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Benefits of Urban Green Stormwater Infrastructure

Swarthmore College STAR Team

GreenPhilly Research Group:

Art McGarity – Swarthmore College – PI

Ben Hobbs – Johns Hopkins University - Co-Pi

Megan Heckert – Swarthmore College & West Chester University - Co-Pi

Christina Rosan – Temple University - Co-Pi

Claire Welty – University of Maryland Baltimore County - Co-Pi

Shandor Szalay – AKRF, Inc. -Engineering Consultant

Acknowledgement and Disclaimer

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

GI Benefits: Common Classification Schemes

Tom Ballestro, PI, UNH STAR Team
Director, UNH Stormwater Center

Well Documented Benefits

- Runoff reduction
- Reduced combined sewer overflows
- Pollutant load reductions
- Reduction in erosion and peak flows

Less Well Documented Benefits

- STEM Education
- Carbon sequestration
- Habitat
- Urban heat island reductions
- Air quality
- Healthy lifestyle promotion
- Food?
- Ecosystem services

PRESENTATION OUTLINE

- CSO Reduction Benefits
  - Results from monitoring and modeling with ParFlow.CLM complementing results from modeling with EPA SWMM (presented earlier)
- Community Benefits
  - Quantifying and prioritizing community benefits
  - Equitable distribution of community benefits
- Developing Win-Win Strategies: Multiobjective StormWISE Model
  - Least cost CSO reduction at watershed scale
  - Integrating community benefits
- Next Steps

Groundwater Monitoring and Modeling

for accurate evaluation of green infrastructure hydrological benefits

Claire Welty, Co-PI

Swarthmore College STAR Team

Professor of Environmental Engineering

Director, Center for Urban Environmental Research and Education

University of Maryland Baltimore County

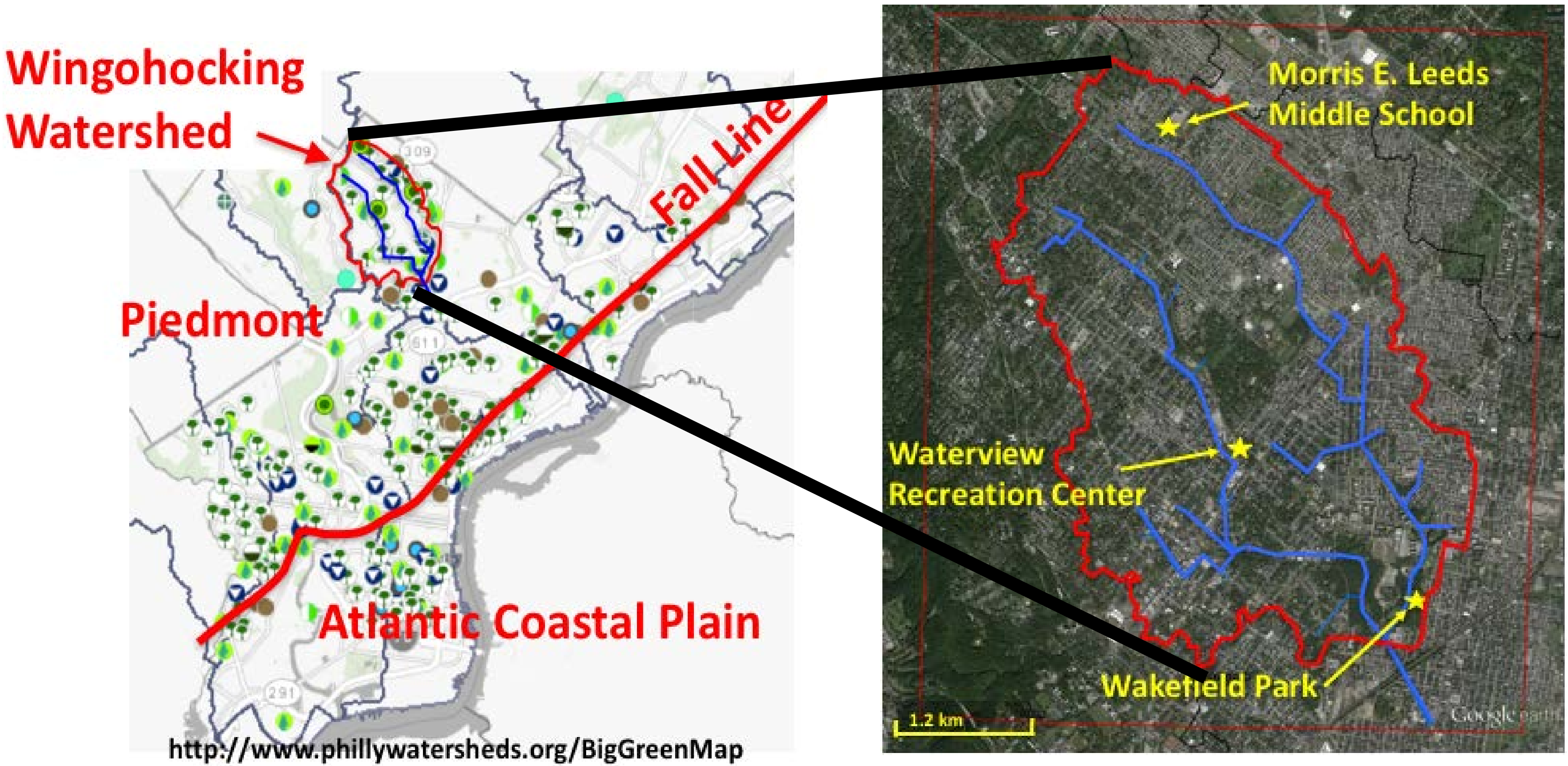
UMBC

AN HONORS UNIVERSITY IN MARYLAND

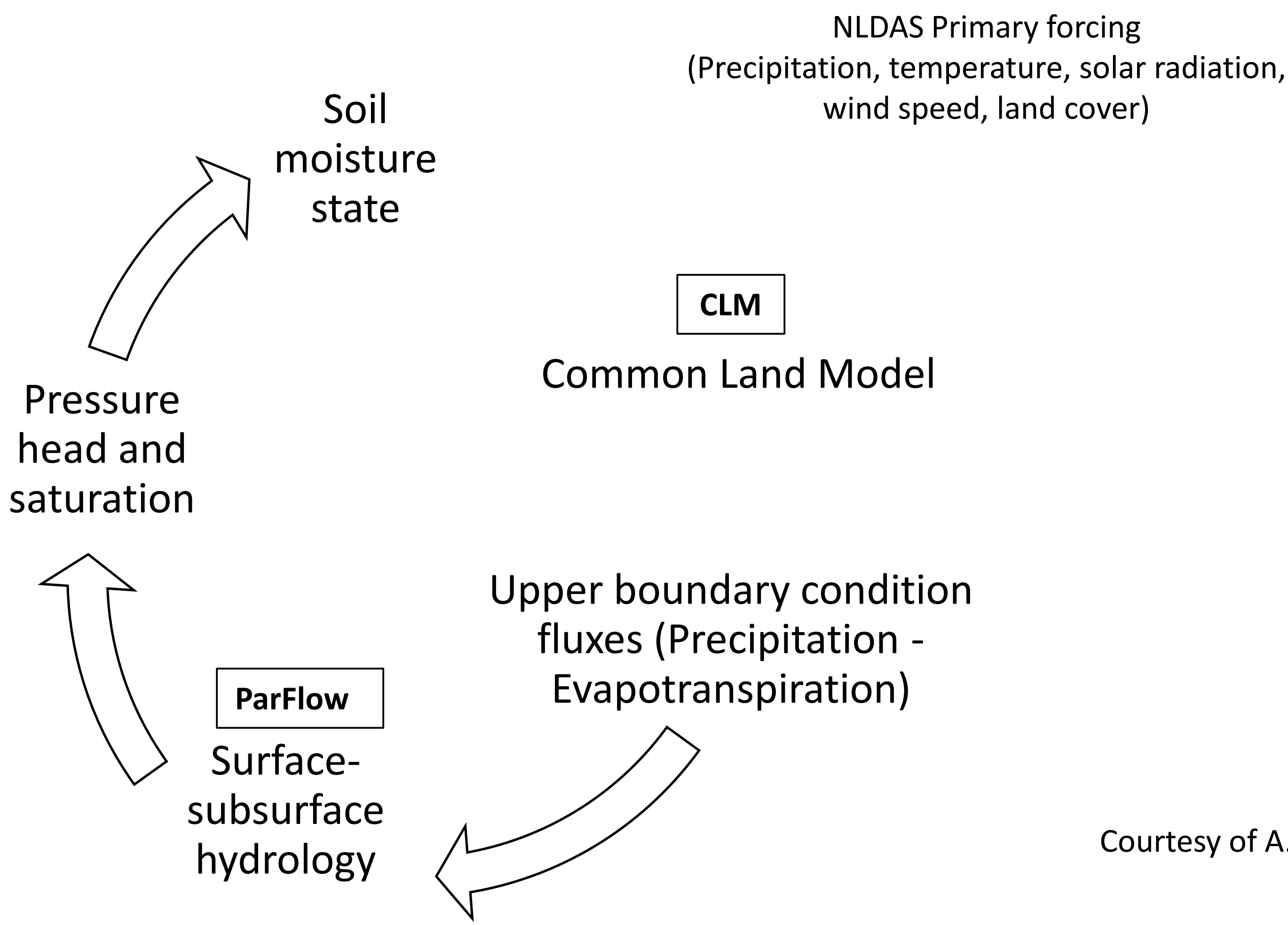
Groundwater monitoring and modeling tasks

- Instrumented three GI sites with tensiometers and wells (pressure transducers) to measure pressure head in the vadose zone and saturated zone
- Carried out 3D coupled land surface-GW-SW modeling using ParFlow.CLM at watershed and site scales
- Monitoring and modeling contributed to evaluation of GI performance

Wingohocking selected as study site

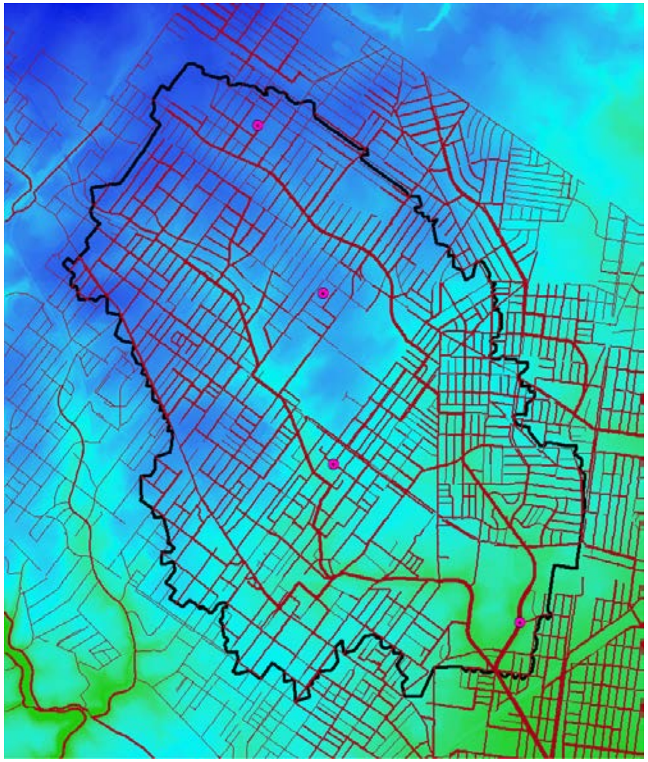


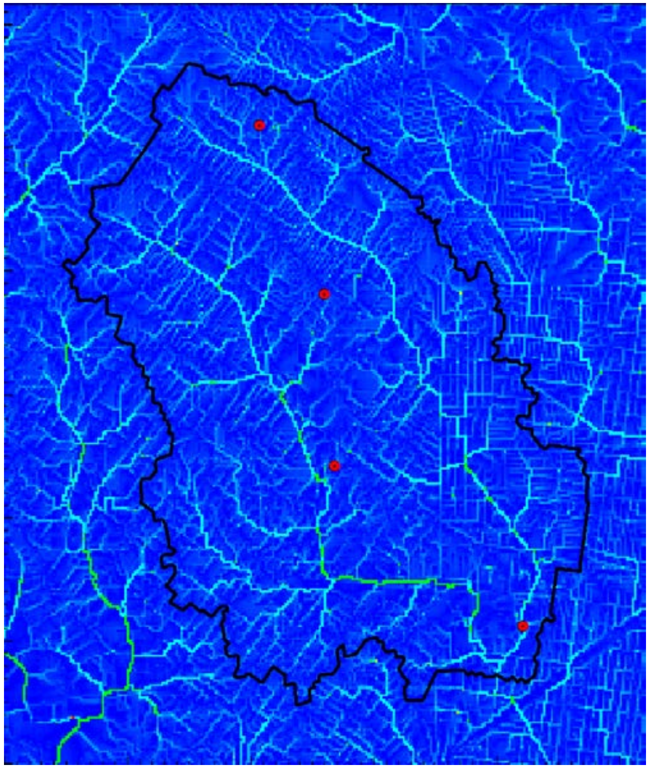
Modeling with ParFlow.CLM



Courtesy of A. Bhaskar

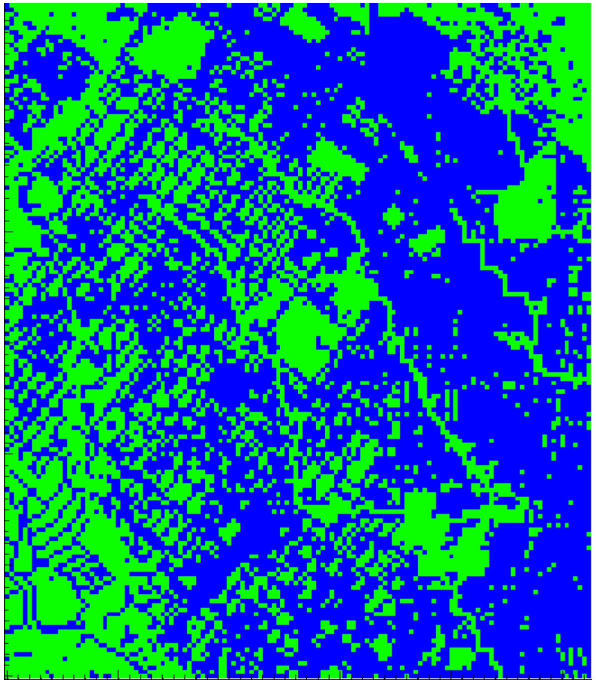
Wingohocking domain and drainage pattern



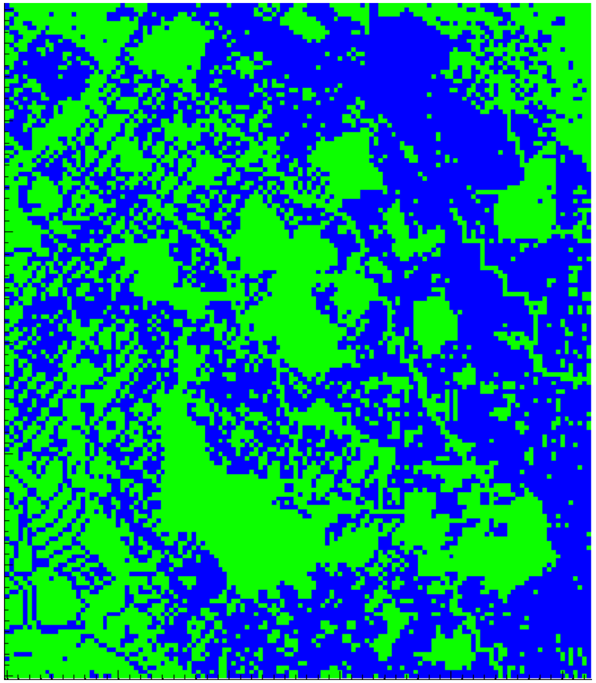


Wingohocking
Green Infrastructure Scenario Testing

Blue = Impervious,   Green = Pervious

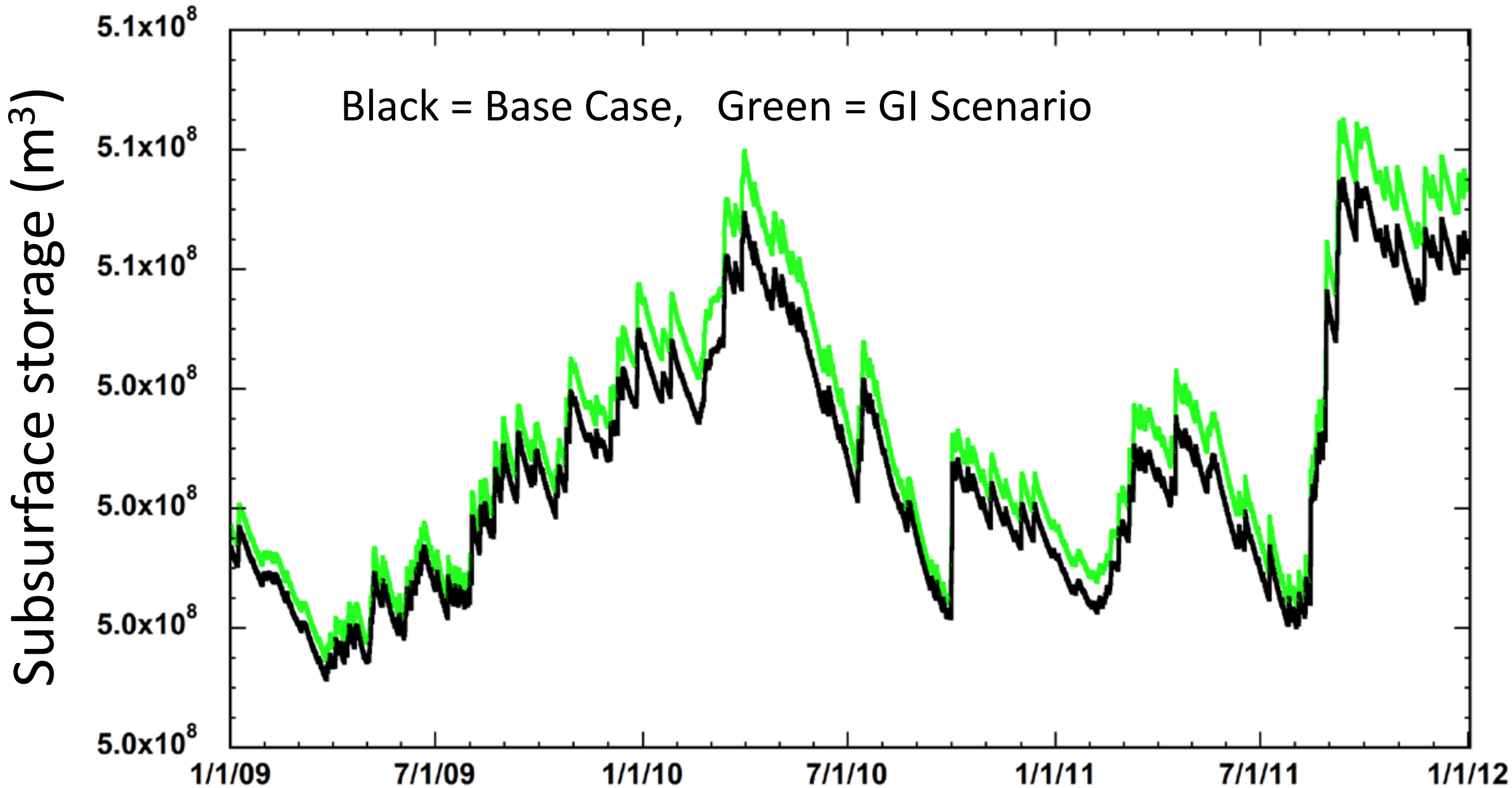


Base Case - Recent

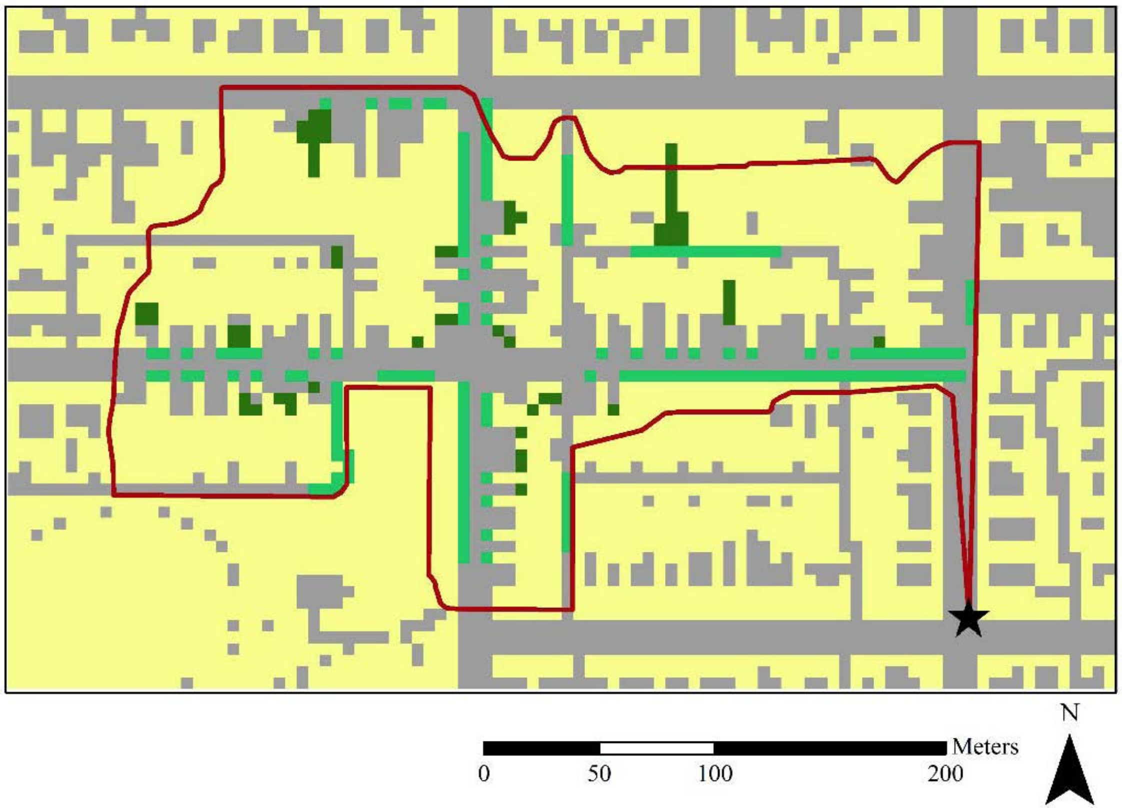


GI Scenario – 33% less Impervious Surface

Example model scenario output



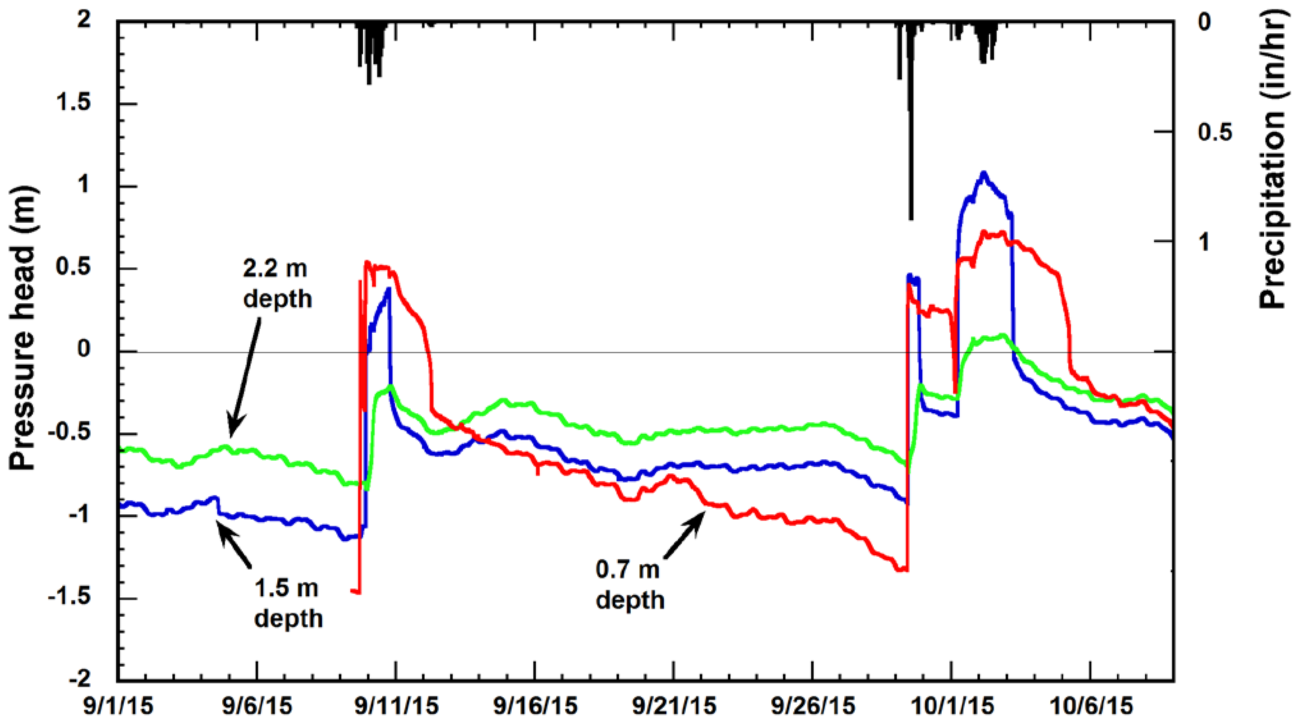
Scenario testing using PF.CLM in Washington, DC



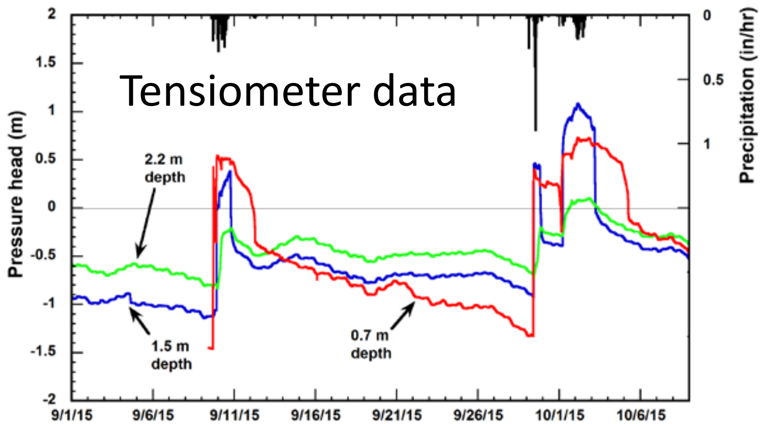
- 0.052 km^2 sewershed in DC
- Separate storm sewer
- Pipe flow measured before and after GI construction
- 1 sq m land cover and lidar DEM, K values from borings used as inputs
- Calibrated PF.CLM model to existing system (base case)
- Conducted scenario testing of alternative GI placement
- Found that pipe flows were insensitive to GI placement

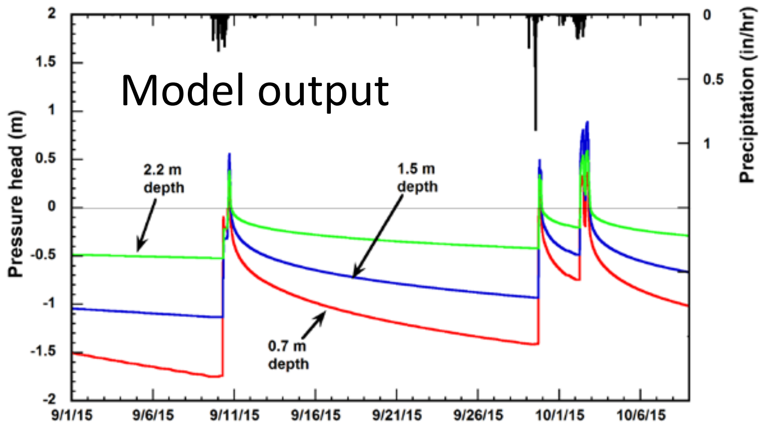
Reference: Lim and Welty, *Water Resources Research*, in revision

Wakefield Park (rain garden) tensiometer data



Tensiometer data and site-scale model output

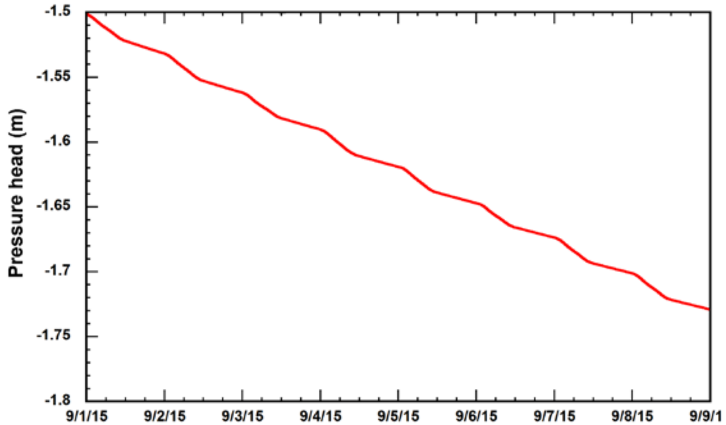




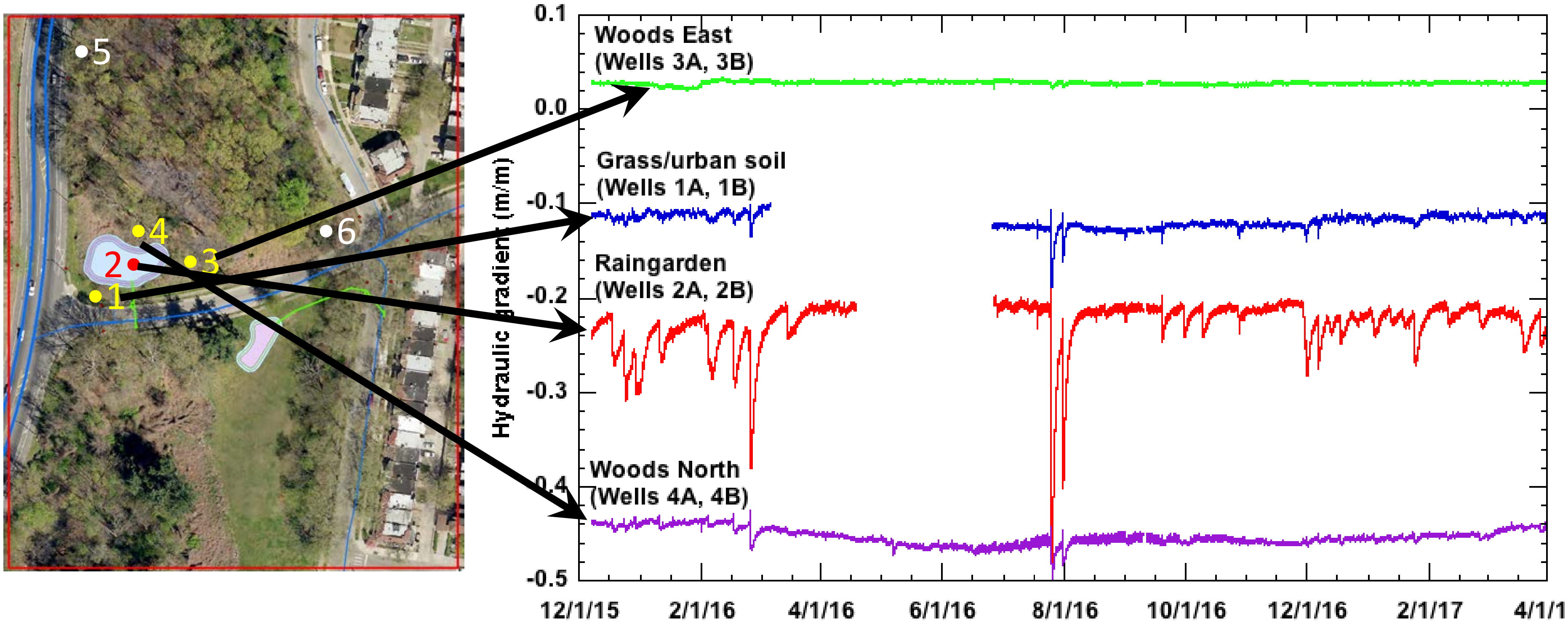
- Data and model both show
  - Similar timing and trends in pressure head
  - ET diurnal cycles
- Tensiometer data
  - Heterogeneity of soil layers
  - Pronounced diurnal ET cycles
  - Reflective of local weather conditions
- Model output
  - Homogeneity of soil layers
  - Muted ET cycles
  - NLDAS data for precip

    1 hr timestep

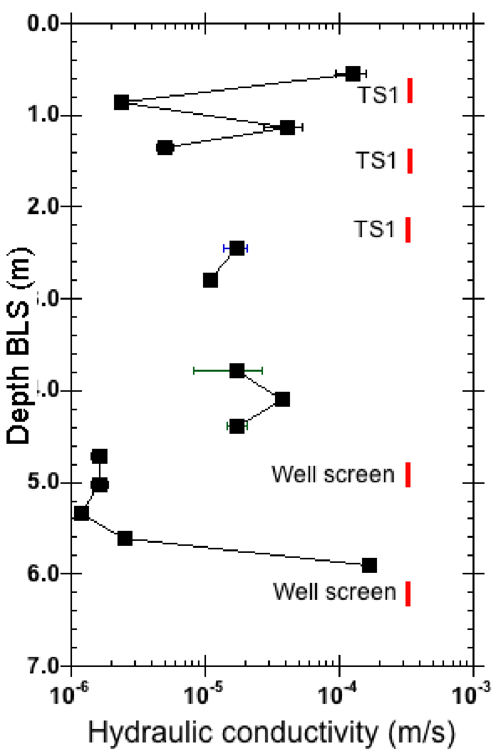
    ~14 km pixels

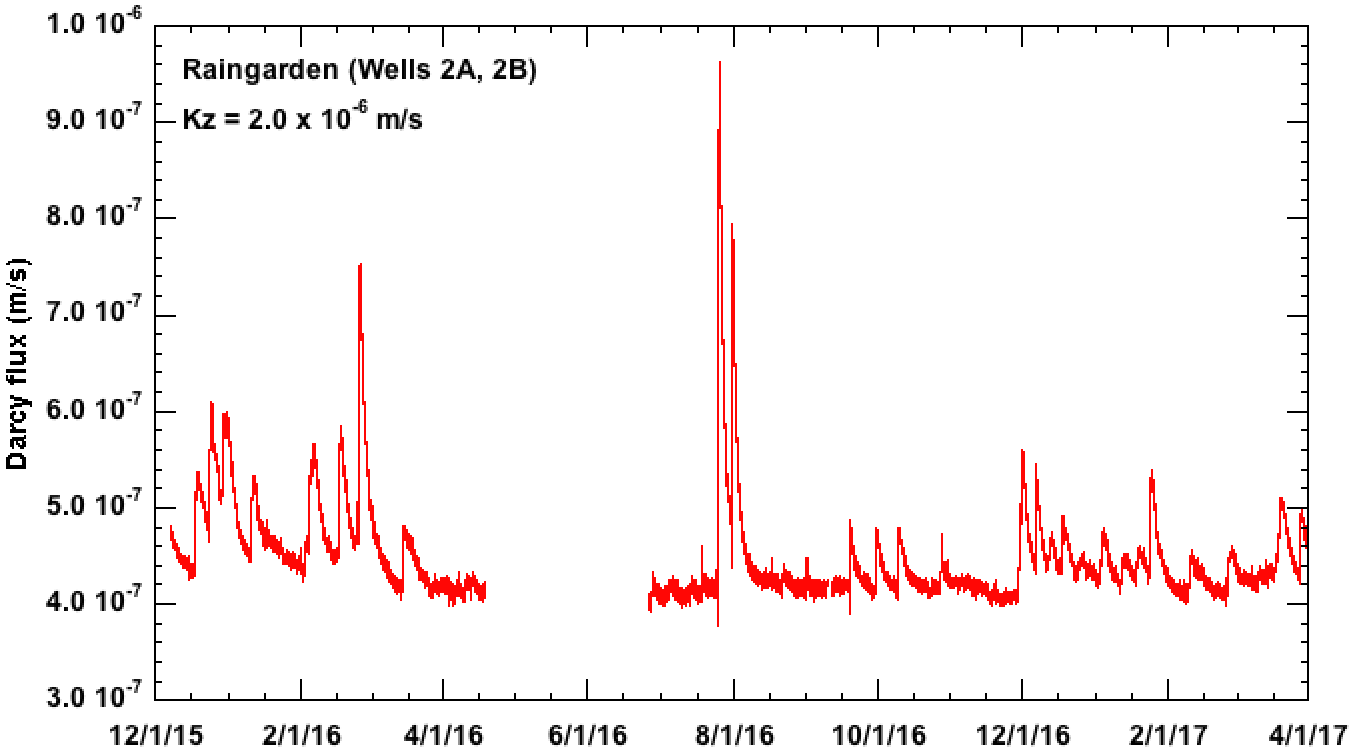


Wakefield Park well data: Calculation of vertical hydraulic gradients from nested piezometers



Calculation of Darcy flux from hydraulic gradients and K values from boring cores





Community Benefits

Collaborating Swarthmore STAR Team Members:

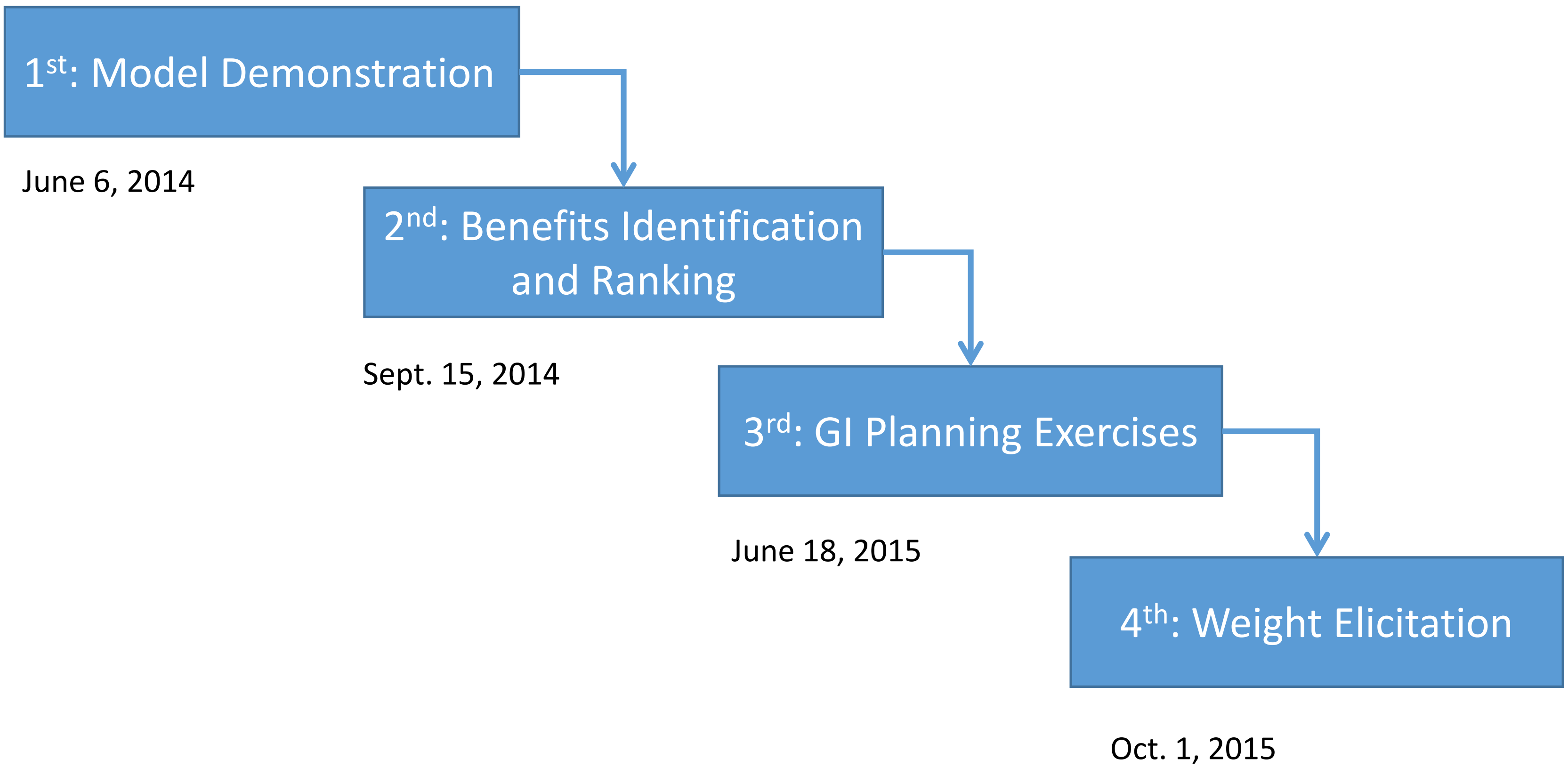
Christina Rosan, Co-PI, Asst. Professor, Temple University

Megan Heckert, Co-PI, Asst. Professor, West Chester University

Ben Hobbs, Co-PI, Professor, Johns Hopkins University

Fengwei Hung, Ph.D. Candidate, Johns Hopkins University

GreenPhilly Community Advisory Board (GCARB) Meetings



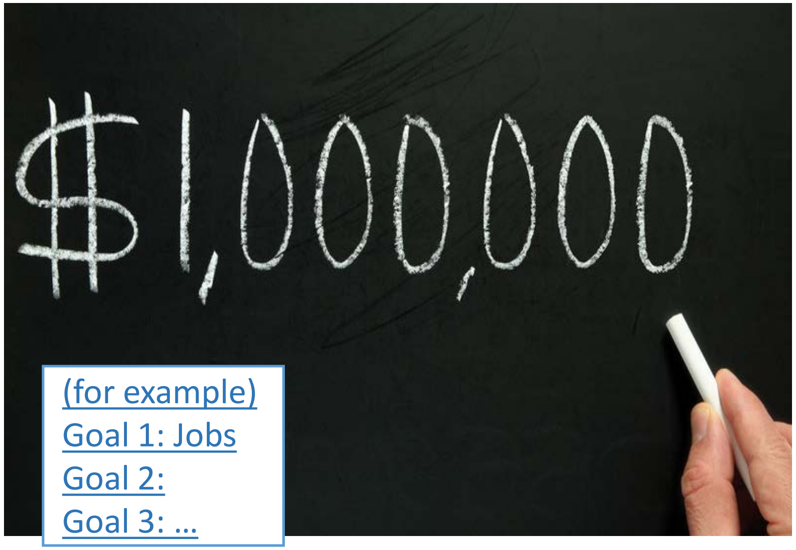
GCARB Meeting Exercises to Identify Community Concerns

- 23 GI benefits identified & ranked by project partners on the GreenPhilly Community Advisory Research Board (GCARB), which consists of community leaders, local experts & government officers.
- Top 10 ranked GI benefits

CATEGORY	GI BENEFIT
Physical benefits	Water pollution removal (ranked 1); runoff reduction (4);
Social concerns	Community amenities (2); equity (3); aesthetics (6);
Economic benefits & costs (personal)	Green jobs (5); property value increases (7)
Health & risk related benefits	Flood impacts (8); air quality (9); heat stress (10)

Quantitative Prioritization

- Conducted a planning exercise that each group has $1 million dollars to spend on GI provided a list of GI with unit cost.
  - GCARB partners formed 5 groups and were asked to role-play as residents in a neighborhood.
  - Each group listed 5 goals that they would like to achieve with $1 M investment.
  - Background information on the case study neighborhood was provided.
  - For this case study, we chose the Village of Art and Humanities neighborhood in N. Philadelphia



(for example)
Goal 1: Jobs
Goal 2:
Goal 3: …

Benefit Categories Chosen for Further Analysis

- We identified goals shared by at least 3 of the 5 groups: Aesthetics, Community Amenity, Green Jobs, Heat Stress Reduction, and Low Maintenance Costs
- We developed a proxy for heat stress: "Green Canopy" = the ratio: (tree cover & green roof installation)/(total area)
- Finally, we added "Stormwater Fee Savings" as a monetary goal to complement maintenance costs. Our results for this benefit to be evaluated by comparing with findings of **David Hsu and the U. Penn STAR Project Team**
- Quantitative Results are shown later in presentation of the Community StormWISE model, where the weights derived from these exercises are used

The Equity Index

<u>Collaborating Swarthmore STAR Team Members:</u>

Megan Heckert, Co-PI, Asst. Professor, West Chester University of PA

Christina Rosan, Co-PI, Asst. Professor, Temple University

need

=

socio-economic conditions

+

the built environment

Indicators

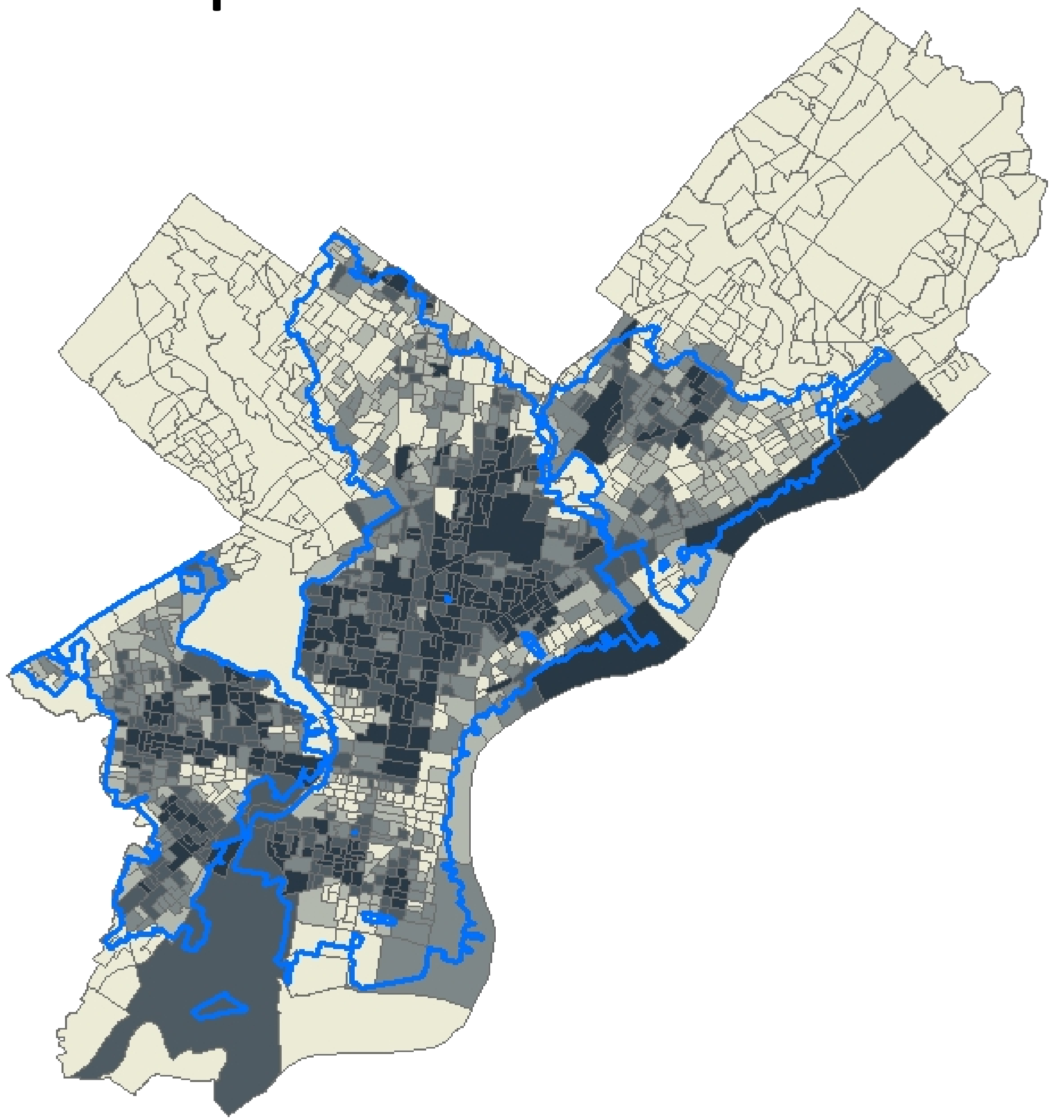
Socioeconomic

- Percent minority
- Percent low-income
- Percent low education
- Percent under 5
- Percent over 64
- Percent owner-occupancy

Built environment

- Proximity to traffic
- Ozone levels
- Particulate matter
- Park access
- Tree canopy cover
- Playground access
- Percent impervious
- Amount of vacant land

Entire Philadelphia CSO Area



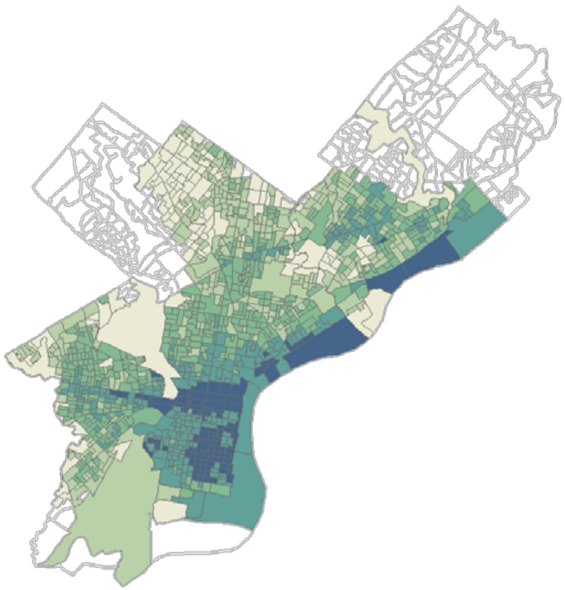
Highest Need Block Groups
Lacking GI Investments

- Bottom 80% of Index Scores
- Top 20% of Index Scores
- Top 20% Need with 0 GI density
- Non-CSO block groups

Creating typologies

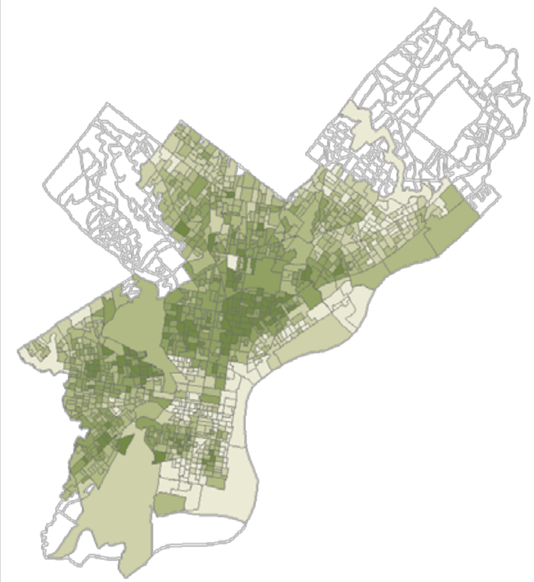
1. Areas of environmental need
   - Traffic, ozone, impervious surfaces, particulate matter
2. Areas lacking amenities
   - Playground density, parks access, tree canopy cover
3. Areas of socio-economic disadvantage
   - Percent minority, low-income, low-educational attainment, under 5, over 64, owner-occupied, vacant land density

environmental need

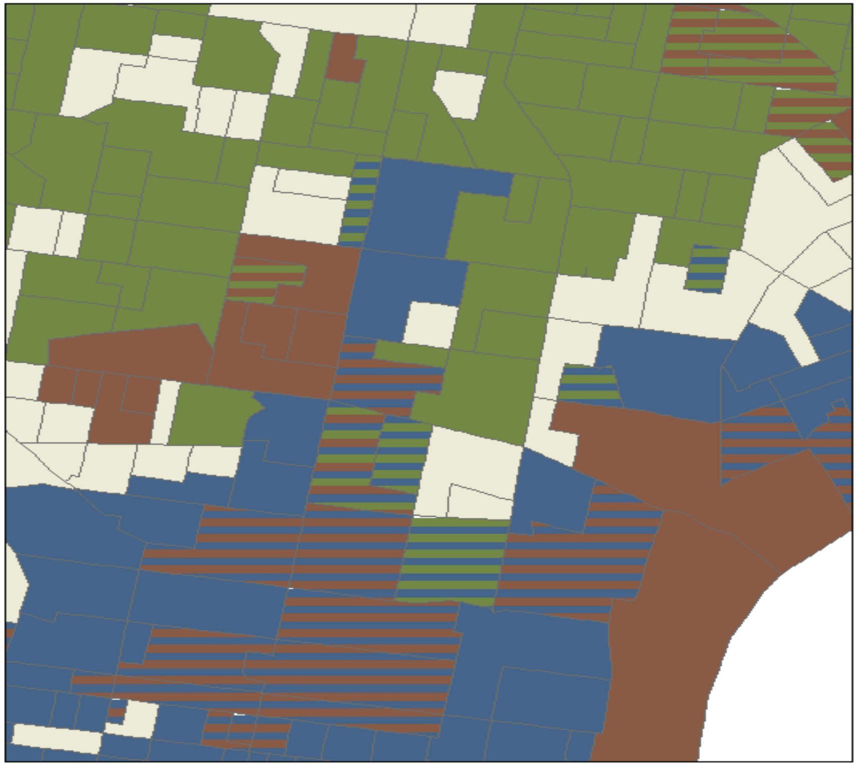


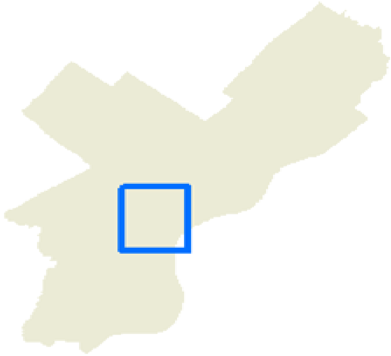
amenity need

disadvantage



Neighborhood Scale Equity Analysis

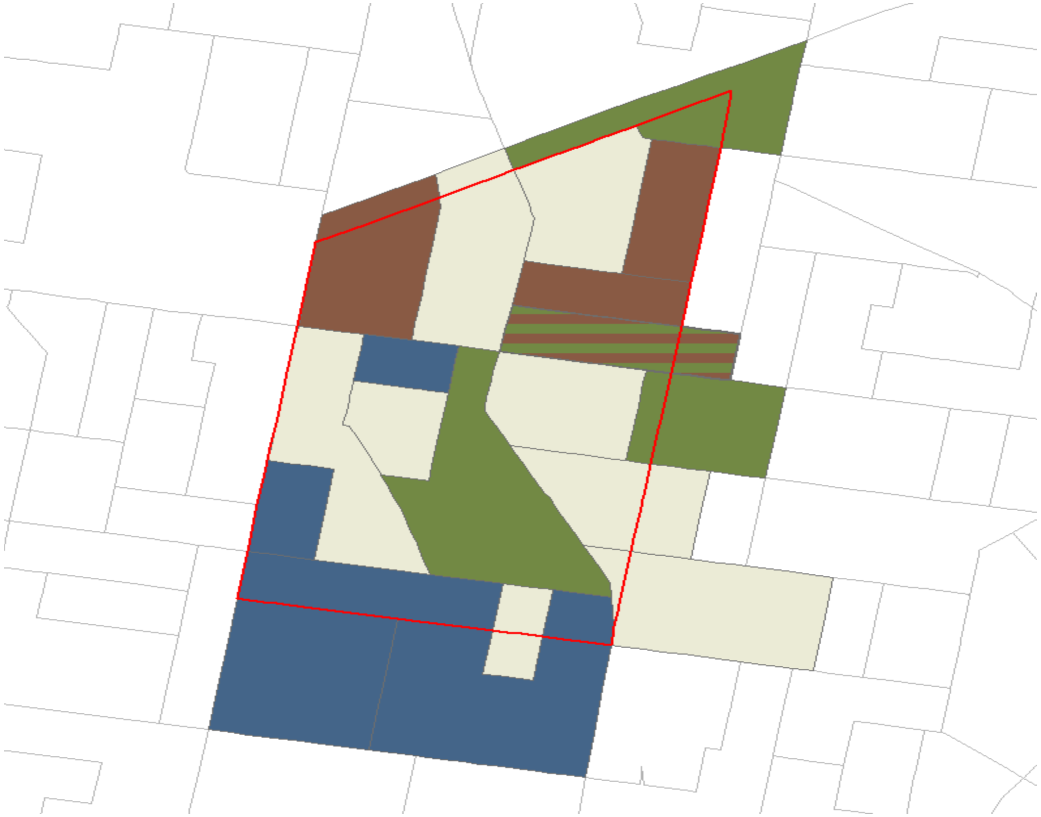




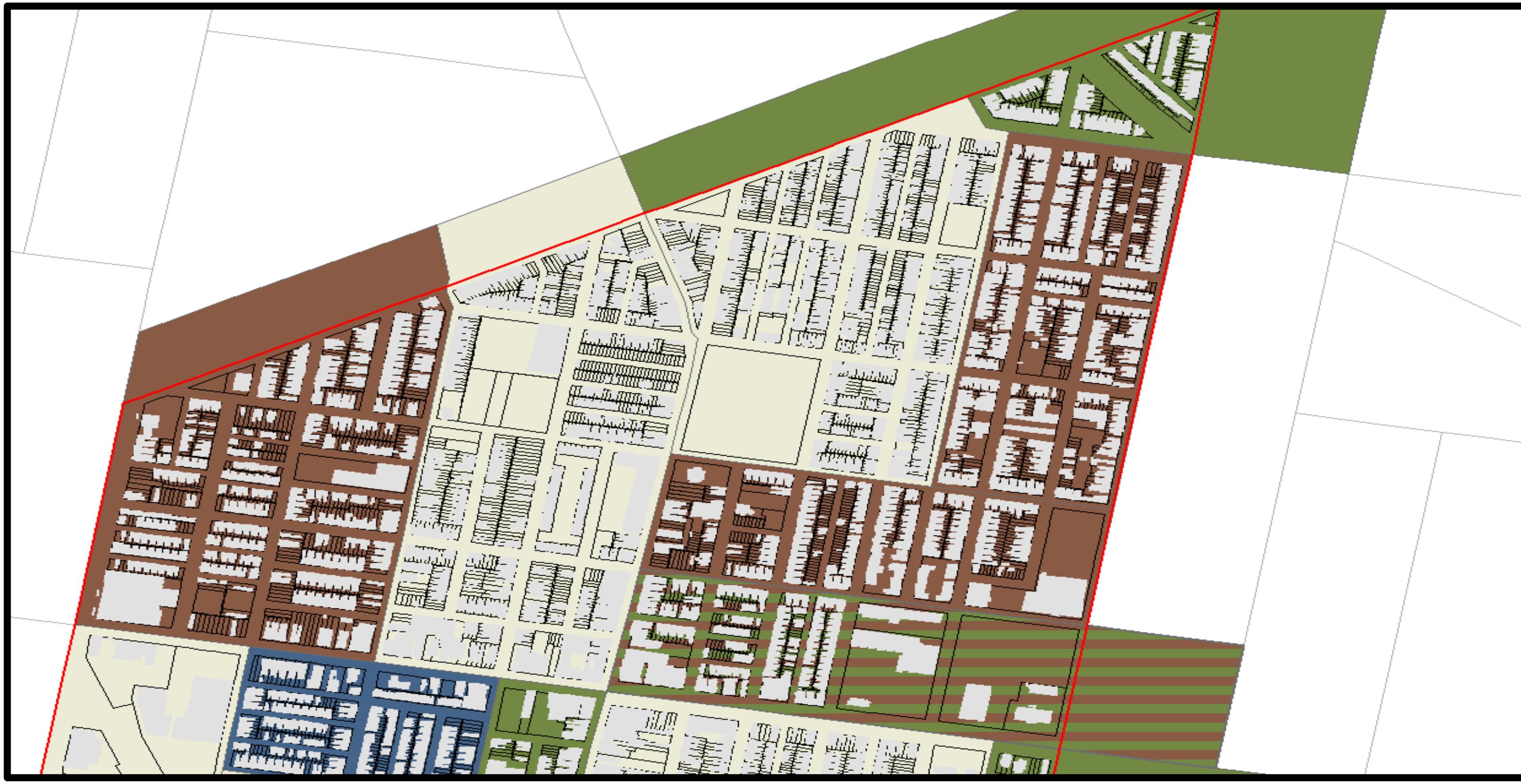
Case Study at Neighborhood Scale: Village of Arts and Humanities

Close-up Within the Village Area

Neighborhood Overview

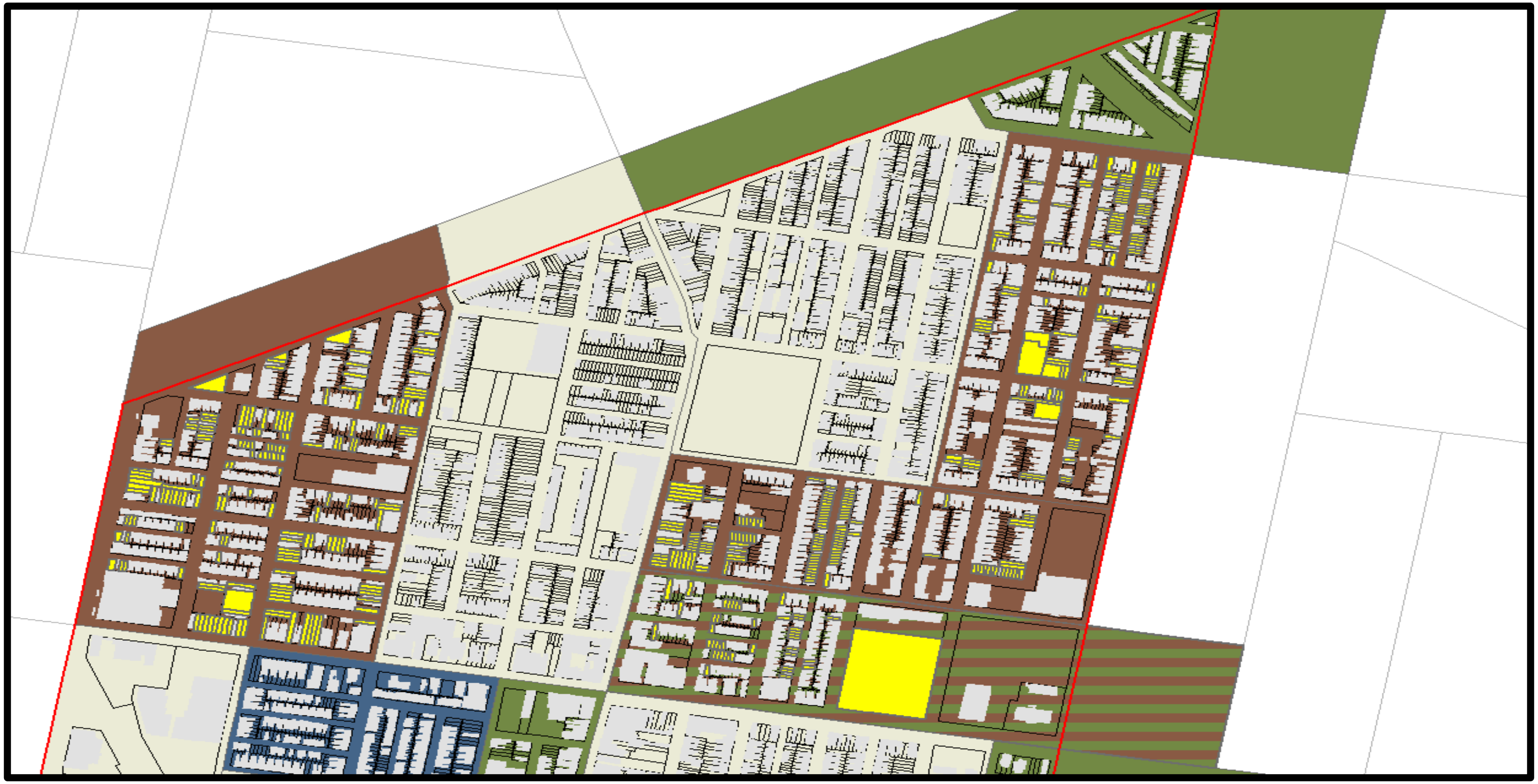


Areas of high amenity need



Schools in high amenity need area

Vacant parcels in high amenity need area (461)



Open Questions

- Do different types of GI produce different types of benefits?

- Do neighborhood characteristics influence the type of benefits that GI practices provide?

Developing Win-Win Strategies When Objectives Conflict

Multiobjective StormWISE* Model

(*Storm Water Investment Strategy Evaluation)

Art McGarity, Swarthmore College STAR Team PI

SWARTHMORE

Two Stage Process:

- Stage 1: Find COST MINIMIZING solutions that achieve specified ANNUAL CSO REDUCTIONS
- Stage 2: Maximize a VECTOR OF BENEFITS subject to an UPPER BOUND ON INVESTMENT $

Stage 1: Least Cost CSO Reduction at Watershed Scale

Analyzing the Construction Costs of Green Infrastructure in Philadelphia

Shandor J. Szalay

AKRF, Inc.

Swarthmore STAR Project

Engineering Consultant

Study Objectives

- Develop regression models to predict Green Infrastructure (GI) construction cost in Philadelphia based on project predictor variables

- Feed cost model into StormWISE optimization engine

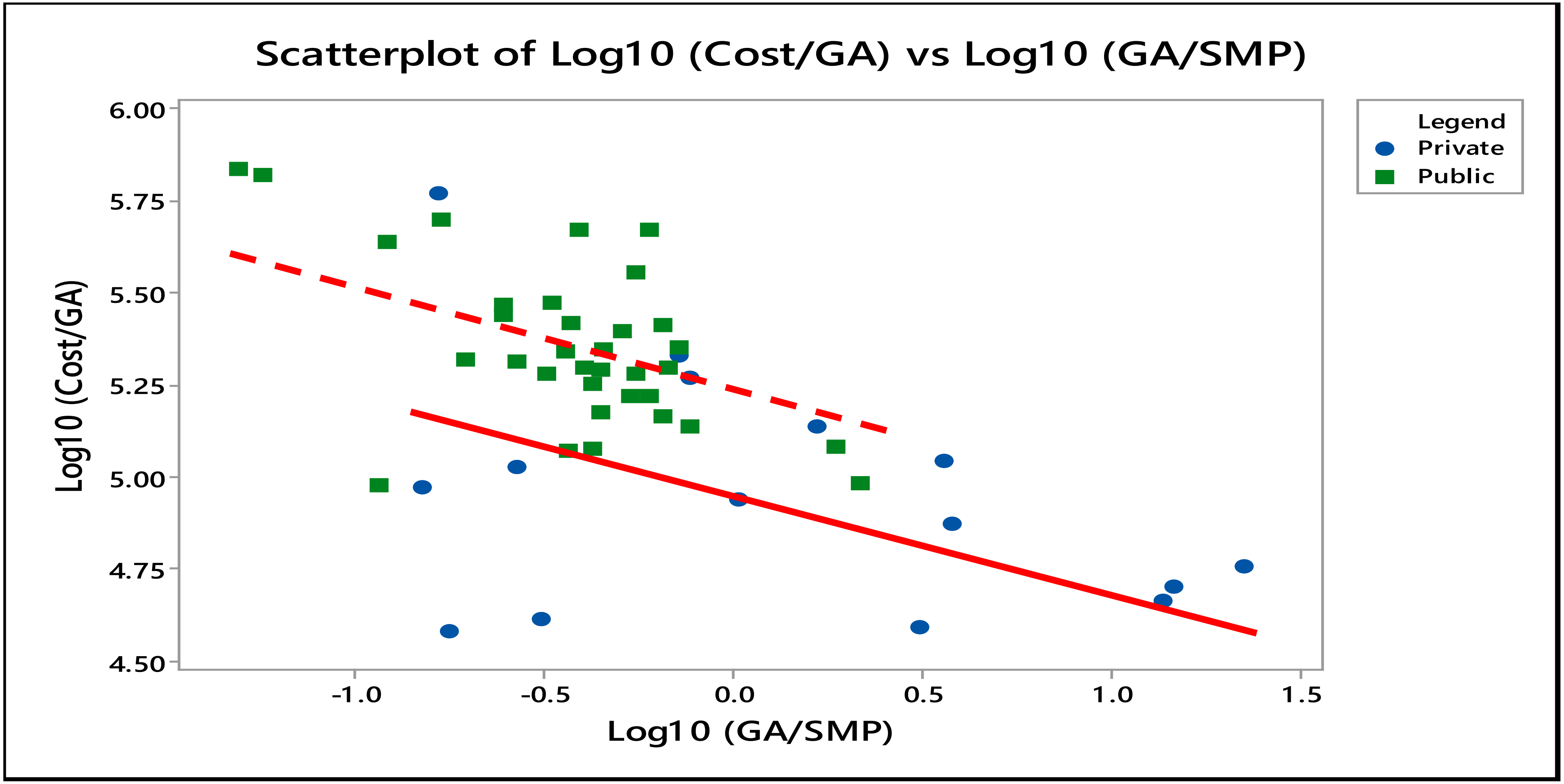
Methods

- Compile built project construction costs and project-level characteristics from two data sets:
  - **Projects on private property** funded through the Stormwater Management Incentive Program
  - **Projects on ROW and public land** directly implemented by Philadelphia Water (PWD)

- Develop linear regression models for unit construction costs using several possible predictors including project size, project type (typology) average practice size, public/private, year built, etc.

Final Regression Model

Project Type	Regression Model	R^2	$R^2_{adjusted}$	$R^2_{predictive}$
Private	$Log_{10}(Cost/GA) = 4.98 - 0.24*Log_{10}(GA/SMP)$	49.1%	46.9%	39.8%
Public	$Log_{10}(Cost/GA) = 5.25 - 0.24*Log_{10}(GA/SMP)$			


Scatterplot of Log10 (Cost/GA) vs Log10 (GA/SMP)
Log10 (Cost/GA)
6.00
5.75
5.50
5.25
5.00
4.75
4.50
-1.0
-0.5
0.0
0.5
1.0
1.5
Log10 (GA/SMP)
Legend
Private
Public

Key Findings

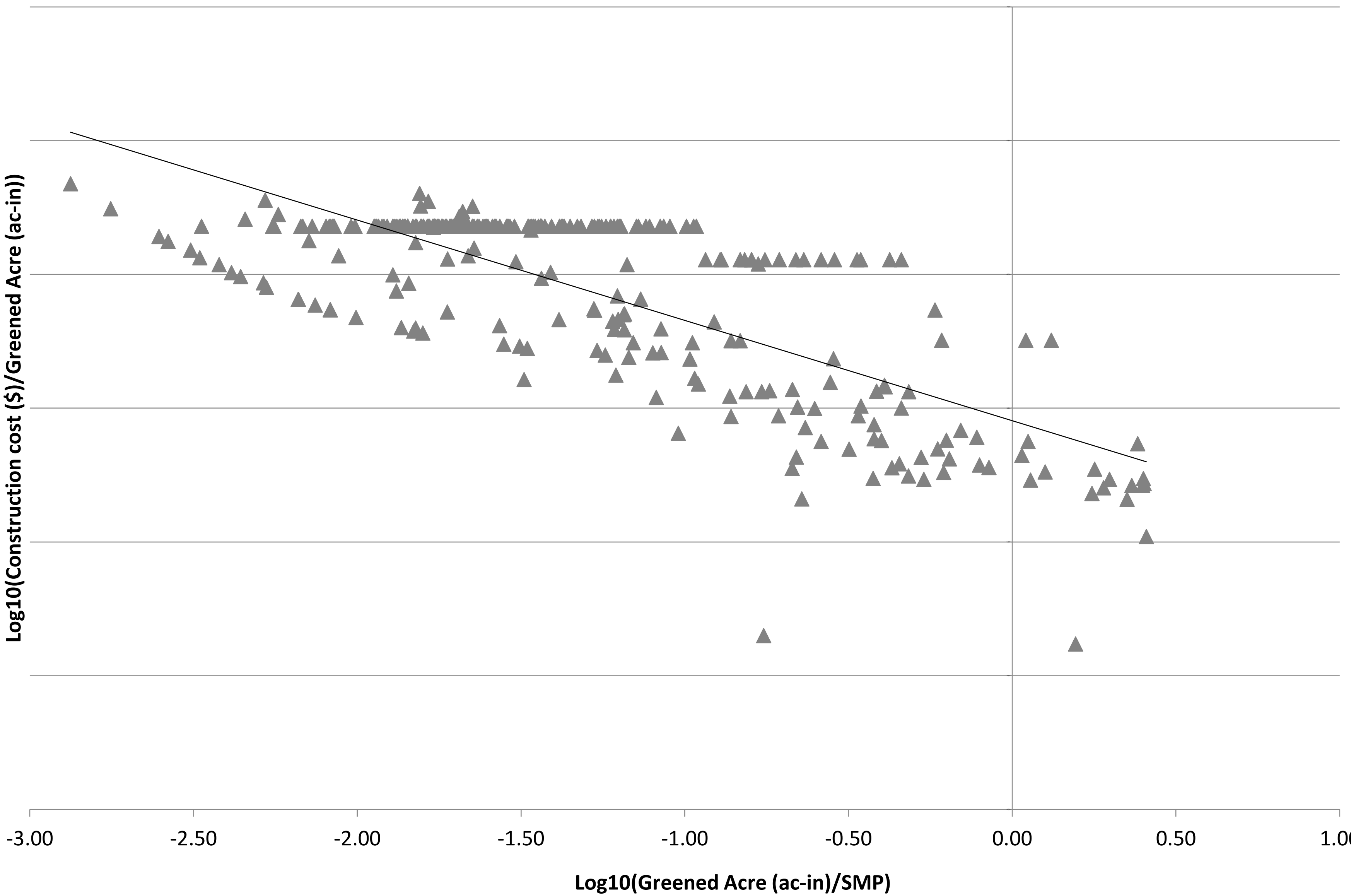
- No significant differences in construction cost between public ROW and off-ROW projects

- Significant scatter in model
  - Lots of other site scale factors involved in cost that are not in model (e.g., utility relocations, disposal method for excavated material)
  - Continue to refine models using additional data and predictor variables

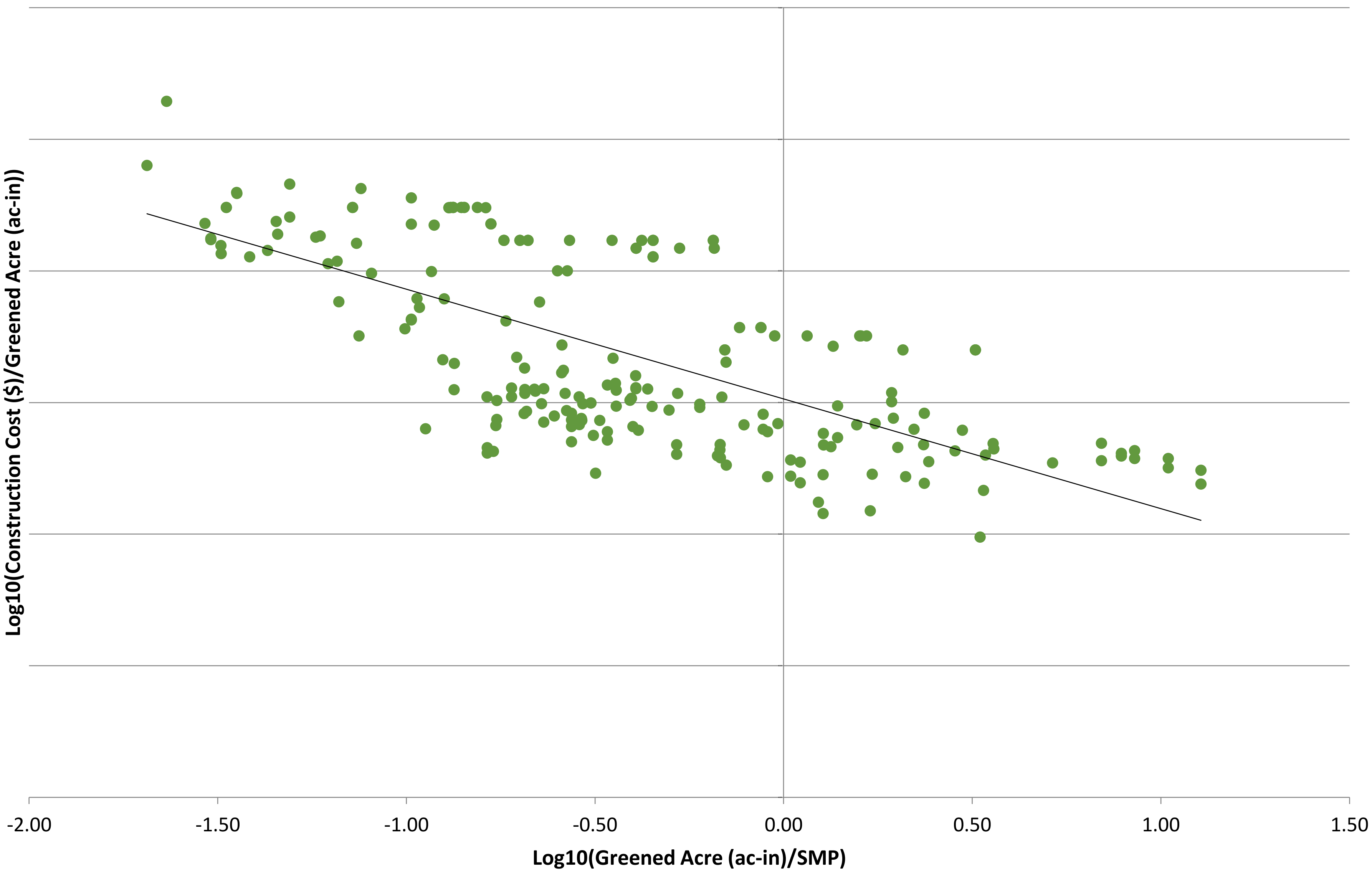
Key Findings

- Significant differences in construction cost between public and private projects.
  - Private projects subject to hard $$ cap, less expensive due to less constrained sites?
- Significant economies of scale for both public and private projects (similar slopes)
  - Related to ***practice*** scale, not ***project*** scale
  - Costs for smaller practice are much more variable than costs for larger practices

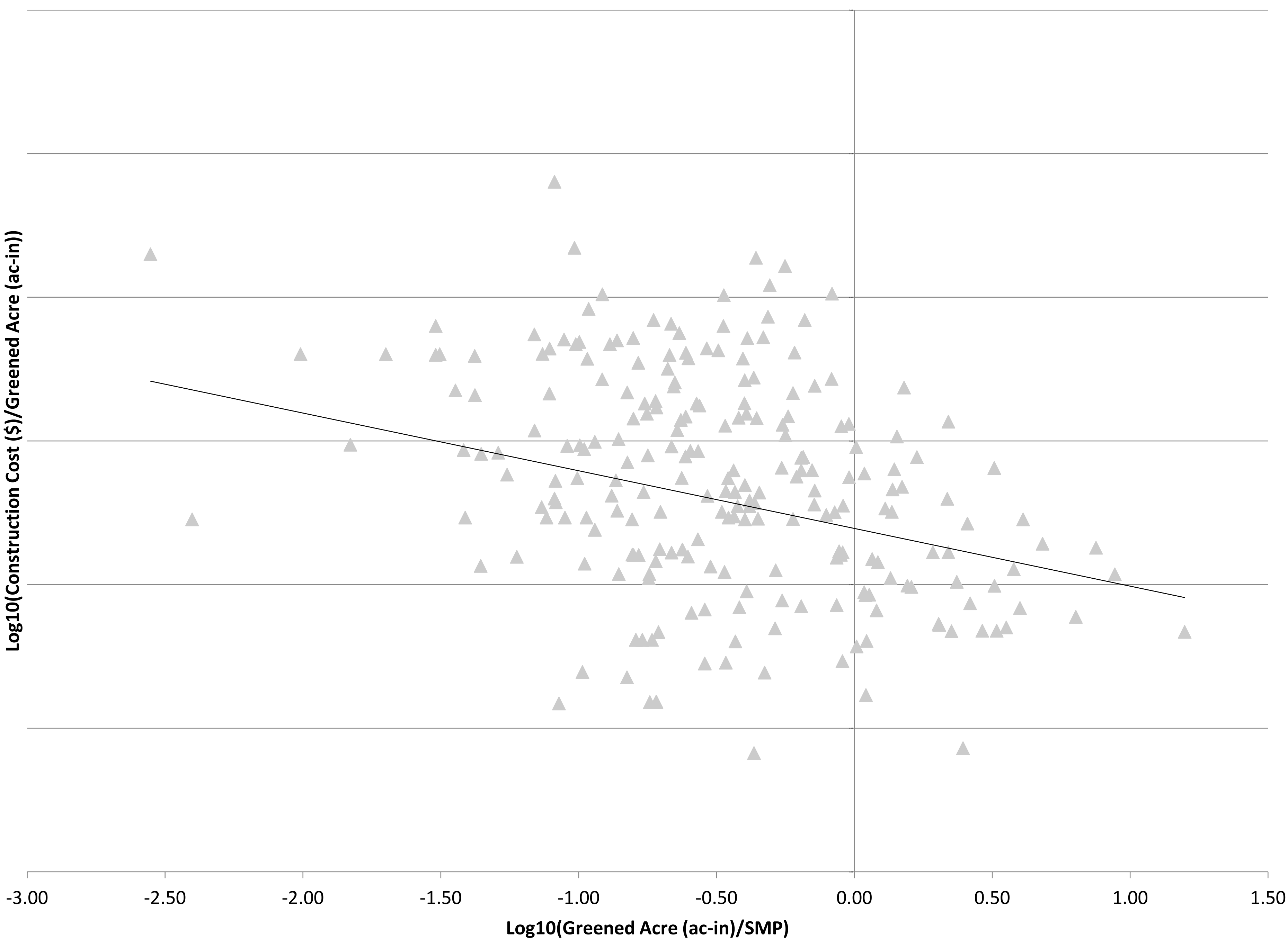
RECENT DATA RECEIVED



Log10(Construction cost ($)/Greened Acre (ac-in))
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
Log10(Greened Acre (ac-in)/SMP)



-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Log10(Greened Acre (ac-in)/SMP)
Log10(Construction Cost ($)/Greened Acre (ac-in))


Log10(Construction Cost ($)/Greened Acre (ac-in))
-3.00
-2.50
-2.00
-1.50
-1.00
-0.50
0.00
0.50
1.00
1.50
Log10(Greened Acre (ac-in)/SMP)

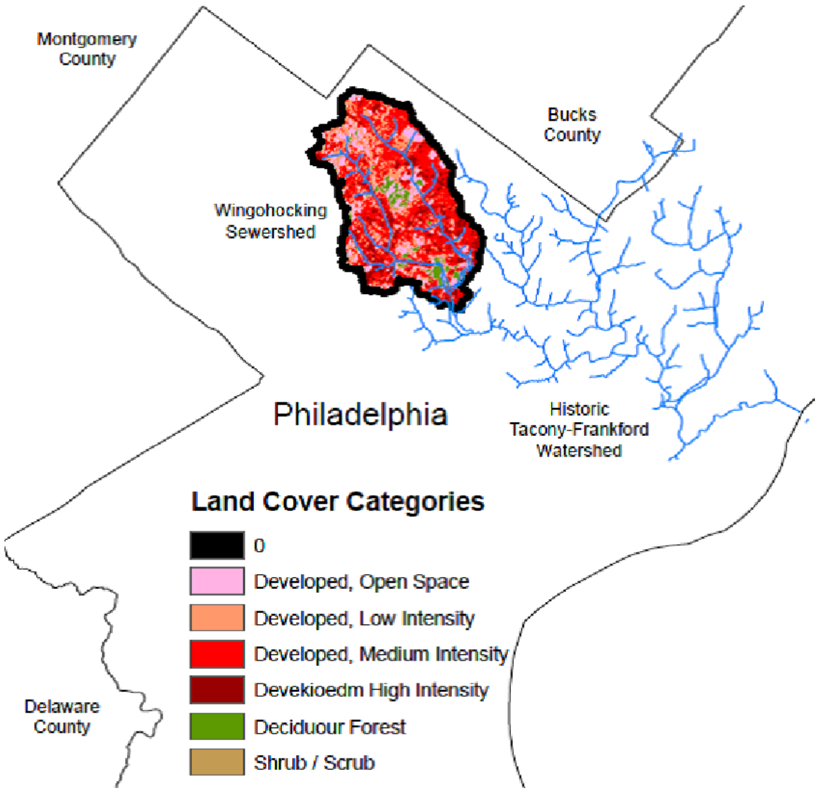
Concluding Thoughts

- Anecdotally, similar cost trends have been observed in other cities analyzed by AKRF as have been reported here.
- So, Philadelphia cost model may suggest a generalizable model that could be applied to other cities – more research is needed.
- Combined with cost/benefit analysis and within the context of an optimization framework, regression models of cost data can help to optimize future investments in GI.
- Cost modeling could be extended to look at full life cycle costs to further enhance decision making.

Stage 1 Continued:
StormWISE GI Investment Strategy Model Applied to the Wingohocking Sewershed

Deploying three GI Practices throughout the sewershed:

- Rain Gardens
- Infiltration Tree Trenches
- Rain Barrels



SWARTHMORE

Least Cost CSO Reduction at Watershed Scale

Mathematical Formulation for Minimizing GI Costs: *c(x)* *and* Prioritizing GI: x = greened acres of GI practices on land uses:

$$Minimize\ c(\boldsymbol{x})$$

subject to:

$$B_t(\boldsymbol{x}) \geq B_t^{min}$$

$$0 \leq \boldsymbol{x} \leq \boldsymbol{u}$$

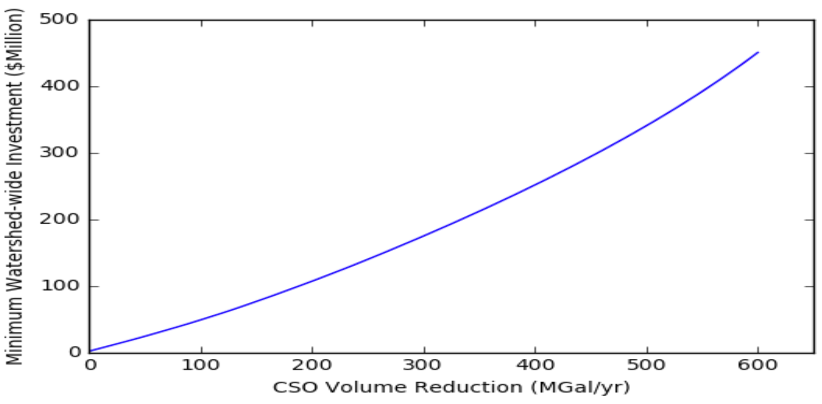
applied in Wingohocking with a single benefit B(**x**) = annual CSO volume reduction,

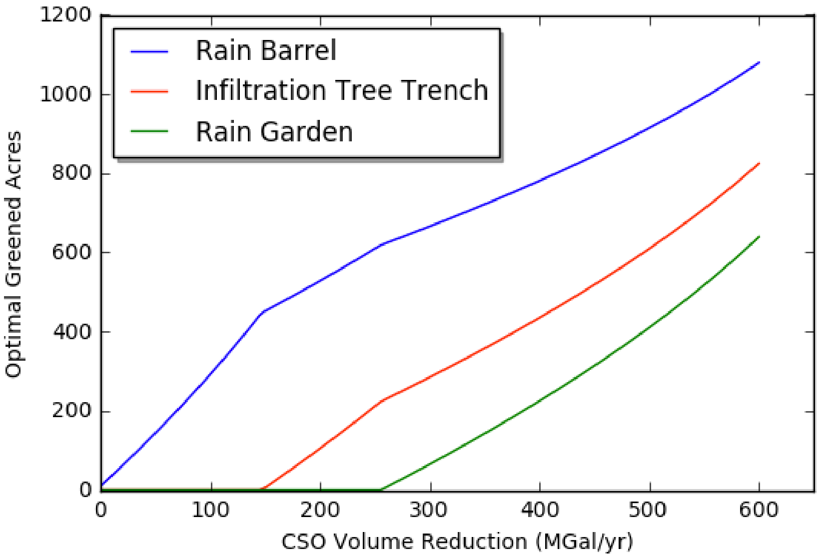
where:

x = vector of decisions specifying how much of each type of GI to deploy and where to placed it,

u = vector of upper bounds on GI deployment, which, for this analysis are set only by impervious area in each subcatchment

Wingohocking StormWISE Optimization Results

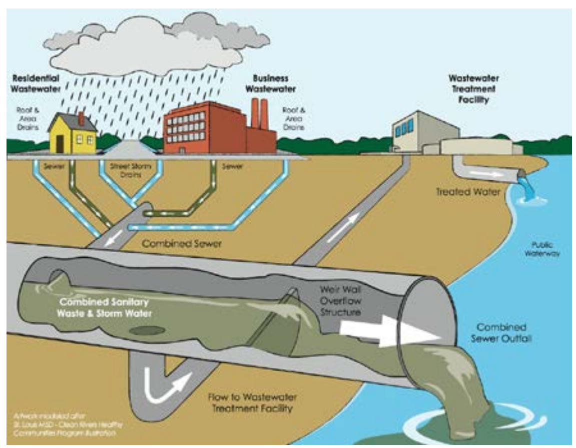




B_t^{min}= Annual CSO reductions specified in the range 0 – 600 MGal/yr

Stage 2: Include Multiple Benefits in the Model

- Runoff Reduction
- Aesthetics
- Amenity Access
- Green Canopy
- Green Jobs
- Fee Savings
- Low Maintenance Cost



STAGE 2 MATHEMATICAL FORMULATION:

Maximize a VECTOR OF BENEFITS (7 benefits in this case)
subject to:

(1) UPPER BOUND ON INVESTMENT
(2) UPPER BOUNDS that limit GSI deployments to realistic levels

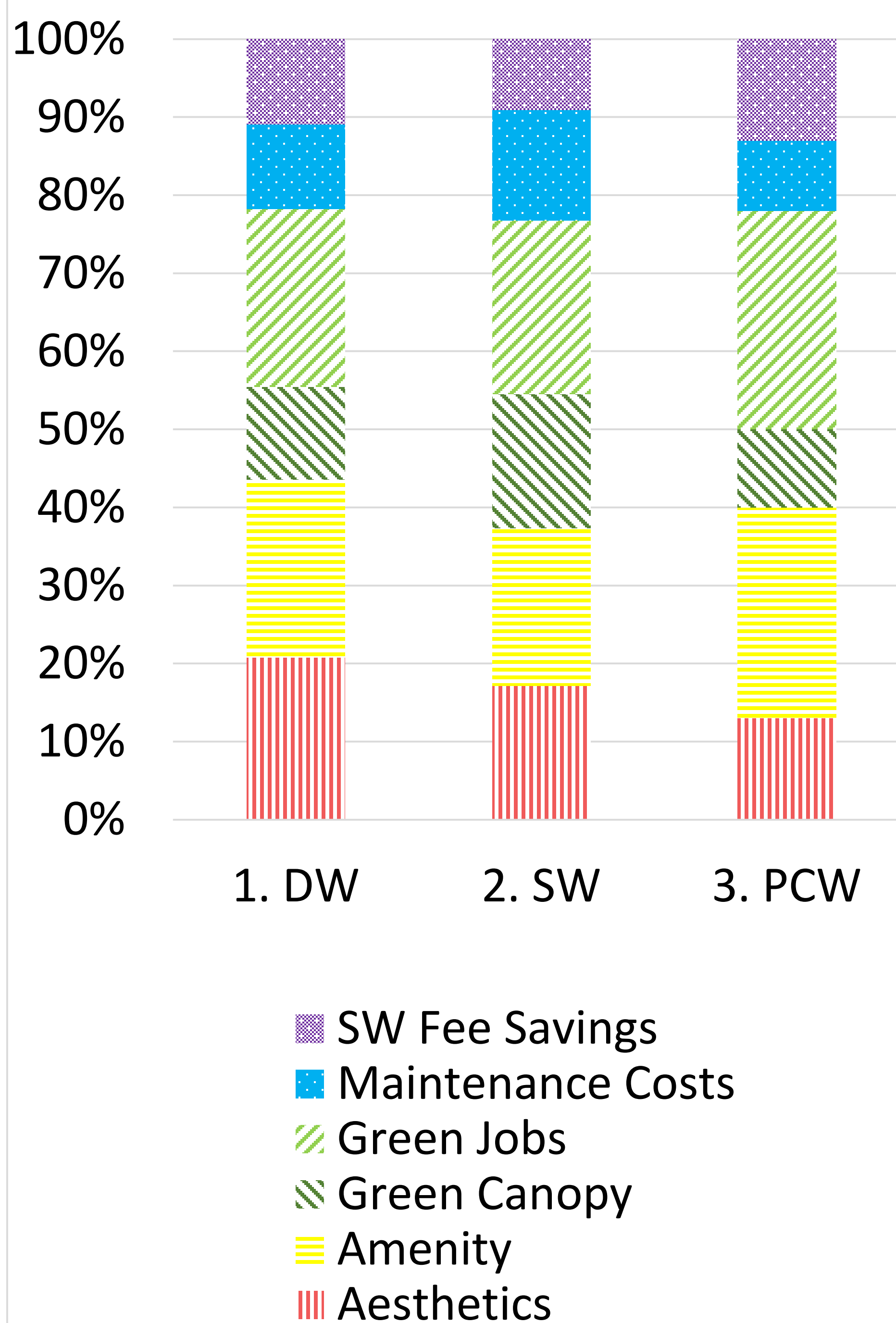
A multiobjective maximization of benefits subject to a budget constraint on total investment costs and upper bounds that limit GSI deployments to realistic levels:

$Maximize\ [B_t(\boldsymbol{x})$ for $t \in T]$ (multiple benefits)
subject to:
$c(\boldsymbol{x}) \leq c^{max}$ (budget constraint)
$0 \leq \boldsymbol{x} \leq \boldsymbol{u}$ (realistic upper bounds)

$\boldsymbol{x}$ = a vector of decision variable solutions specifying how much of different types of GSI to install in the watershed and where to place them

We Apply Three Different Benefit Weighting Techniques

1. Direct Weighting
   - Assign number directly to co-benefit
2. Swing Weighting
   - "If you can swing just one co-benefit from its worst value to the best, which one would you choose?"
3. Pairwise Comparison Weighting
   - Compare and give relative ratings to a pair of GI investment plans
   - Then statistically infer implied weights



Normalized Weighted Benefit Function

$$B_t(x) = W_t * Ben_t(x)$$

$$Ben_t(x) = \frac{\left(\sum\sum slope_t\,(j,k) * x(j,k)\right) - Ben_t^{min}}{Ben_t^{max}}$$

Piecewise linearization of benefit slopes:

- j indexes different land uses in the subwatershed
- k indexes different GI practices

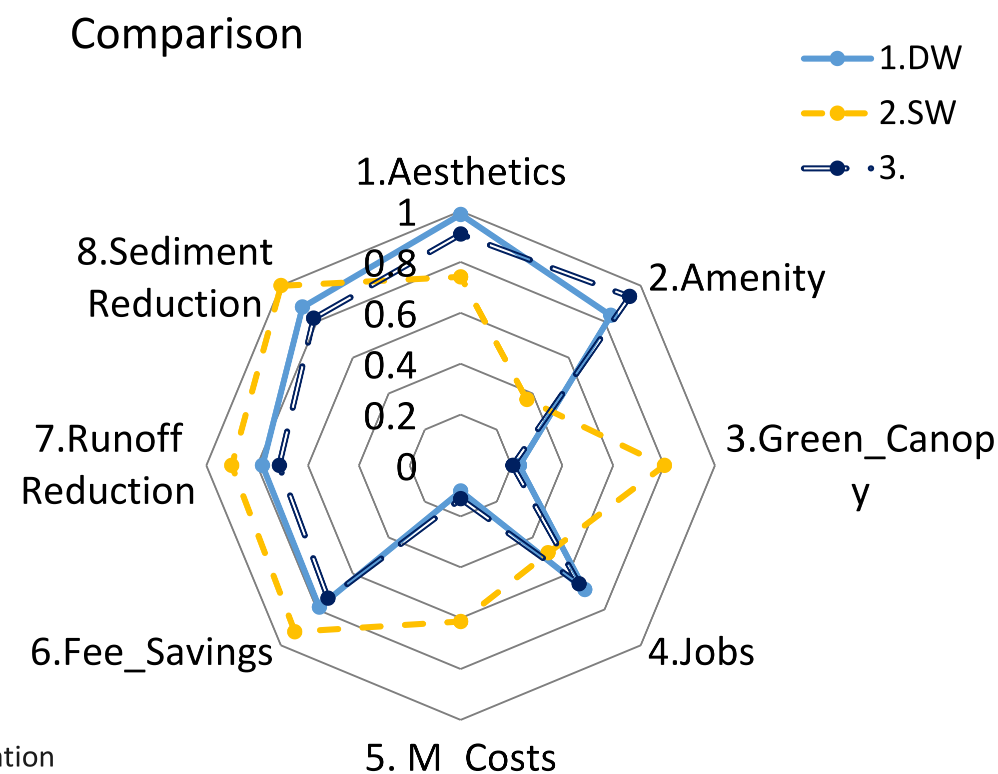
Normalize by setting realistic minimum and maximum for each benefit:

- Ben_t^{min} = *minimum level for benefit t*
- Ben_t^{max} = *maximum level for benefit t*

Community StormWISE Model Results

Case Study: Village of Arts and Humanities in North Philadelphia

- Adapted StormWISE model (McGarity, 2012) to accommodate community benefits
- This version reports:
  - ❖2 stormwater benefits: runoff & sediment reduction
  - ❖6 co-benefits



*McGarity, A. (2012). "Storm-Water investment strategy evaluation model for impaired urban watersheds." *Journal of Water Resource and Planning Management*, *138* (2), 111-124.

NEXT STEPS

GI and Property Values: Hedonic Approaches

<u>COLLABORATORS</u>:
Megan Heckert, West Chester University, Swarthmore STAR Team
Siddhartha Sen, Morgan State University, Villanova STAR Team

Overall idea: house prices are based on a range of characteristics (of house and neighborhood) whose importance and effect can be modeled

Price = constant + housing characteristics + neighborhood characteristics + …

MSU / Villanova Methodology

- 500 sales within ¼ mile of GI
- Before/after sales 2011-2017
- House characteristics: number of bedrooms, bathrooms, size of lot, square footage of home
- Location characteristics: distance from city center, walkability, bikability, transit accessibility, proximity to schools, proximity to parks
- Type of GI, number of GI, and number of types of GI per property

WCU / Swarthmore Methodology

- 5,000 sales 2014-2015
- Value at previous sale, length of time since previous sale
- Square footage
- Use spatial regression models to account for spatial autocorrelation
- Determine whether private/public, different types of GI, different neighborhoods have different effects

New Philadelphia Partnership:
Overbrook Environmental Education Center

- Mission: “remove barriers from the public's full appreciation of our region’s technological and environmental resources” (http://oeecintern.wixsite.com/)
- Partnership with Philadelphia Water Department to maintain Green Stormwater Infrastructure (GSI) in neighborhood

phillywatersheds.com

Goals
- Green Commercial Corridor expansion
- Create walkable environment for residents and visitors

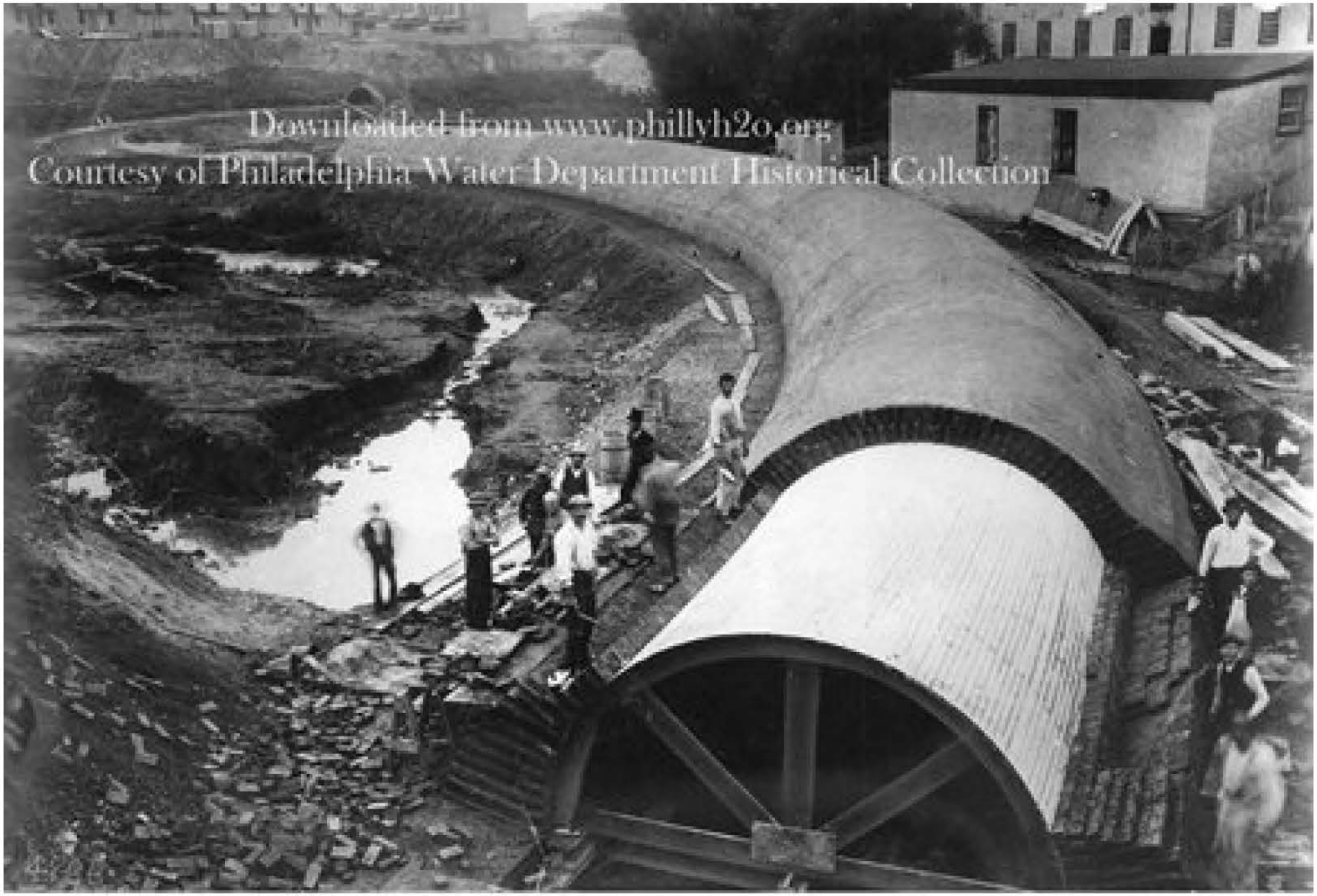
STEM Benefits
- Integrate with existing high school programs
- Two Swarthmore College Engineering Students Senior Engineering Design Projects: Jon Cohen ‘17 and Alexandra Philyaw ’17 (work presented here)

Incorporating Overbrook Data and Priorities

- Land area and land use categories
- Natural benefit minima and maxima
- Benefit slopes
- Treatable fractions
- GSI Types

phillywatersheds.com

Mill Creek

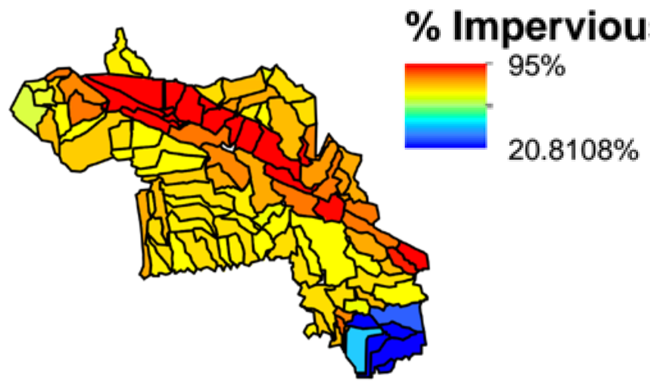


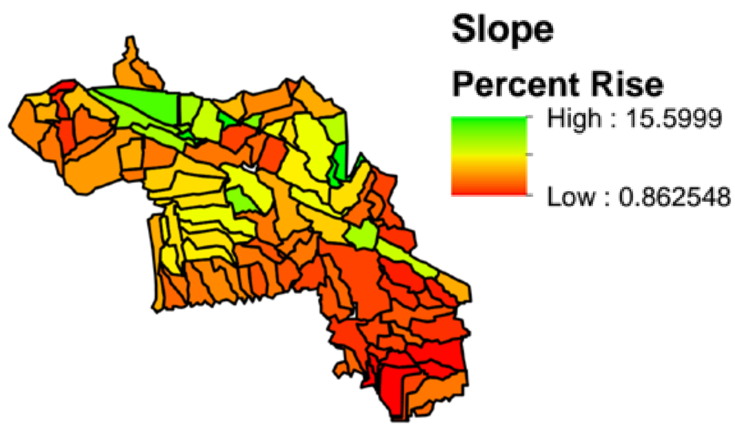
— Mill Creek Sewer between 47th & Haverford. —

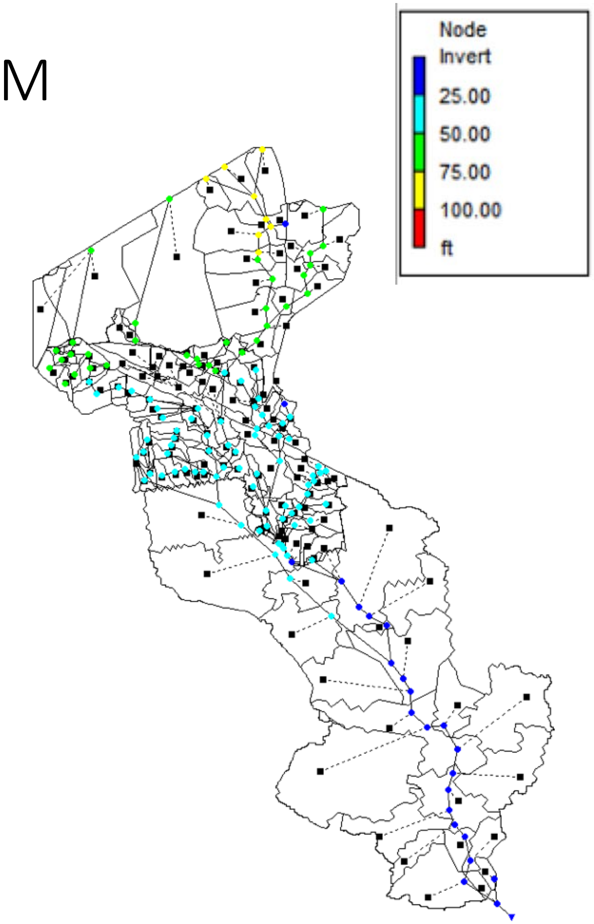
www.phillyh2o.org

Obtaining Subcatchment Parameters for SWMM

- % Imperviousness
- Drainage Width
- Slope
- Infiltration Parameters

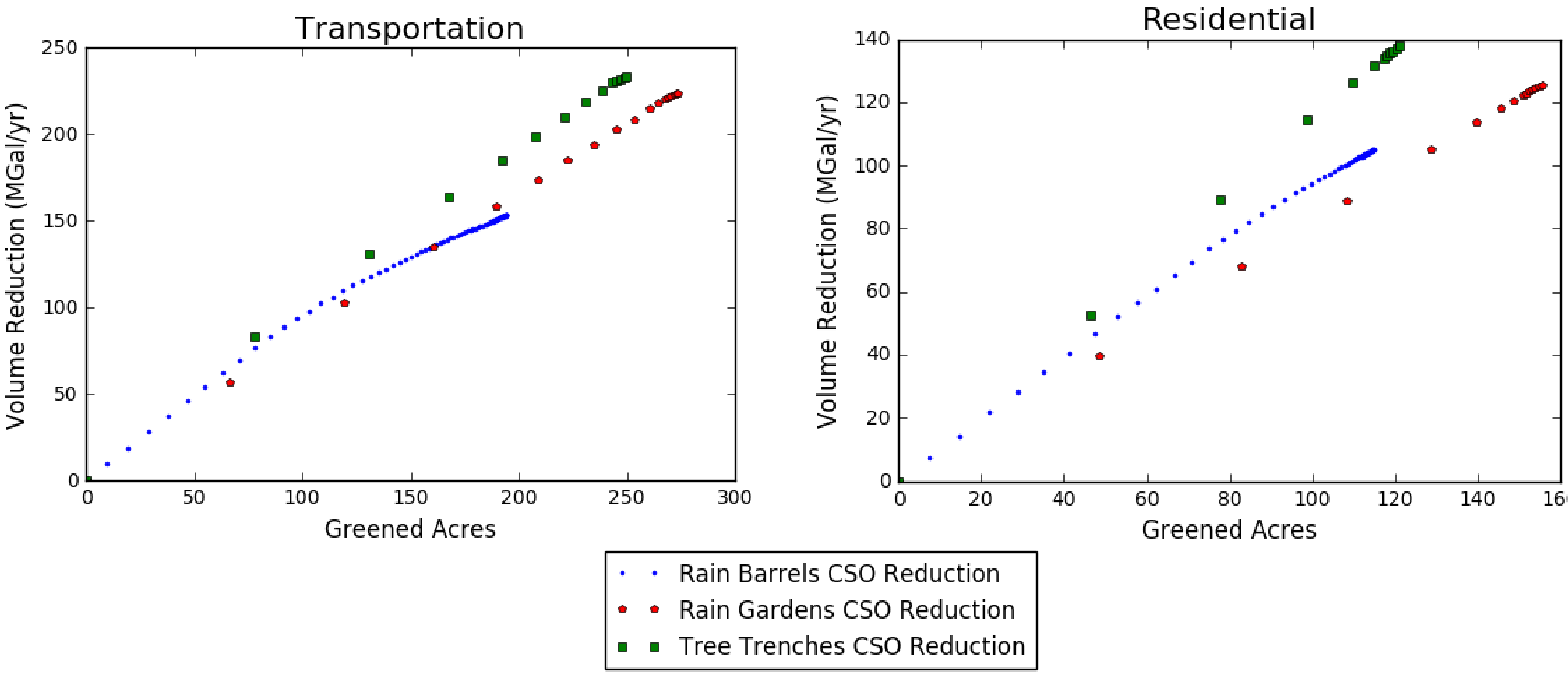




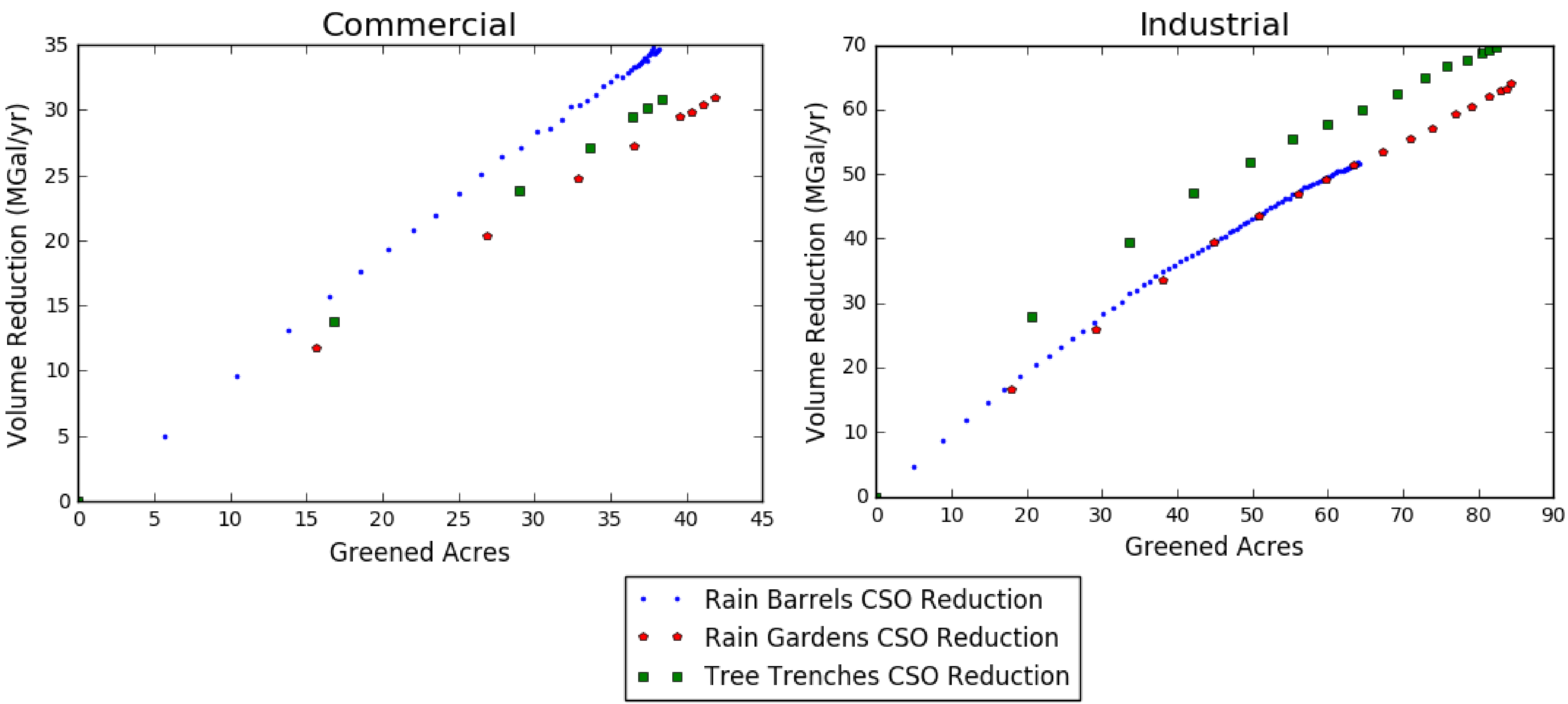


SWMM Simulations of Three GI Deployed on Specific Land Uses

Transportation and Residential



Commercial and Industrial



Community StormWISE Web App Screen Shot:

- Uses Django framework to interface with StormWISE Engine in Python
- Input: Budget, runoff goal, benefit priorities
- Output: StormWISE results of investment and benefit totals by land use categories and GSI types

Budget: $ 500000

Runoff Reduction Goal: 5

Benefit:	You Set Benefit Priority	Benefits Actually Achieved
Runoff Reduction (million gal.)		5.02
Aesthetics (% increase)		22.71
Amenities (% increase)		3.85
Green Canopy (% increase)		4.20
Green Jobs (# jobs)		0.95
Maintenance Cost ($1000)		3.63
Fee Savings ($1000)		6.41

STEM Components

- Hopkins Ph.D. Candidate Fengwei Hung – Ph.D. Dissertation
- UMBC Masters Candidate Elvis Andino-Nolasco – Masters Thesis
- Temple undergraduate urban studies courses, projects, internships
- Swarthmore undergraduate engineering courses and summer research internships
- Swarthmore senior engineering design projects, Spring, 2017
- Swarthmore undergraduate non-engineering outreach course Environmental Protection – included high school GI curriculum development
- Overbrook Environmental Education Center – Summer High School Science Program focusing on Stormwater and Green Infrastructure
- Swarthmore undergraduate summer internships at Overbrook Environmental Education Center – Summer, 2017
- Village of Arts and Humanities and the Philadelphia Horticultural Society - Urban Green Spaces and Digital Technologies Initiative to increase youth engagement with urban green spaces and developaAn interactive portal and digital map of community gardens that includes photographs and videos