate both the individual performance and combined effectiveness of GI practices?

What local parameters will affect the scalability and transferability of these approaches?

How can cities use lessons learned from these scaled approaches to guide successful implementation and adaptive management strategies?

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Acknowledgment statement:
This research has been supported by a grant from the U.S. Environmental Protection Agency's Science to Achieve Results (STAR) program.

How can cities establish <u>sub-watershed scale</u> approaches to <u>monitor and evaluate</u> both the <u>individual performance</u> and <u>combined effectiveness</u> of GI practices?

Monitoring

- Watershed (drainage area, changes to landuse)
- Meteorology (rainfall, temperature, etc.)
- Stormwater Management Practice (SMP)
  - Inflow / outflow
  - Water storage system
  - Groundwater
- CSO/sewer/outfall flows

Evaluation – Modeling - Monitoring

- GIS – watershed
- SMP performance Individual / combined / system
  - Inspection / maintenance
  - Time frame
  - Future rainfall
- CSO/sewer/outfall

Villanova Project Team

- Civil and Env. Engineering
  - Robert Traver, Ph.D., PE. D.WRE
  - Andrea Welker, Ph.D., PE.
  - Bridget Wadzuk, Ph.D.
  - Virginia Smith. Ph.D.
  - Cara Albright, Ph.D. Candidate
- Mechanical Engineering
  - Garrett Clayton, Ph.D.
- Philadelphia Water Department
  - Stephen White

PHILADELPHIA WATER DEPARTMENT

Stormwater Tree Trench

Rain Gardens

Stormwater Planter Trench (Sidewalk)

Source: PWD (all images)

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Monitoring Challenges

- Sites already constructed
- Runoff bypass
- Trash + sedimentation = clogs
- Power and communications
- Lack of commercially available products
- Cost

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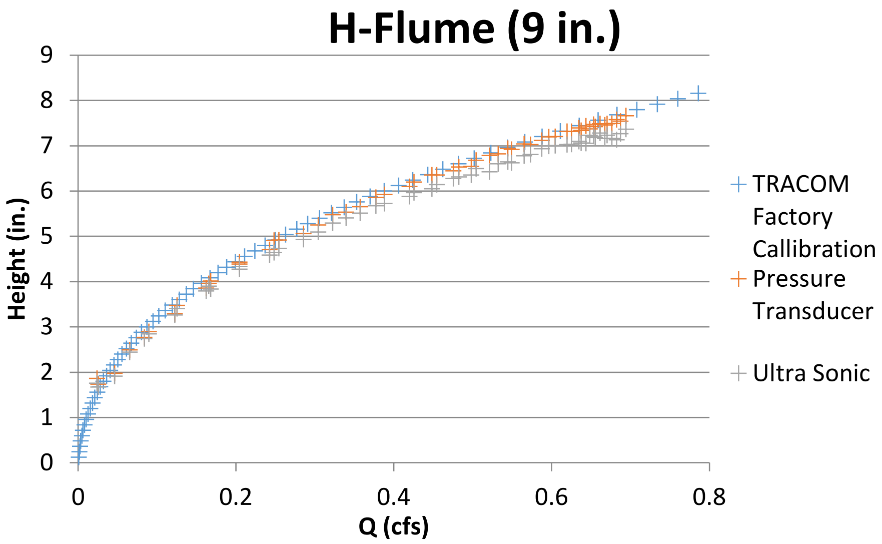
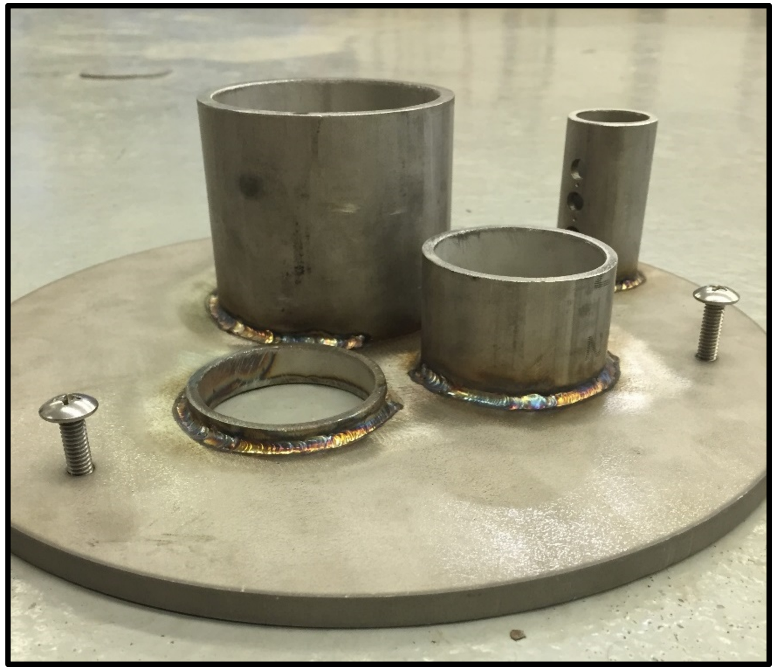
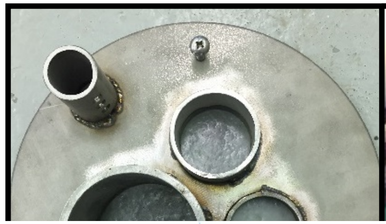
Monitoring & maintenance costs: equipment - Inflow: H flume

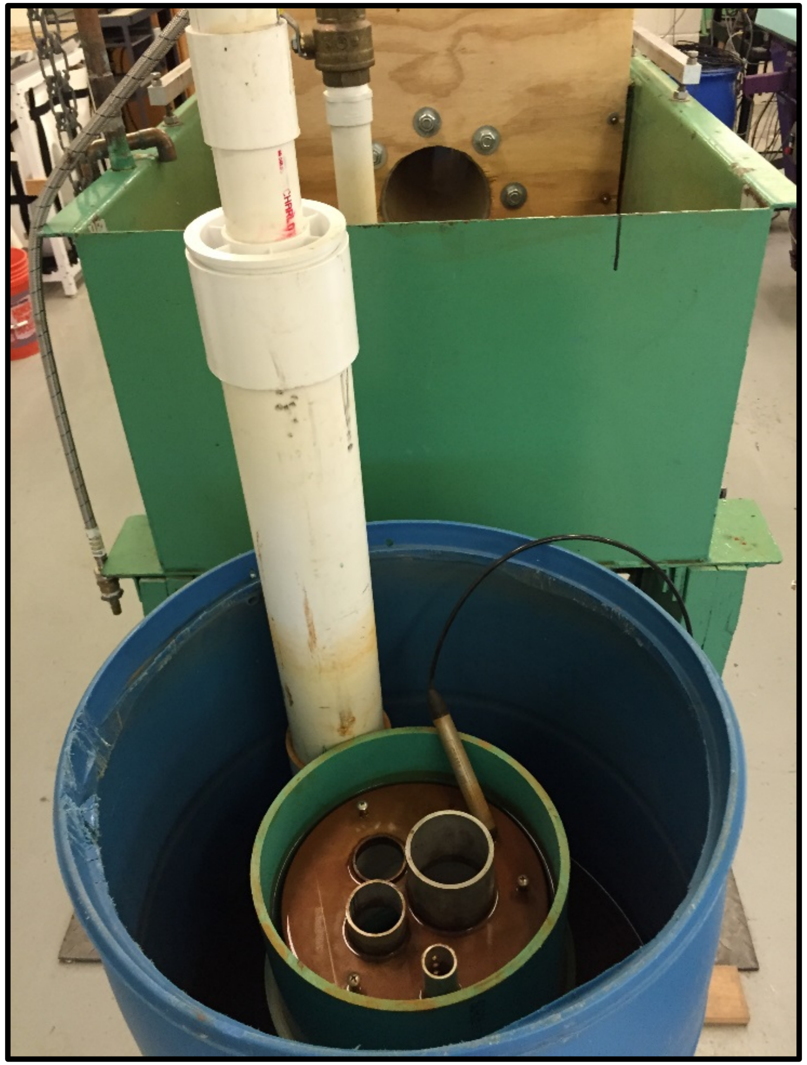
- Zoo rain garden inlet
- Custom made inlet H flume
- Extensive design and testing process
- Installed in 2015



Overflow Measurement Device







- Custom configuration of the "pipe organ orifice"
- Extensive design and testing process
- Installed at Zoo rain garden in 2015
- To be fully installed at Roosevelt sidewalk planters in 2017

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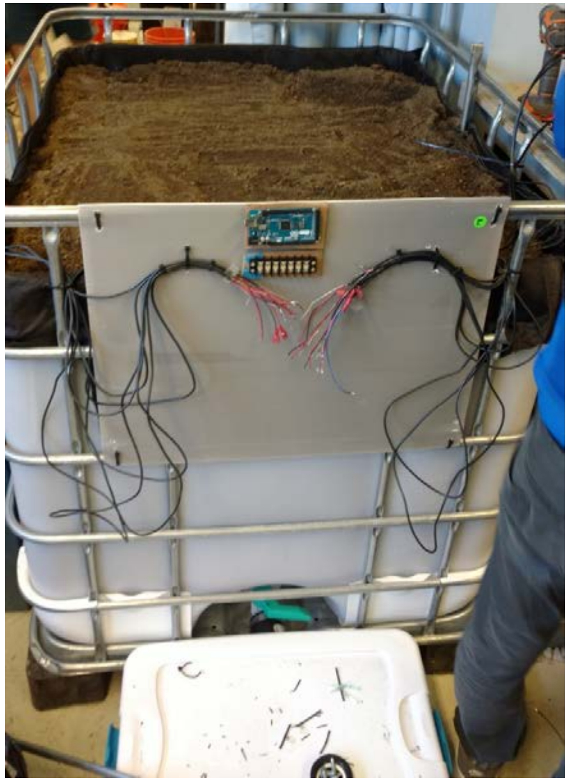
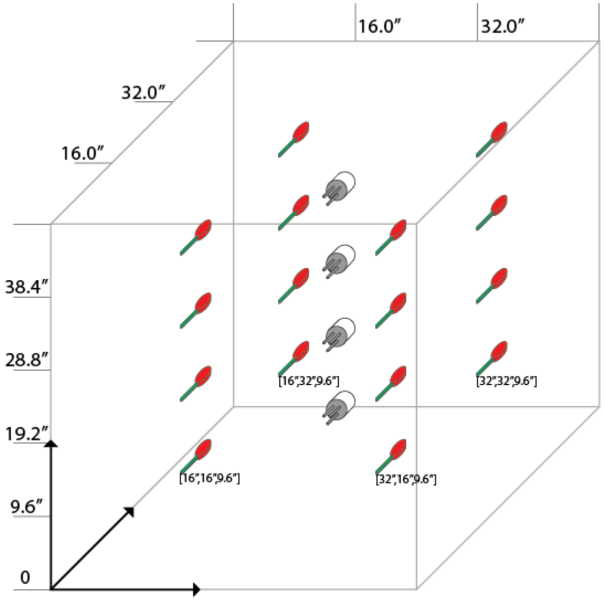
Low-cost Sensors

Comparing low-cost soil moisture sensors (Vegetronix) with conventional sensors (Hydraprobe)

- Experiment is setup
- Beginning to collect data





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If it doesn't get in, we can't measure it

Surface flow bypassing trench drain

Effects of post-construction enhancements

Inflow backing up due to debris and clogging

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Hill Freedman World Academy

Modeling urban green infrastructure with ArcHydro

Dr. Virginia Smith

VUSP
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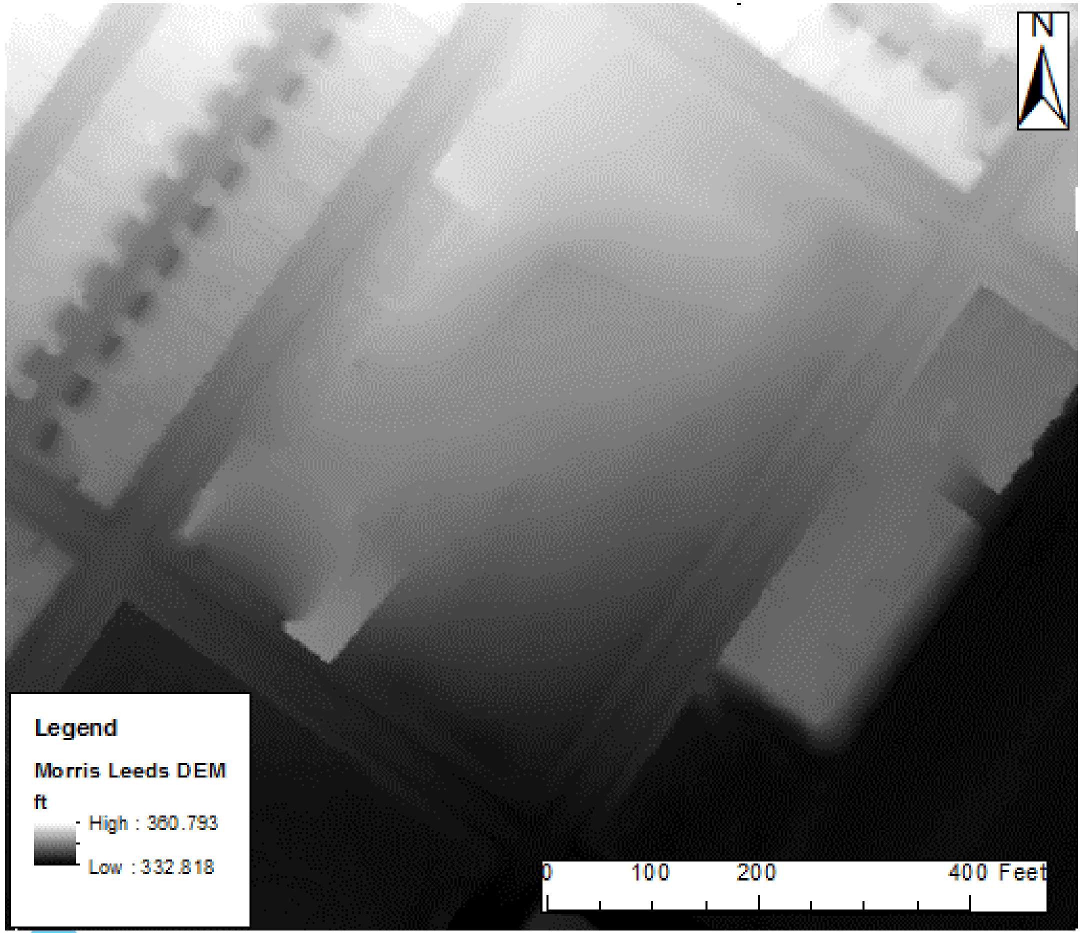
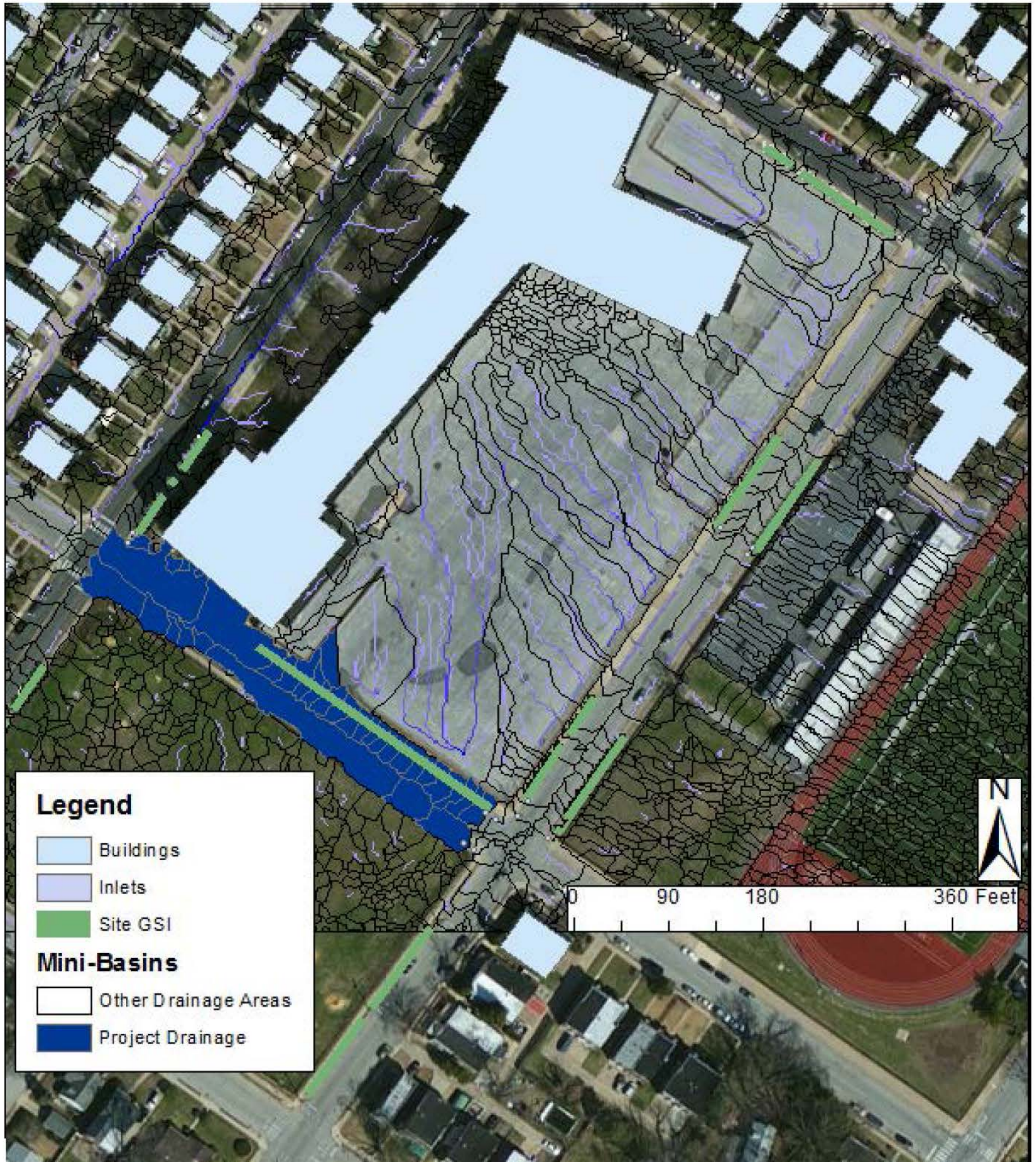
Hill Freedman World Academy



VILLANOVA URBAN STORMWATER PARTNERSHIP



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Site Evaluation Strategies

- Performance assessment on multiple levels
  - Process
  - Single SMP
  - Entire system (3 SMPs)
- Scalable, transferrable methods
  - Continuous monitoring data
  - Field tests
  - GIS/LiDAR
- Focus: universities, partners, Cfa/Dfa cities

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Example: Rain Gardens

- Compound system
- Current generation + next generation
- Surface inflow from Girard Avenue via trench drains
- 23,600 ft^2 total drainage area
- 68% impervious
- 11:1 hydraulic loading ratio
- Systems sized equivalently

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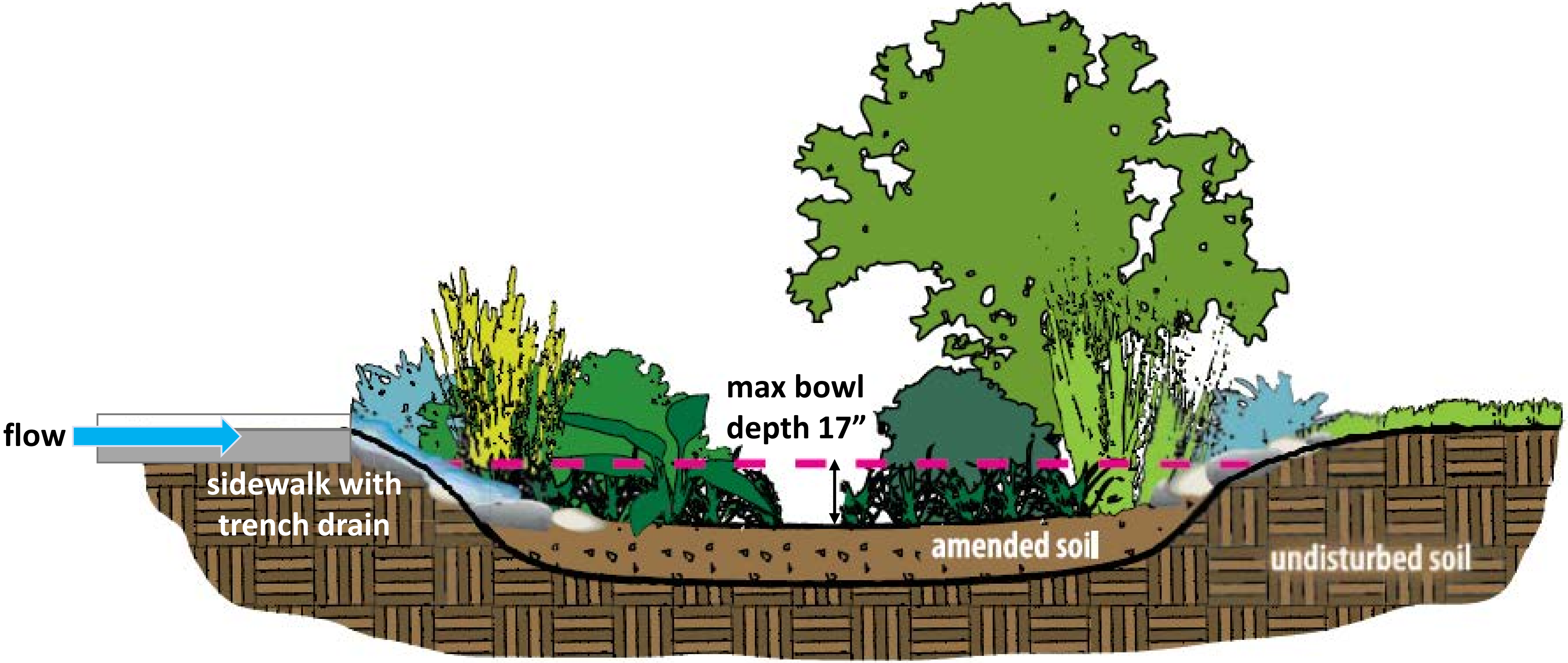
Current Generation Design: Upper Rain Garden



Next Generation Design: Lower Rain Garden

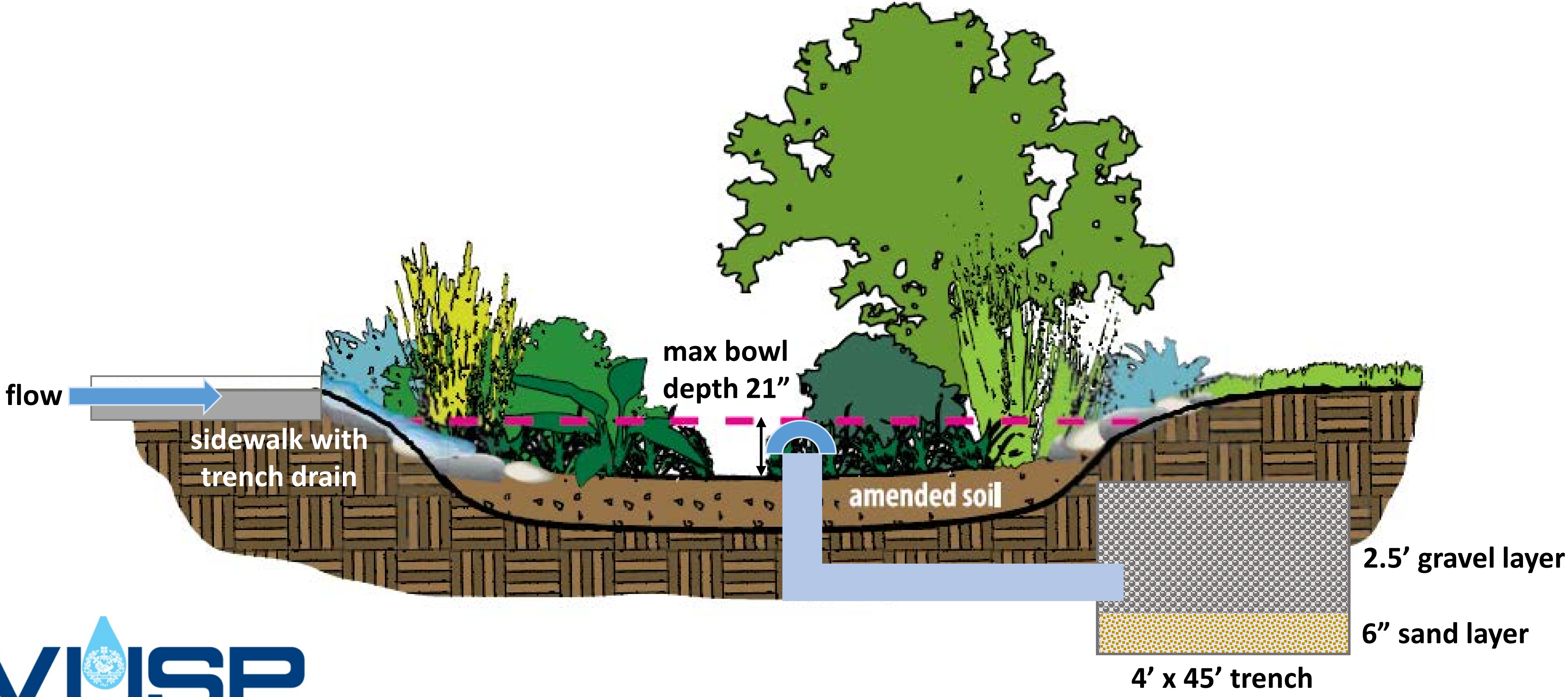


Image adapted from East Multnomah Soil and Water Conservation District (EMSWCD), Northwest Oregon/Portland Metro Area

Analysis Approach

- Conservation of mass
  - Inflow, overflow, storage
  - Rates – filling, recession, drying
- Observations
  - Small and medium storms: no overflow to storage
  - Large storms: no system overflow
  - Water reaches gravel through soil
  - Captures target events
  - Handles large, intense storms

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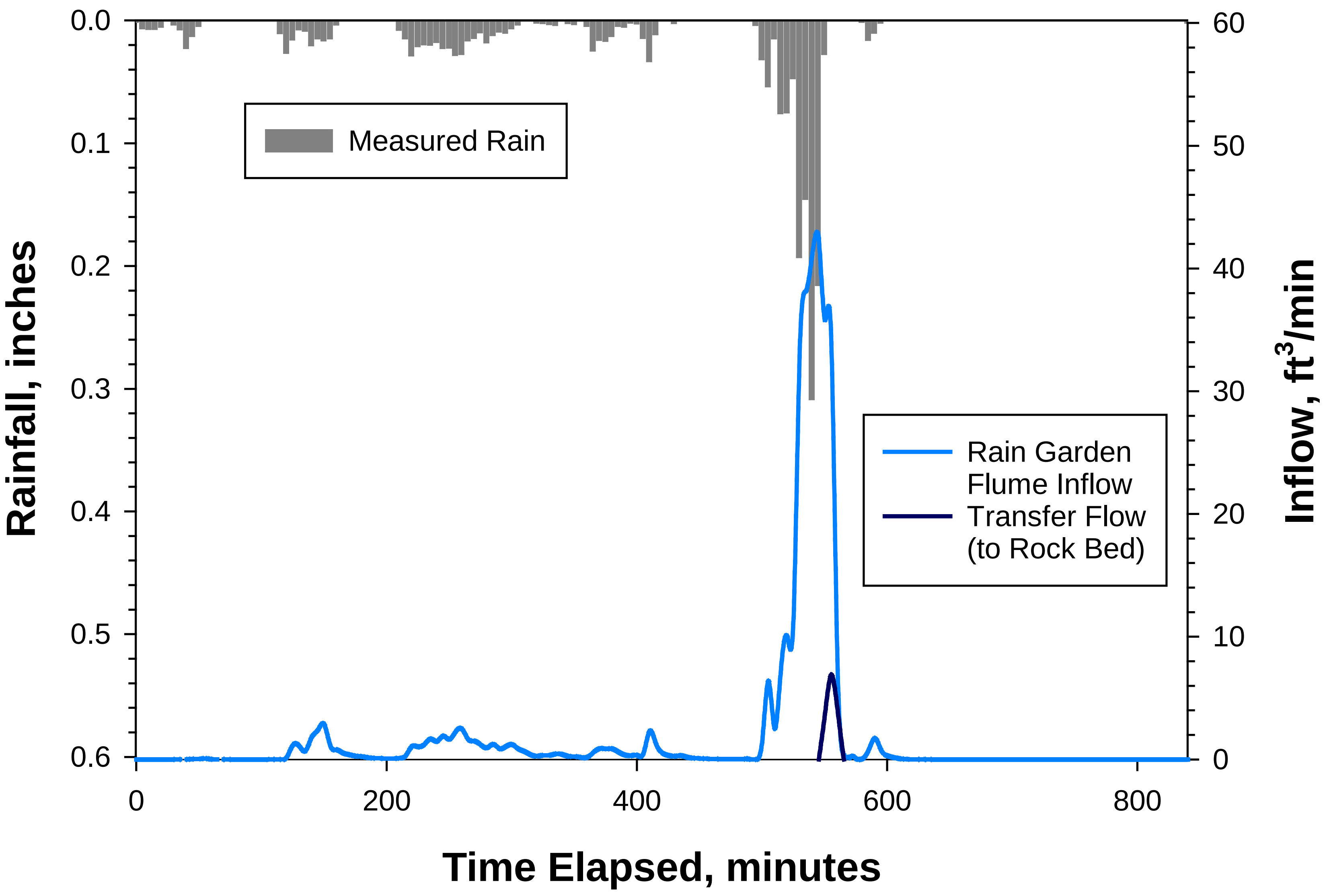
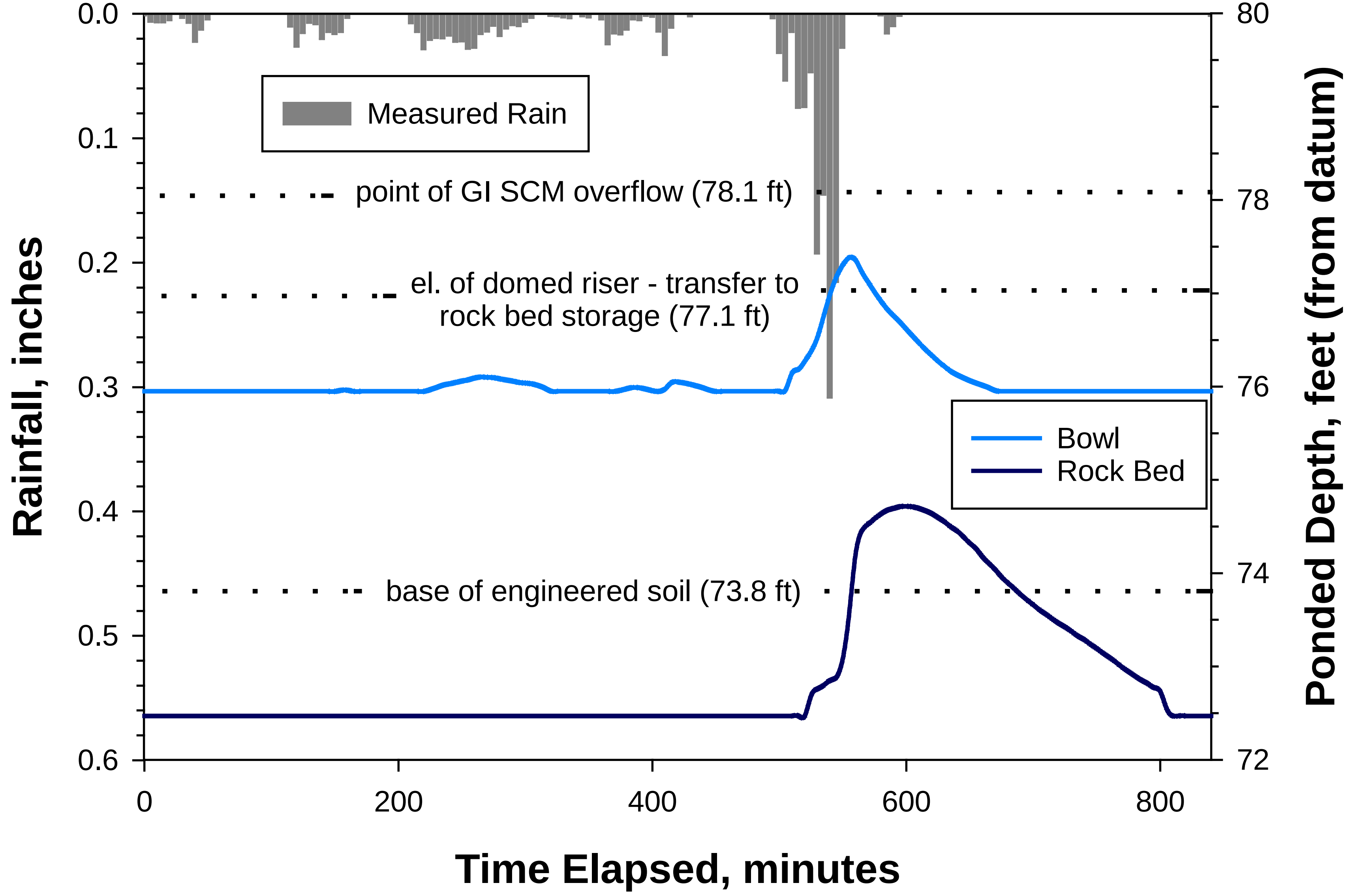
Rainfall Event: 29 May 2016

- Rainfall depth: 1.92 in
- Duration: 10 hrs
- Peak intensity: 3.7 in/hr
- No weir flow generated
- Transfer pipe to rock bed barely used



Rainfall Event: 29 May 2016



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Field Tests: It's not madness… and we've got methods

SRT = SIMULATED RUNOFF TEST

- Amazing research tool!
- Validation and monitoring
- WL-1250 calibrated at Villanova (2016)

STORM VOLUME

- DCIA runoff to site
- PWD 'Greened Acre' concept

SIZE OF RAINFALL EVENT

- Small ≈ half inch
- Mid-sized ≈ one inch
- Large ≈ two or more inches

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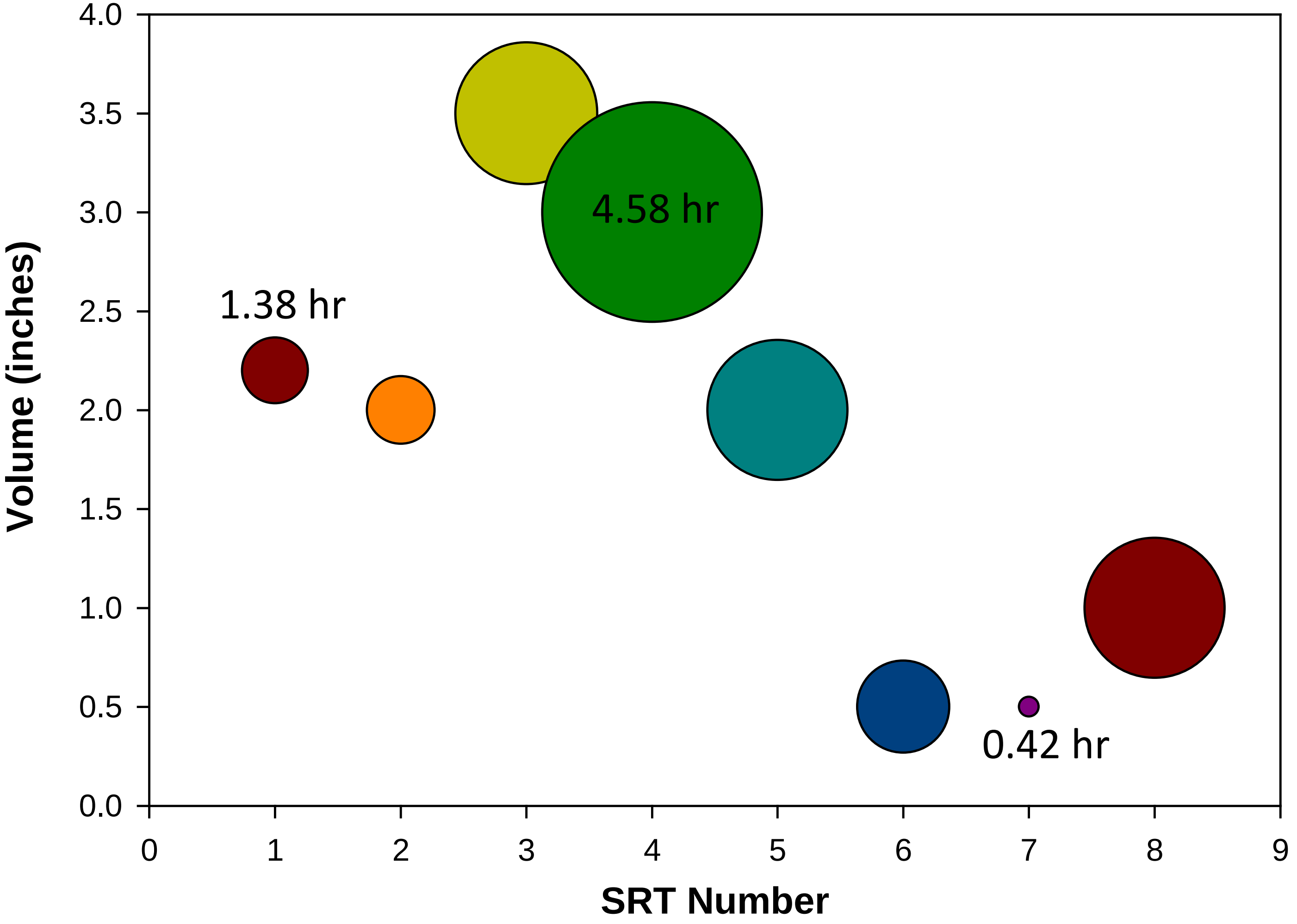
We Are The Rainmasters



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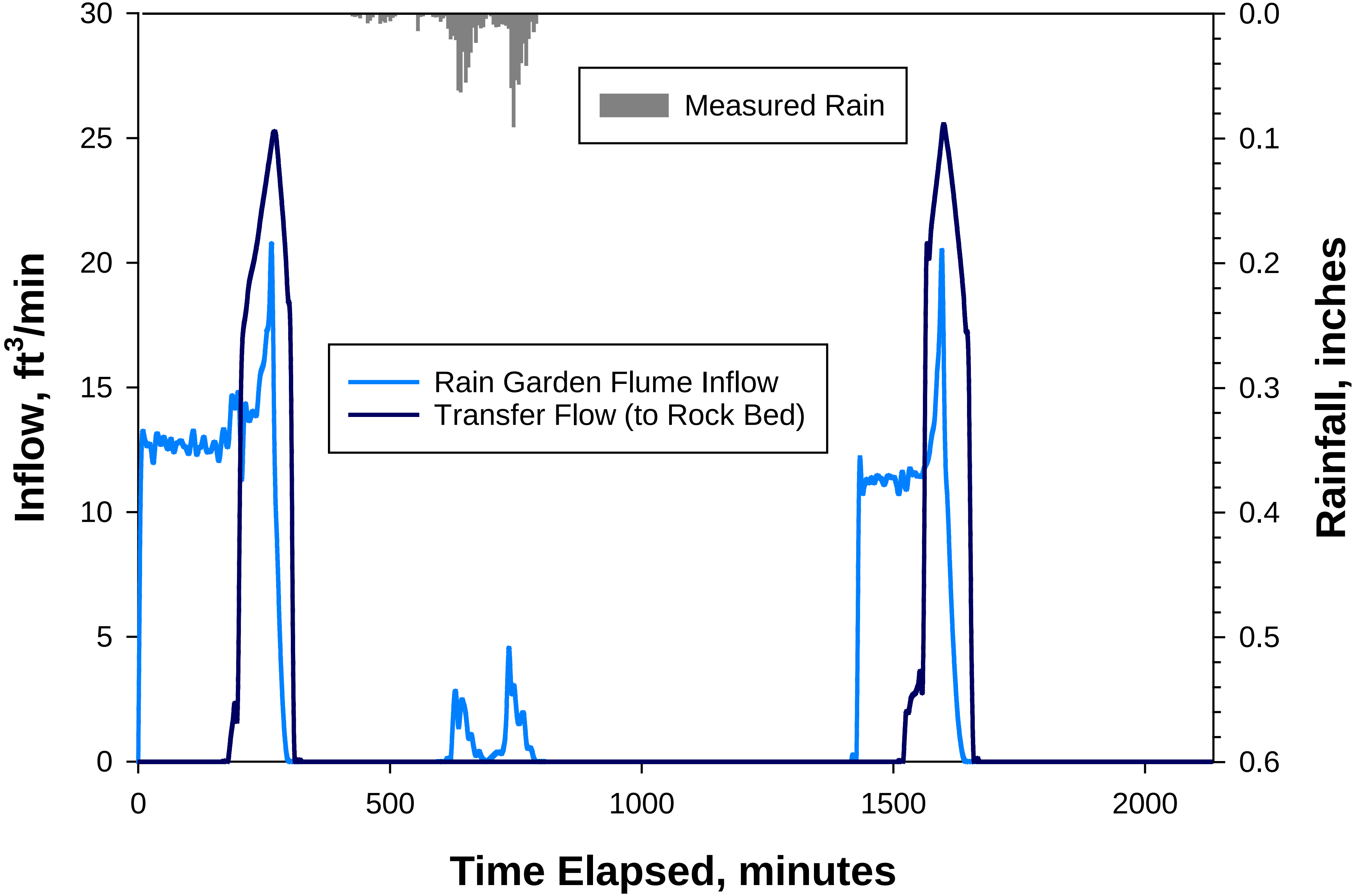
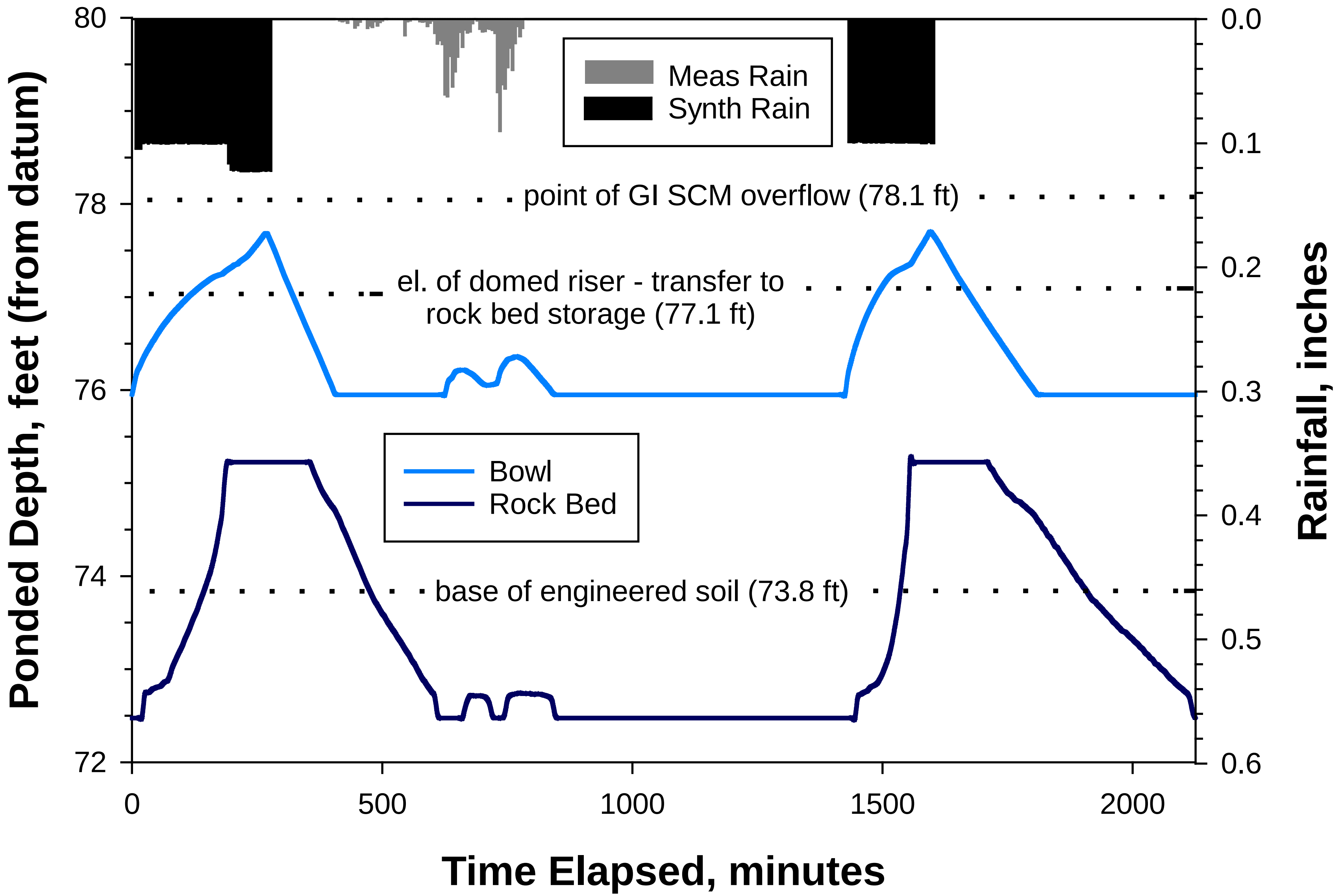
SRT 4 & 5: 26-27 June 2016



VILLANOVA URBAN STORMWATER PARTNERSHIP

SRT 4 & 5: 26-27 June 2016



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The Bottom Line (Not Up Front)

Using intense hydrologic monitoring to connect varying precipitation patterns and system flexibility to resilience is the key to advancing the field of urban stormwater management.

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Acknowledgements

- Research funded by the US Environmental Protection Agency's Science To Achieve Results (STAR) program (grant #83555601)
- Philadelphia Water, Office of Watersheds: especially Jason Cruz, Stephen White, Chris Bergerson, and many, many coops

@VUSPTEAM

VILLANOVA URBAN STORMWATER PARTNERSHIP

vusp@villanova.edu (610) 519-4959

\+ PHILADELPHIA WATER DEPARTMENT = TEAM

The Watershed Approach

- Before – focus was on optimizing site locations for highest modeled gain (cost, pollutant load reduction, etc.)
- Suggested – Seize opportunities (build something, while there is value in studies water quality does not improve until something is constructed)

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New Project Approach to Meet Watershed Goals

- Desktop designs invariably change when in-depth site specific investigations begin.
- Better to quickly and coarsely develop a handful of candidate sites
- Conduct inexpensive site queries (hot spot analysis) of local areas of concern to further develop a practical mitigation approach.
- Implement where and however much feasible
- municipal implementation efforts adapt or innovate “text book” research-based designs with what is practical for a public works department working in an urban setting leading to lower costs, practical maintenance/inspection, and more effective systems.

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The Reality of Monitoring Individual System Performance

- Labor intensive
- Expensive
- Time consuming
- Very challenging to do well

Regional performance curves for design and credits offer more effective implementation

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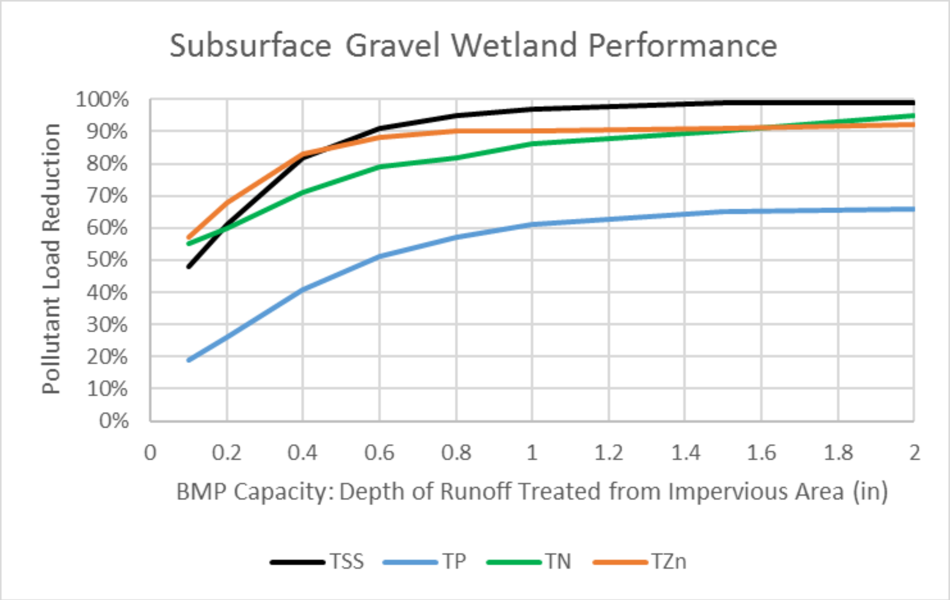

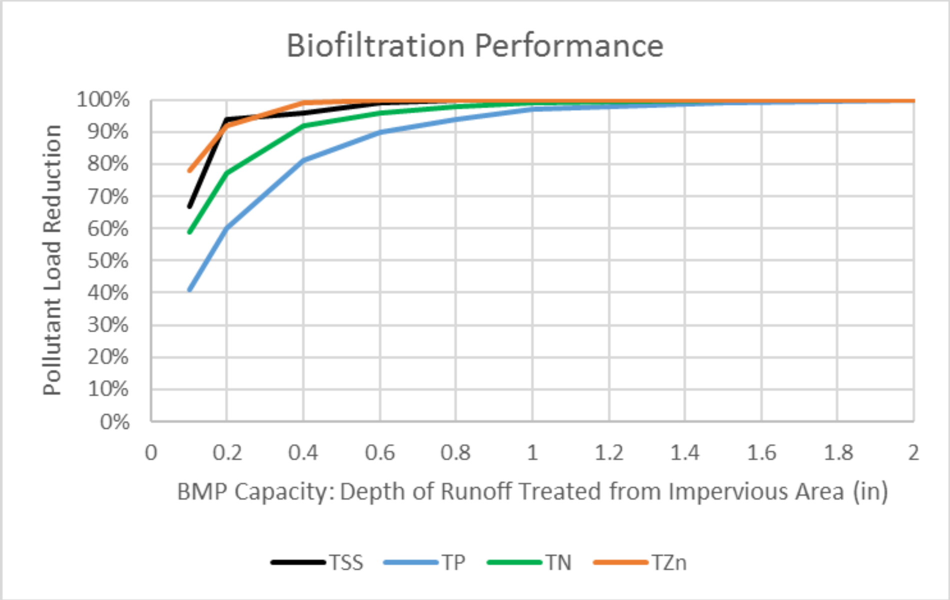

physical storage capacity - runoff depth from IA (in)

Analyte	Depth txt	Modeled RE	Measured RE
TSS	0.1	48	75
TZn	0.1	57	75
TN	0.1	55	23
TP	0.1	19	53

Analyte	Depth txt	Modeled RE	Measured RE
TSS	0.23	70	81
TZn	0.23	88	86
TN	0.23	60	27
TP	0.23	35	45

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Stormwater Management Design - 70.5 acre Ultra-Urban Drainage Area			
Sizing Comparison of Capital Costs and Relative Phosphorus Load Removal Efficiency			
Best Management Practice Size	Depth of Runoff Treated from Impervious Area (in)	*Storage Volume Cost ($/ft³)	**Total Phosphorus Removal Efficiency (%)
Subsurface Gravel Filter - Minimum Size	0.35	$1,016,912	62%
Subsurface Gravel Filter - Moderate Size	0.5	$1,452,732	80%
Subsurface Gravel Filter - Full Size	1.0	$2,905,463	96%
*Storage Volume Cost estimates provided by EPA-Region 1 for Opti-Tool methodology, 2015-Draft			
**Total Phosphorus %RE based on Appendix F Massachusetts MS4 Permit			

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Region 1 GI Cost Estimates

BMP (From Opti-Tool)	Cost ($/ft³) [1]	Cost ($/ft³) – 2016 dollars[6]
Bioretention (Includes rain garden)	13.37 [2,4]	15.46
Dry Pond or detention basin	5.88 [2,4]	6.80
Enhanced Bioretention (aka-Bio-filtration Practice)	13.5 [2,3]	15.61
Infiltration Basin (or other Surface Infiltration Practice)	5.4 [2,3]	6.24
Infiltration Trench	10.8 [2,3]	12.49
Porous Pavement - Porous Asphalt Pavement	4.60 [2,4]	5.32
Porous Pavement - Pervious Concrete	15.63 [2,4]	18.07
Sand Filter	15.51 [2,4]	17.94
Gravel Wetland System (aka-subsurface gravel wetland)	7.59 [2,4]	8.78
Wet Pond or wet detention basin	5.88 [2,4]	6.80
Subsurface Infiltration/Detention System (aka-Infiltration Chamber)	54.54[5]	67.85

[1] **Footnote: Includes 35% add on for design engineering and contingencies**

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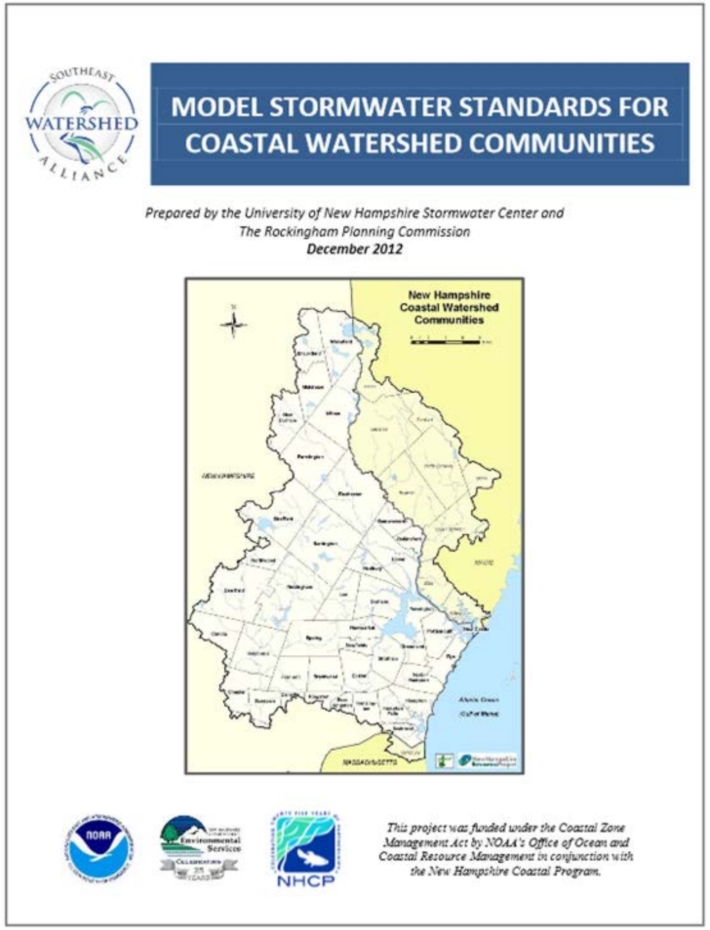
SWA Model Stormwater Ordinance/ Regulations (Dec. 2012/Updated May 2017)

- Core Elements:
  - Promotes LID Planning and "Green Infrastructure"
  - Groundwater Recharge and Volume Control
  - Addresses existing IC through redevelopment requirements
  - Requires Operations and Maintenance



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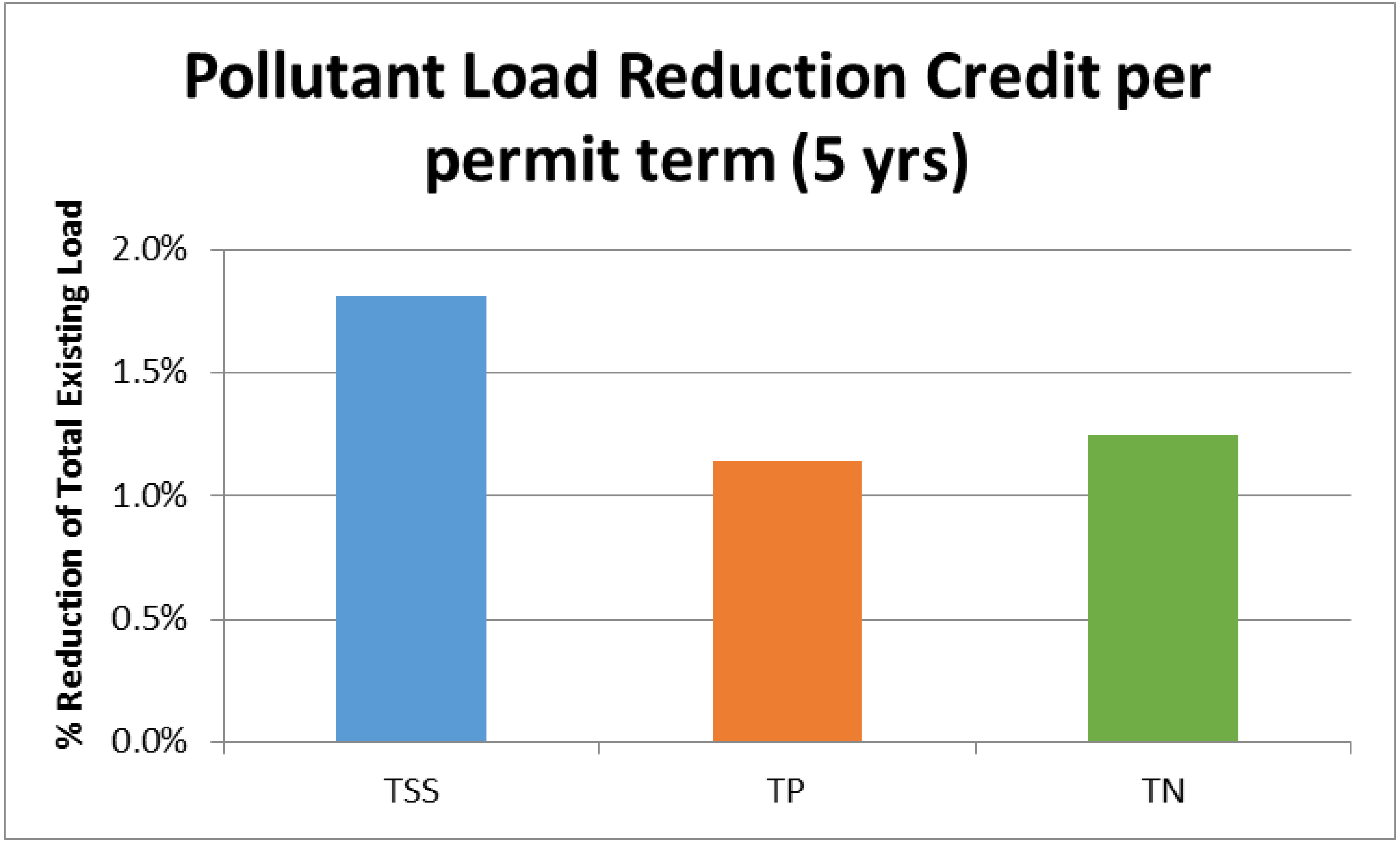
Potential Reduction Credits from Baseline



EP-W-000122: Pollution Prevention through Green Infrastructure Requirements in Commercial Land Uses

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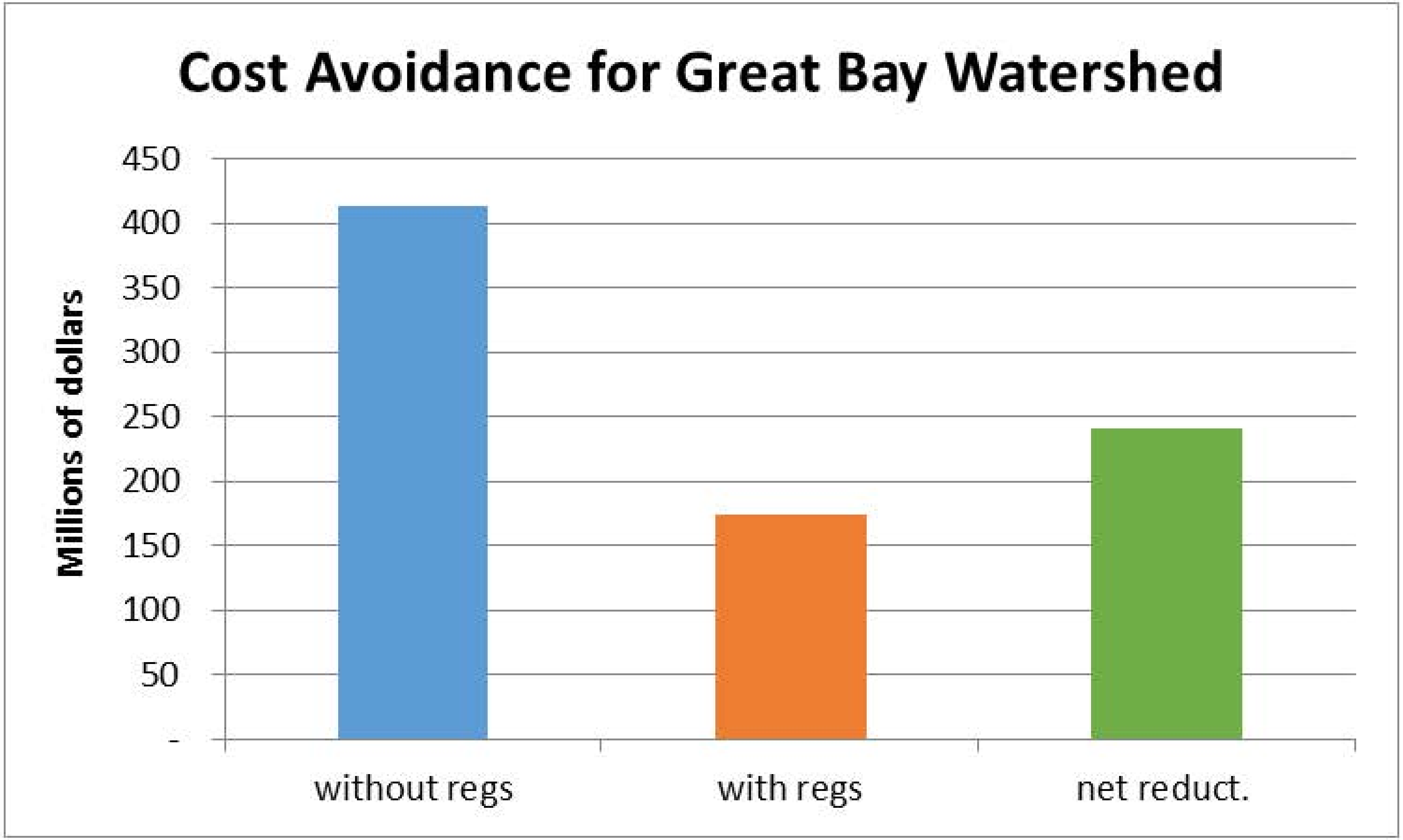

EP-W-000122: Pollution Prevention through Green Infrastructure Requirements in Commercial Land Uses

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Parameters and Transferability

- Physical
  - Climate
  - Watershed
- Technical
  - Knowledge base
  - Ability to include new designs
- Social
  - People
  - Trust
  - Interactions
- Regulatory
  - Codes
  - Specifications
  - Ability to innovate
- Municipal
  - I-O-M
  - Ability to innovate

Using Lessons

- Infiltration cuts both ways
  - Volume reduction
  - Nuisance
- Full sizing not always practical
  - The reduction in water quality performance is less than the reduction to WQV
- Residents near systems should be involved
- Lincoln (Lydgate) was right, “you can never please all of the people all of the time”

How can cities establish sub-watershed scale approaches to evaluate individual performance and combined effectiveness of GI Practices?

Hydrological Analysis of GI at the Sub-watershed Scale

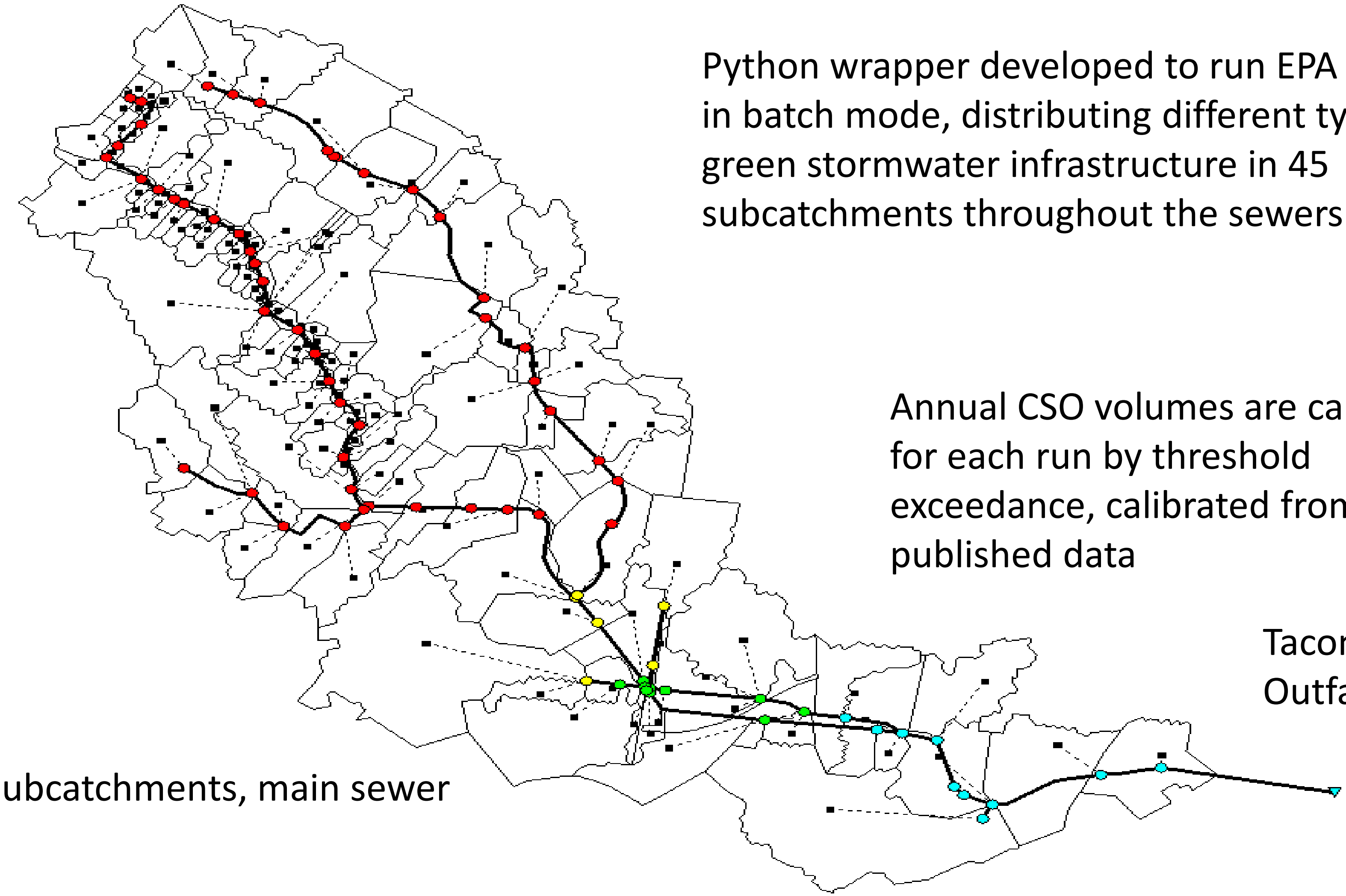
Art McGarity, PI
Swarthmore College STAR Team
Department of Engineering, Swarthmore College

Running SWMM in a Python Wrapper

EPA SWMM model for calculating sewer flows at 15 min. intervals over a full year (provided by Philadelphia Water)

Wingohocking Sewershed

North Central Philadelphia – Piedmont Region
(Largest CSO Outfall in the City)



Python wrapper developed to run EPA SWMM in batch mode, distributing different types of green stormwater infrastructure in 45 subcatchments throughout the sewershed

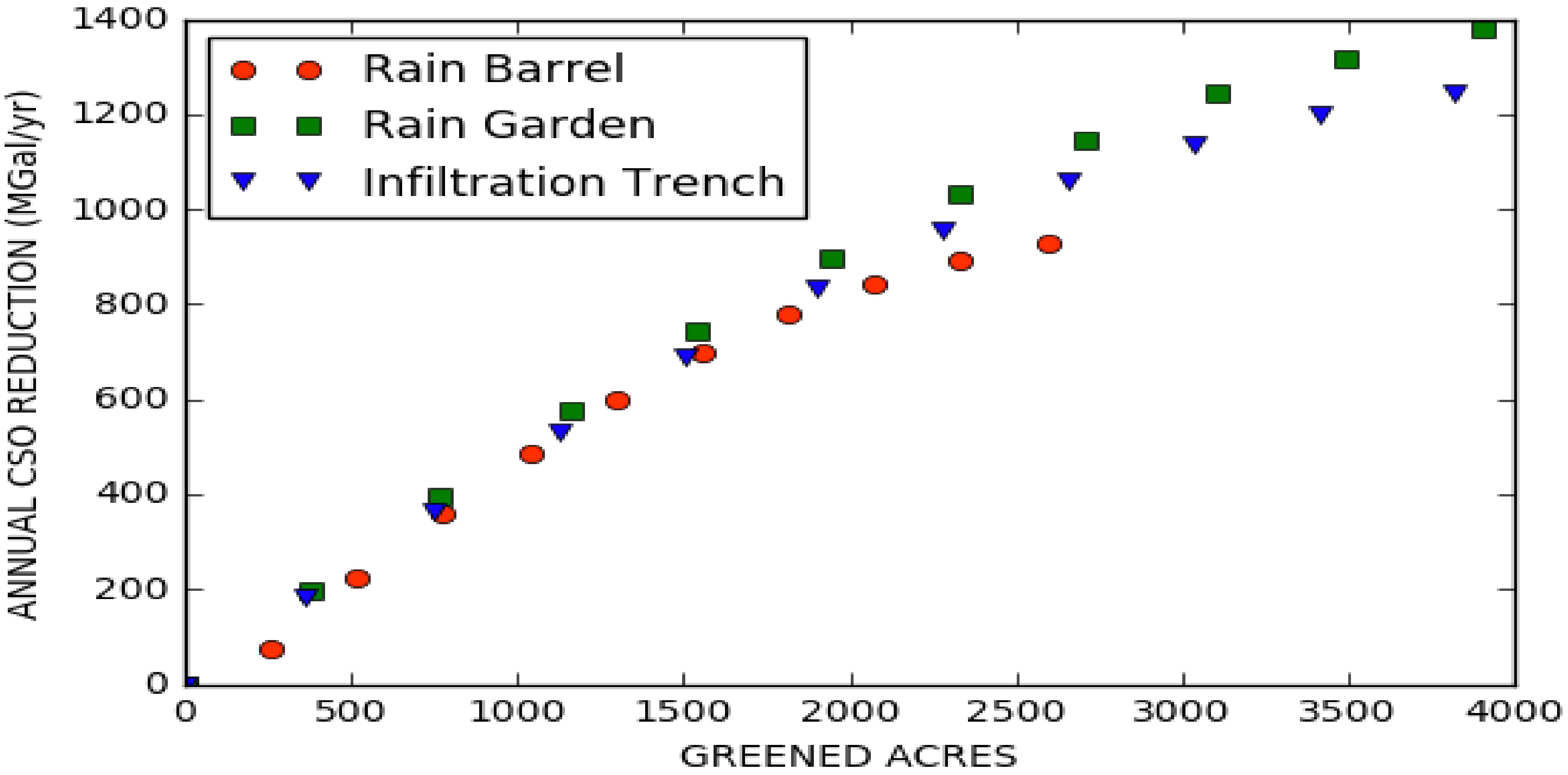
Annual CSO volumes are calculated for each run by threshold exceedance, calibrated from published data

Tacony Creek CSO Outfall: T-14

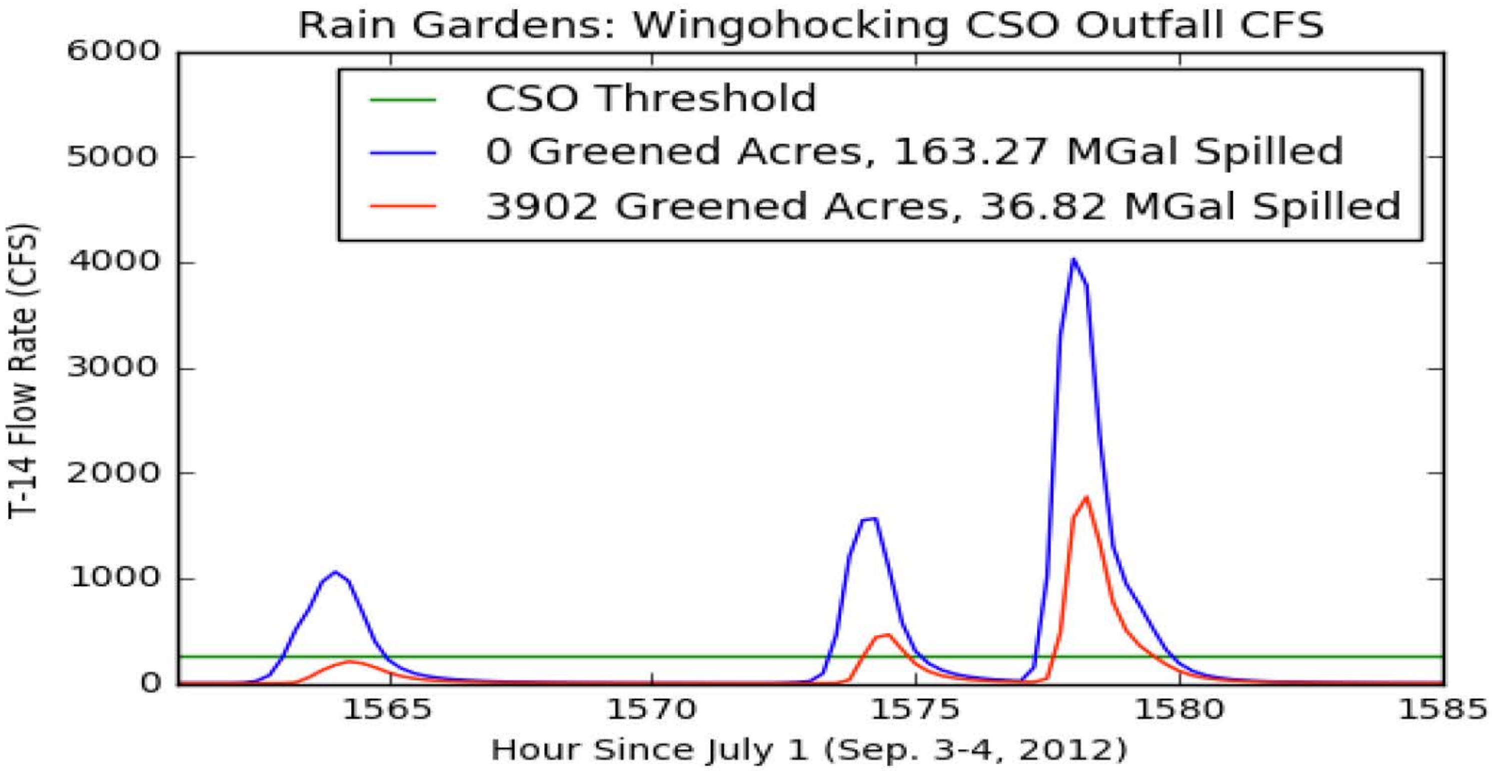
Map showing SWMM subcatchments, main sewer lines, and CSO outfall

Results for Individual GI Practices:

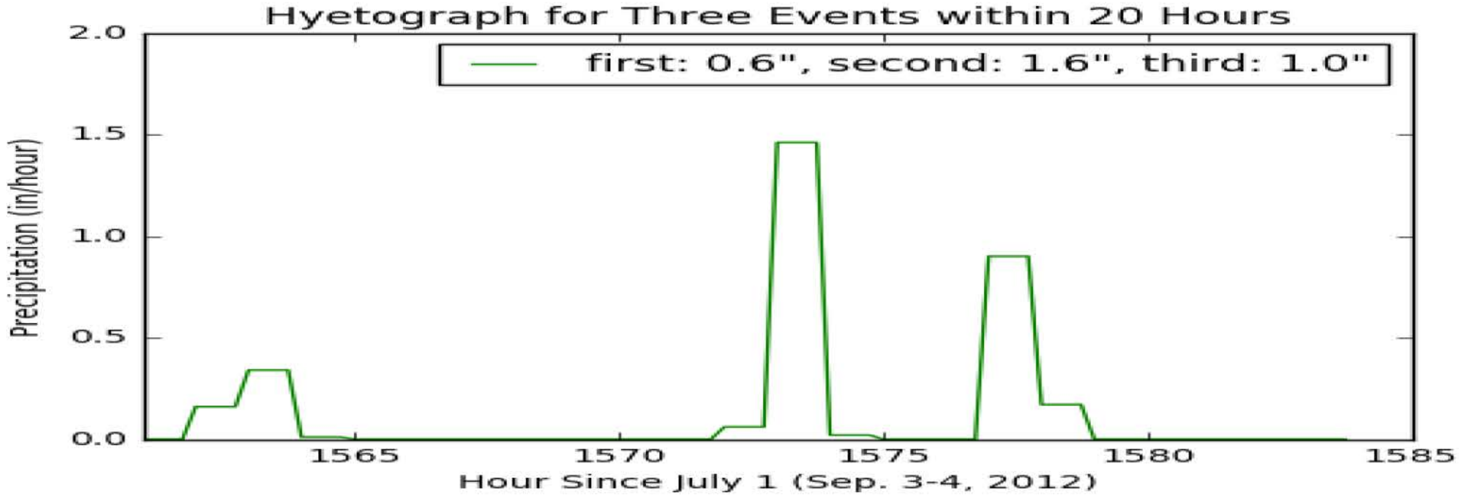
Each run is for increasing numbers of a SINGLE GI PRACTICE uniformly distributed across 45 subcatchments



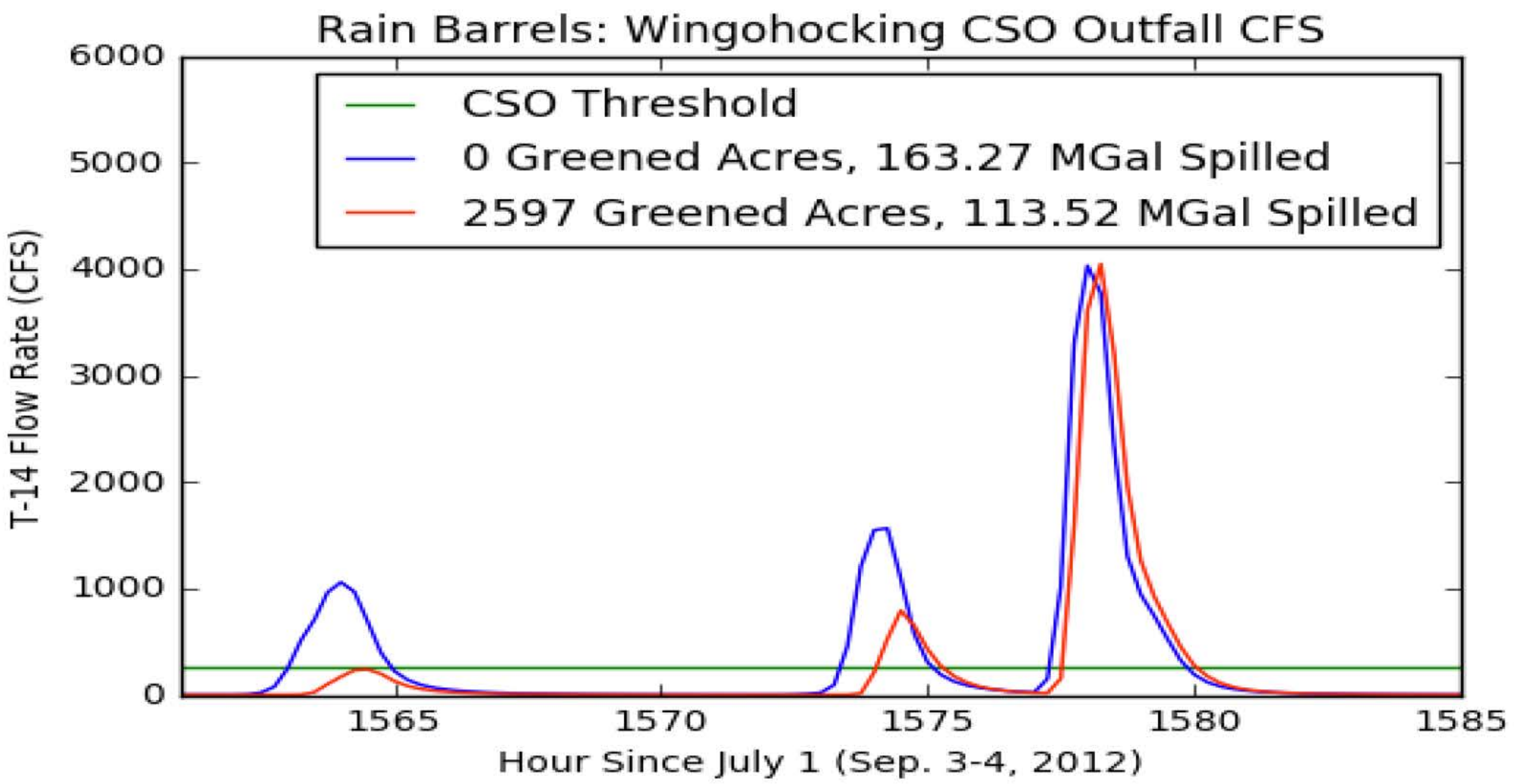
Note: CSO threshold calibrated using published value of 1565 MGal CSO Volume for July 2012 through June 2013

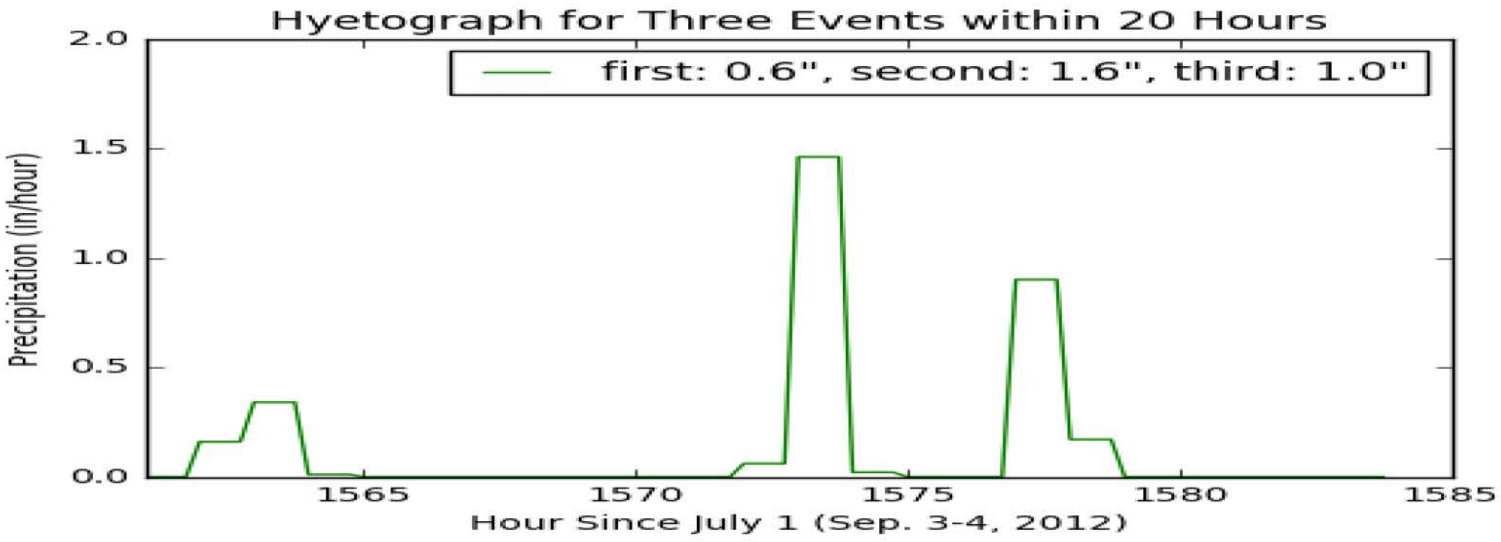


Rain Gardens: Wingohocking CSO Outfall CFS
CSO Threshold
0 Greened Acres, 163.27 MGal Spilled
3902 Greened Acres, 36.82 MGal Spilled
T-14 Flow Rate (CFS)
6000
5000
4000
3000
2000
1000
0
1565
1570
1575
1580
1585
Hour Since July 1 (Sep. 3-4, 2012)

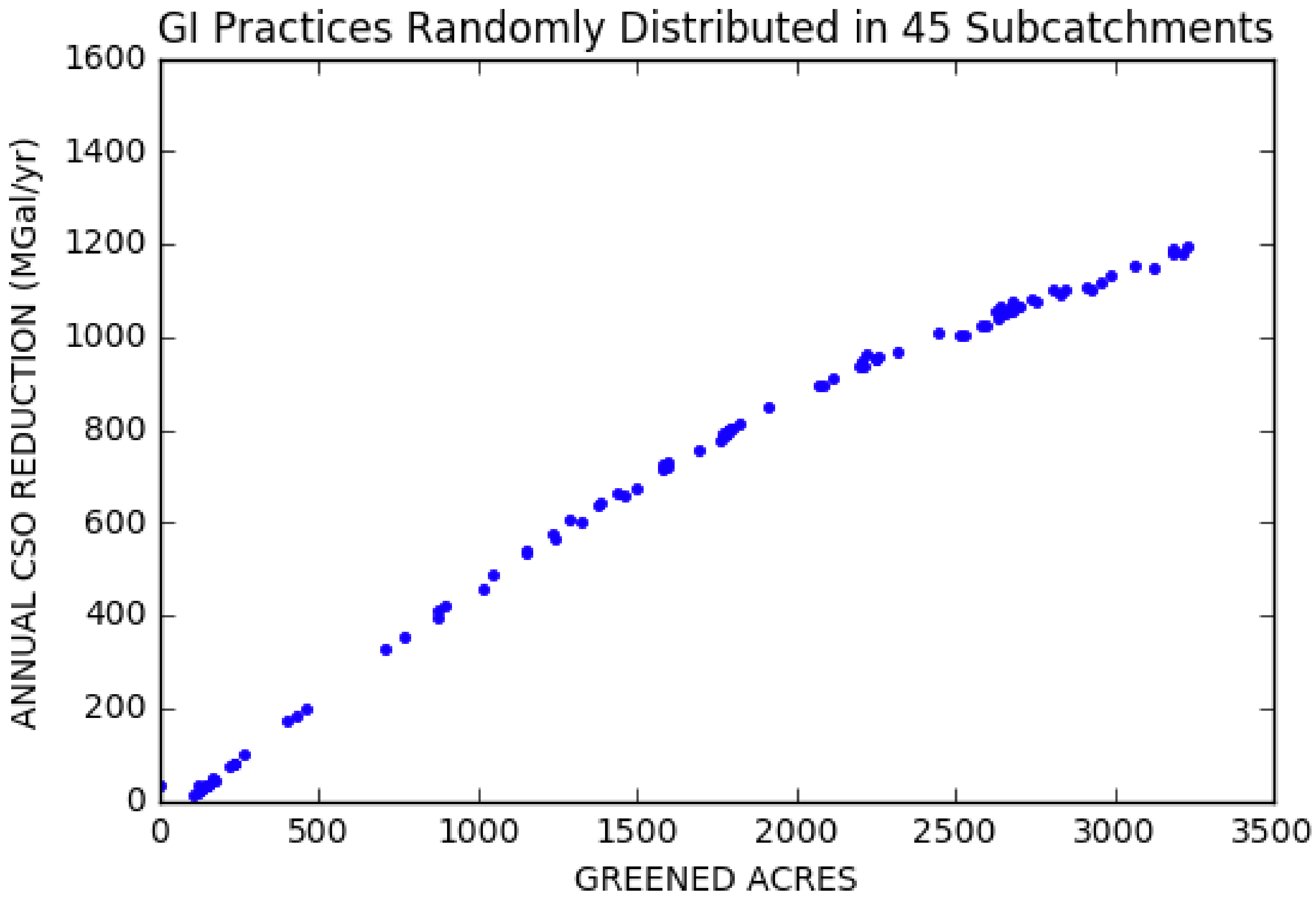


Hyetograph for Three Events within 20 Hours
first: 0.6", second: 1.6", third: 1.0"
Precipitation (in/hour)
2.0
1.5
1.0
0.5
0.0
1565
1570
1575
1580
1585
Hour Since July 1 (Sep. 3-4, 2012)


Rain Barrels: Wingohocking CSO Outfall CFS
CSO Threshold
0 Greened Acres, 163.27 MGal Spilled
2597 Greened Acres, 113.52 MGal Spilled
T-14 Flow Rate (CFS)
6000
5000
4000
3000
2000
1000
0
1565
1570
1575
1580
1585
Hour Since July 1 (Sep. 3-4, 2012)


Hyetograph for Three Events within 20 Hours
first: 0.6", second: 1.6", third: 1.0"
Precipitation (in/hour)
2.0
1.5
1.0
0.5
0.0
1565
1570
1575
1580
1585
Hour Since July 1 (Sep. 3-4, 2012)

Rain Barrels, Infiltration Tree Trenches, and Rain Gardens Randomly Distributed Throughout 45 Wingohocking Subcatchments



Conclusions:

1. Greened acres metric enables evaluation of combined performance multiple GI practices
2. Placement of GI has minor effect on subwatershed CSO reductions
3. Therefore, GI placement can focus on maximization of community benefits

Note: CSO threshold calibrated using published value of 1565 Mgal CSO Volume for July 2012 through June 2013

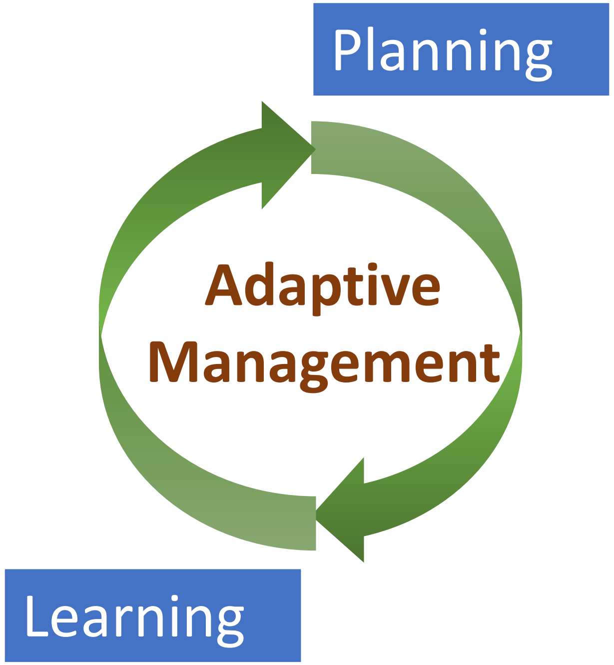
How can cities use lessons learned to guide successful implementation and adaptive management strategies?

Decision Support for GI Investment Strategies Including Adaptive Management

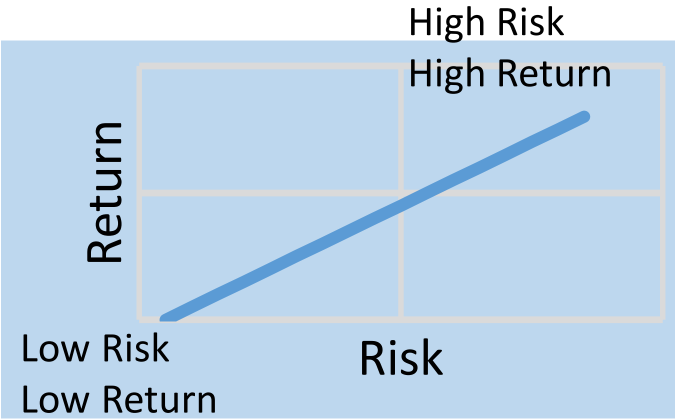
Fengwei Hung, Ph. D. Candidate
Swarthmore College STAR Team
Dept. of Environmental Health and Engineering
Johns Hopkins University

Decision Support for GI Investment Strategies Including Adaptive Management

- Adaptive management is a continuous process of learning and planning (Bormann et al., 1994).
- Key questions:
  - How much of our current GI investments should be directed towards: (a) achieving CSO reduction goals using what we know now about GI performance and cost, VERSUS (b) improving our understanding of GI (through monitoring/research) to improve the performance of future GI investments?
  - How does the opportunity for future learning change the optimal mix of current GI investment decisions?
  - How can an adaptive investment strategy alter the risks of program failure?
- We present methodology to address these questions, guiding GI investment planning to account for learning opportunities and to enable quantification of risks.



Conceptual Diagram of Methodology



Input

- Least acceptable risk level with a specified confidence level (e.g. 95%)
- Expectation of future **learning**

Model

- Two-stage Stochastic Programming
- Risk is constrained by Conditional Value of Risk (CVaR)
- Learning can reduce risk (**variance**) and/or increase efficiency (**mean**)

Output

- Priorities for current investments (GI types, numbers, and locations) that maximize multiple benefits under the specified risk-level
- Risk-benefit tradeoff curves

Model Variants Included in Methodology

Partial Learning | **Full Learning**

Multi-level Learning w/ Technology Improvement

To reduce uncertainty & improve performance?

Multi-level Learning

How much do we want to learn: Imperfect info or perfect info?

Threshold Learning

To learn or not to learn?

Automatic Learning

Now or Later?

How can cities establish sub-watershed scale approaches to monitor and evaluate both the individual performance and combined effectiveness of GI practices?

Establish permanent monitoring SMPs for understanding long term performance

Design future sites to facilitate low cost monitoring for breath

Integrate Monitoring with Modeling to support decisions

Explore low cost monitoring and inlet changes to reduce maintenance costs.

Team with University Researchers to synergize resources for improvement.

Utilize GIS tools to evaluate potential and assess land use change.

Develop Regional Curves or Relationships for crediting.

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What local parameters will affect the scalability and transferability of these approaches?

Enthusiasm / buy in of municipal team - across the dept/agency

Legal Code (Western States)

Climate ** (especially with snow vs no snow, including snow maintenance)

Soils - Urban Landscape

Trash load

Otherwise, it is just a mass balance.

How can cities use lessons learned from these scaled approaches to guide successful implementation and adaptive management strategies?

Be proactive/flexible. Be willing to change.

Standardize what you can, but not at the costs of lost opportunity.

INSPECTION DURING CONSTRUCTION! As rigorously as if it was a building. Having the systems constructed correctly gets you at least half way there.

Test After Construction – PWD's SRTs

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SWARTHMORE

Philadelphia Parks & Recreation After School Program: Roosevelt Playground

Green Roof Model with Low Cost Sensing

Villanova, PWD, EPA, Fairmount Water Works, and SLA Beeber Academy