Quantifying Benefits of Green Stormwater Infrastructure in Philadelphia

Arthur McGarity[1], Fengwei Hung[2], Christina Rosan[3],

Benjamin Hobbs[2], Megan Heckert[4], and Shandor Szalay[5]

[1]Department of Engineering, Swarthmore College, 500 College Ave., Swarthmore, PA, 19081; email: amcgarity@swarthmore.edu

[2]Department of Geography and Environmental Engineering, Johns Hopkins University, 3400 Charles St., Baltimore, MD, 21218; email: fwhung0807@gmail.com, bhobbs@jhu.edu

[3]Department of Geography and Urban Studies, 320 Gladfelter Hall, Temple University, Philadelphia, PA 19122; email: cdrosan@temple.edu

[4]Department of Geography and Planning, West Chester University of Pennsylvania, 700 South High St, West Chester, PA 19383; email: MHeckert@wcupa.edu

[5]Senior Vice President and Director of Water Resources Practice, AKRF, Inc., 307 Fellowship Road Suite 214, Mt. Laurel, NJ, 08054; email: SSzalay@akrf.com

ABSTRACT

Philadelphia's Green City Clean Waters program is an innovative plan to reduce the frequency and environmental impact of combined sewer overflows through massive, citywide implementation of green infrastructure practices. The program has been approved by regulatory agencies based on the assumption that a variety of direct benefits and co-benefits will be realized over a 25-year period. We report research on methodology for developing green stormwater infrastructure (GSI) *benefit functions* that express direct runoff reduction benefits and ancillary co-benefits of GSI as functions of investment levels. Functions for direct benefits are generated by coupling a multiobjective evolutionary optimization algorithm (MOEA) to a hydrologic simulation model. Functions for co-benefits are developed through community-based participatory research enabling prioritization of benefits and GSI implementation strategies that reflect the values of the communities that are served. Benefit functions are used in the StormWISE multiobjective decision support framework to optimize GSI investments at the subwatershed level.

INTRODUCTION

Philadelphia's Green City Clean Waters (GCCW) program provides a context for research on how best to manage innovative urban stormwater practices that reduce runoff volume at the source. Implementing a green stormwater infrastructure (GSI) approach presents municipal officials in charge of urban sewer systems with new and complex challenges compared to the "gray" alternatives, such as concrete tunnels to hold overflow volume, that are specified and designed by a handful of technical experts and approved by a committee of decision makers. The GSI approach requires, rather, that the decisions of thousands of individuals managing land parcels in neighborhoods and districts throughout the city be coordinated to achieve common goals.

The complexities of GSI implementation are being addressed by transdisciplinary research (Rosenfeld, 1992) on methodologies to generate guidance for municipal managers and regulators for creating conditions that contribute positively to the desired program goals. Here, we report progress in the development of methodology for maximizing GSI benefits within a context of realistic constraints on overall cost, equitable distribution of benefits, and political feasibility. A fundamental aspect of our research approach is the idea that these methodologies should be developed and applied from the "bottom-up" by engaging municipal and community partners in all stages of the research and project design.

BENEFIT FUNCTIONS

An emerging key concept useful for evaluating alternative strategies for GSI investments is the subwatershed-scale "benefit function," a mathematical representation of one or more of the benefits that are generated by implementation of GSI practices. Benefit functions model GSI implementation as an idealized saturation process that initially deploys practices in locations where they generate the greatest benefits per dollar invested. As the more favorable sites are occupied, deployment on remaining sites costs progressively more to obtain similar levels of benefits. Although these functions are idealized representations of the implementation process, we will show that they can provide useful guidance in the development of cost-effective GSI investment strategies that aim to achieve multiple benefits.

Benefit functions are associated with delineated zones of green infrastructure (ZGIs), which are geographically contiguous collections of land parcels that have similar characteristics affecting the implementation of GSI. Within a particular ZGI, the benefits and costs of the various GSI practices and technologies implemented on a particular land cover category are represented by a collection of mathematical functions describing diminishing marginal benefits for increasing levels of investment. Estimates of the numerical parameters of benefit functions can be used in a model, such as the Storm Water Investment Strategy Evaluation (StormWISE) framework (McGarity, 2012, 2013) to support decision making related to prioritization of GSI investments at the subwatershed scale.

Philadelphia's Green City Clean Waters program of GSI implementation provides an excellent case study to test methodologies for constructing benefit functions. In this paper, we explore the use of a simple saturation function to provide an accurate fit to output from a simulation model, EPA's SWMM (http://www2.epa.gov/water-research/storm-water-management-model-swmm), which calculates flow reductions at a subwatershed outlet created by installation of GSI. The function has the form: $B = B_{\max}\frac{X}{(H+X)}$, where B = a GSI benefit which, in this case, is the annual reduction in flow volume, $B_{\max}$ = maximum possible annual flow reduction benefit, X = subwatershed total investment in GSI ($), and H = "half-cost" – the investment required to treat one-half of the land area ($). Values of the parameters B_{max} and H, normalized by land area, are expected to vary geographically depending on attributes such as land cover, soil type, and drainage zone (headwaters versus lowland).

RUNOFF VOLUME REDUCTION

Our methodology for generating runoff volume reduction benefit functions involves repeated runs of a detailed hydrological simulation model (EPA's SWMM) at the subwatershed scale for an entire hydrological year. Simulations are run for GSIs located at many different locations and for a range of sizes to produce a large number of different combinations, including installations on different drainage zones and land uses. This approach has been shown by McGarity and McGarity (2013) to be useful for generating scatter plots of annual runoff volume reduction versus total subwatershed GSI investment from which the noninferior "Pareto" frontier can be extracted. A curve fit to the points comprising the Pareto frontier represents a benefit function because it quantifies the maximum runoff volume reduction achievable at each investment level over a range.

In this paper, we present an extension of this approach in which the Pareto frontier is generated automatically using a multiobjective evolutionary optimization algorithm (MOEA) to place and size GSI installations on parcels throughout a subwatershed. The optimization process proceeds by identifying GSI configurations that increase runoff volume reduction benefits while simultaneously decreasing total costs. With the MOEA generating the GSI configurations run in the simulation model, the total number of simulation runs is greatly reduced from that required to generate a benefit function from a random or exhaustive search process.

We have developed a case study adapted from Chapter 4 of the SWMM Applications Manual (Gironas, et al., 2009). EPA's SWMM engine (Rossman, 2010) and Penn State University's Borg MOEA (Hadka and Reed, 2013), both available in the portable C language, are "glued" together by a script written in Python. A graphic of the post-development subwatershed is shown in Fig. 1. Infiltration trenches, labeled S_IT_1 – S_IT_4 are shown in the upper part of the image applied to land use categories labeled M (medium density), L (low density), and DL (duplex). Grass filter strips, labeled S_FS_1 – S_FS_4 are shown in the lower area where they are applied to land use categories labeled M and S (apartment high density).

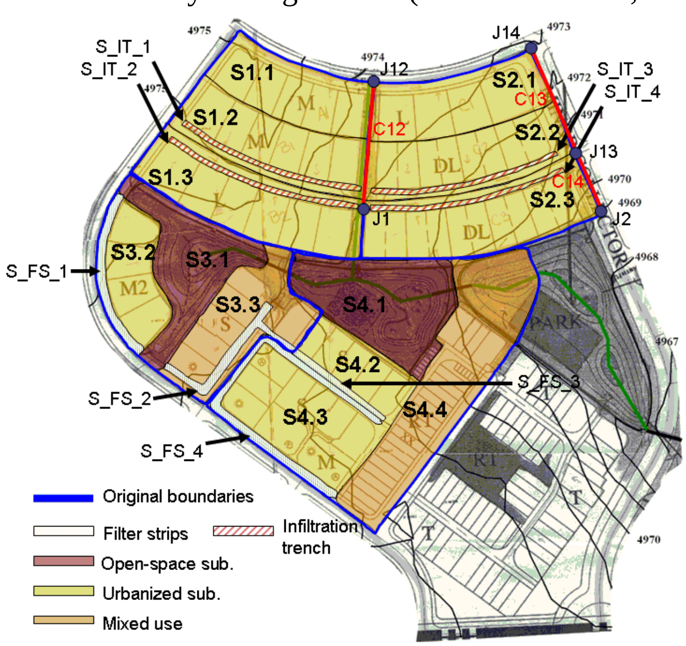

Fig. 1. Case study adapted from Gironas, et al., 2009

The watershed outlet is shown as a channel flowing off the diagram to the right. The four filter strips are four ft. wide and have lengths in the range 410-894 ft. The four infiltration trenches are three ft. wide and have lengths in the range 450-470 ft. Both of the GSI practices have zero imperviousness.

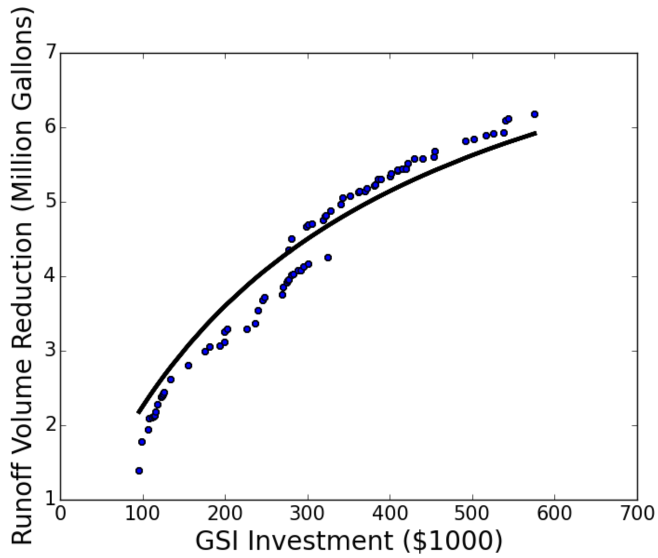

Fig. 2. Benefit function derived from MOEA optimizer

The effect of installing these runoff reducing practices is reduced annual flow volume at the watershed outlet. We run SWMM for this example watershed using one year of weather data for Philadelphia.

In order to model variations in the placement and size of these flow reduction practices, we independently vary both the imperviousness and width of each filter strip and each infiltration strip. Imperviousness parameters are varied from zero to 100%. The widths are varied using a multiplier ranging from one to four, thereby increasing the surface areas of the installed practices by as much as a factor of four.

GSI investments are represented by construction costs only. Filter strip costs are calculated by multiplying the surface area by $\$5/ft^2$ and a scale factor based on the impervious percentage, with 100% impervious corresponding to no GSI installation and, therefore, zero cost. Infiltration trench costs are calculated by multiplying the maximum stored water volume by $\$10/ft^3$ and they are similarly scaled by impervious percentage. Trenches are assumed to be six ft. deep and filled with stone having a void fraction of 0.4. GSI construction costs vary widely, and these values are assumed to be reasonable based on a review of available cost data.

The Borg MOEA was configured to run 600 SWMM annual simulations, maximizing watershed runoff volume reduction and minimizing total watershed GSI investment. The 600 runs required about two hours on a Macintosh laptop. Of the 600 runs, 78 were selected by Borg as being Pareto optimal. Fig. 2 plots the solutions in the form of a benefit function. A saturation function is fit to the results having parameters B_{max} = 9 million gal. and H = \$300,000. The function is shown as a solid line. A plot of all 600 solutions would show points scattered generally below and to the right of the curve, with the 78 Pareto optimal points on the “northwest” frontier.

These results indicate that the methodology investigated here is useful for generating realistic benefit functions and that the saturation function is a useful model for representing the results. The next step in our research is to repeat this exercise for a subwatershed we have selected for investigation in North Philadelphia in the Wingohocking sewershed. We are also investigating statistical models, developed from the output of MOEA driven simulations, that can be used as an alternative approach for generating benefit functions requiring less computation and less parcel-specific input.

PHILADELPHIA COMMUNITY ENGAGEMENT

Research on "Collaborative Environmental Management" (CEM) finds that by engaging a diverse group of stakeholders in the framing and development of environmental policy, stakeholders are empowered, and policies developed can be effective (Ostrom 1990, Cuthill 2002, Koontz 2006). Other research suggests that it is critical to engage stakeholders in knowledge production, particularly in the early phases of research design and development (Phillipson et al. 2012). Philadelphia's Green City Clean Waters program is an innovative approach to managing the city's stormwater that is intended to provide environmental, social, and economic benefits. In order to develop a realistic model of effective GSI implementation strategies from the Philadelphia case study that may be transferrable to other cities with combined sewer overflow problems, it is critical to determine how different stakeholders in different parts of the city value GSI. To develop protocols for measuring program effectiveness, we are using a community-based research process to produce the implementation, monitoring, and evaluation plans. By engaging community development corporations (CDCs) and other watershed partnership groups (that have been active in the GCCW program) in our research design, we expect that our decision-support model will accurately reflect the on-the-ground realities facing communities.

Different neighborhoods in the City of Philadelphia have very different socio-spatial realities, which may impact GSI benefits. For instance, a green infrastructure project located in the thriving Center City with already high real estate values, low rates of crime, and minimal vacancy may provide different economic and social benefits than one in communities with high rates of poverty, crime, and vacancy. In addition, there may be different considerations that need to be taken into account when planning for, implementing, monitoring, and maintaining GSI projects in neighborhoods with different typologies.

Designing a transferable process for implementing and monitoring GSI projects or measuring the impacts and effectiveness of GSI programs necessitates recognizing the various unique challenges facing different neighborhoods in the city. To better understand these issues in Philadelphia, we formed an advisory committee composed of community-based leaders in the Philadelphia community who will play an advisory role throughout our project. To form the committee, we worked with the Philadelphia Water Department (PWD) to identify CDCs and water-related partnership groups across the City. We invited groups from across Philadelphia representing constituencies with different socio-spatial characteristics and demographics to be members of a "GreenPhilly Community Advisory Board." This group helps us determine how different communities may value GSI projects by sharing their experience with how projects are planned and implemented in different community contexts. The group also helps ensure that we are asking the right questions as to how to evaluate the role and effectiveness of green infrastructure, particularly when it comes to developing mechanisms to quantify social and economic benefits.

Our first GreenPhilly Community Advisory Board meeting was held on June 6, 2014 at Temple University. During the workshop, we introduced the project to the meeting participants and developed a plan for next steps. Our second meeting, held on September 15, 2014, focused on identifying possible benefit metrics to include in the Green Infrastructure model. Professor Benjamin Hobbs and his doctoral student Fengwei Hung ran an exercise where Advisory Board members gave feedback on how to quantify different kinds of benefits in the model. The results appear below.

Our next step in the community engagement process is to work with our advisory board to refine our decision-support methodology by further developing the concept of Zones of Green Infrastructure (ZGIs). In order to make the ZGIs more tangible and relevant to existing planning already going on in the City, we are initially matching the ZGIs with the City of Philadelphia's Planning Districts. However, since the Planning Districts are large, we will start by focusing on a lower level with Philadelphia's Registered Community Organizations (RCO). We have begun working with the Village of Arts and Humanities, a community based non-profit near Temple University that serves as the RCO for the neighborhood, and we are planning a series of meetings on GSI in one neighborhood to get feedback on what variables we should be including in the modeling for the ZGIs. We will then attempt to reproduce this process in another neighborhood.

CO-BENEFITS QUANTIFICATION

Studies have shown that Green Stormwater Infrastructure (GSI) not only improves water quality and reduces stormwater runoff, but also provides social and ecological benefits, such as improving aesthetics, creating green jobs, and increasing biodiversity. These GSI co-benefits may be more of interest than water quality and runoff to stakeholder communities and thus should be incorporated in the urban stormwater management scheme. However, what benefits are important to the communities and how important are they may vary from one community to another, depending on the demographic characteristics and geographical scale of the community (Gómez-Baggethun and Barton, 2013).

Co-benefit identification and ranking. We initially worked with our community advisory board to obtain feedback on how perceptions of co-benefits may vary among diverse community groups. During the first advisory board meeting, co-benefits were discussed and written comments were collected. Twenty-three community benefits or concerns were identified (Table 1) which cover most benefits found in literature. To prioritize the co-benefits, we conducted an importance survey of GSI co-benefits in the second advisory board meeting. The survey asks the respondents to score from 0 to 4 for each benefit and cost by pair comparison, i.e. the one with score 4 is strictly more important than the one with score 3 and so forth. 0 means not at all important and 4 means very important. The responses were collected and compiled immediately after submission. Board members then verbally expressed their ideas about important benefits and costs during a follow-up discussion. Table 2 shows the highest rated benefits with corresponding average scores and key metrics.

"Improving water quality" was ranked highest with an average score of 3.93. Interestingly, "increasing community amenities" and "reducing inequality" ranked second and third, respectively, ahead of "reducing runoff," which may challenge some traditional engineering thinking in stormwater management. That eight are social-economic concerns suggests that some communities may value social benefits more than environmental benefits. Clearly, a necessary requirement for a model of effective GSI implementation is accurate representation of these social-economic benefits.

Metrics. Some benefits can be easily quantified through direct measurements and simulations (e.g. water quality, runoff reduction), while others are more difficult to quantify (e.g. biodiversity, community amenity, equality). We note that the co-benefits may involve several metrics and may or may not be reduced into a single metric (Gómez-Baggethun and Barton, 2013). However, to inform decision making, it is helpful to use indices that are commonly used in describing the co-benefits and are easy to communicate. For example, to describe energy saving, kWh and MJ are both suitable units for electricity and heating, respectively. But, to describe biodiversity, we may need to quantify both biomass and the number of species, or simply the wiliness to pay (WTP). Monetary value is sometimes preferable and is often used as a proxy for benefits like biodiversity and amenity, because of their simplicity. However, the choices of metrics depend on the application. Table 2 also includes examples of commonly used metrics for co-benefits. Defining conditions and contexts where different values may be combined using single metrics and defining boundaries within which different valuation approaches can be consistently combined, are crucial for GSI research (Gómez-Baggethun and Barton, 2013), but they are beyond the scope of this paper.

The economic methods commonly used in benefit valuation are revealed preference methods (e.g. hedonic pricing), stated preference methods (e.g. contingent valuation and travel cost method), and avoided cost analysis (Wise et al., 2010), each of which may be appropriate in different situations. Hedonic pricing is most commonly used in impact analysis on property value; contingent valuation can apply on benefits without direct measurements, e.g. aesthetics, amenity, and biodiversity; and avoided cost analysis can be seen in assessments of cost saving in wastewater treatment using GSI and in rain water harvesting. Nonetheless, the values generated from economic methods are not necessarily comparable. For example, 50% biodiversity and 50% runoff reduction is not the same as 0% biodiversity and 80% runoff reduction though their monetary values may be equal. Therefore, it is often preferable to keep tracking the value of each benefit category independently and not to combine them into one single unit.

Benefit ranges from literature. Our initial efforts at quantifying co-benefits focus on obtaining ranges of co-benefits from literature, as shown in Table 3. These ranges can be used as upper and lower bounds to construct initial estimates of saturation functions. Note that community amenity, equality, aesthetics, property values, and flooding-related impacts are not listed because they are highly dependent on local social-economic and hydrologic characteristics.

NEXT STEPS

Co-benefit measurement. Spatial analysis of GSI benefits will focus on three potential impacts of GSI projects: changes in property values, changes in neighborhood health statistics, and changes in overall amount of greenspace in communities. A large body of research has demonstrated that parks and other greenspaces often contribute to increased property values in surrounding communities (Crompton, 2001, 2005), though these impacts have sometimes been shown to differ based on other neighborhood characteristics (Conway, et al., 2008; Heckert & Mennis, 2012; Troy & Grove, 2008). Insofar as GSI projects create new greenspaces, there is reason to believe that they will positively impact property values.

Access to neighborhood greenspaces has also been shown to have positive health benefits (Branas et al., 2011; Hartig, et al., 1991; Maas, et al., 2006; Mitchell & Popham, 2007). The area's only existing health database, the Public Health Management Corporation's Southeastern Pennsylvania Health Survey, provides survey data at the census tract level. Statistical techniques including difference-in-differences analysis and hierarchical linear modeling are being applied to determine whether health outcomes as reported to PHMC have changed in association with the implementation of GSI projects, similar to the approach used by Branas et al. (2011) to measure impacts of greening vacant lots on health and crime.

Additional benefits of GSI might include such intangibles as increased neighborhood satisfaction and increased sense of safety (Kuo, Bacaicoa, & Sullivan, 1998; Kuo, Sullivan, Coley, & Brunson, 1998; Sullivan, et al., 2004). We will use geographic information systems to quantify the overall increase in greenspace in communities that is attributable to the GCCW program as a proxy for improved quality of life. This information will also be combined with the results of our community based research efforts (described above) to develop a framework for more explicitly quantifying potential quality of life impacts of GSI.

GSI costs. The costs of implementing GSI in urban environments are highly variable and they depend on a number of interrelated factors, including site location, the type of GSI practice, and other site specific factors including project scale. These factors can introduce significant uncertainty into planning level decision tools, but this uncertainty is often poorly quantified and rarely explicitly incorporated into decision analysis. We are developing a calibrated cost model that can quantify uncertainties associated with GSI design and construction costs, based primarily on the analysis of built GSI projects in Philadelphia. The work includes collecting and synthesizing existing cost data from Philadelphia Water Department and other local sources, and developing regression models to predict cost based on several predictor variables including GSI practice type, setting (e.g., on vs. off right-of-way, park vs. commercial setting, etc.), scale, and location (e.g., neighborhood, planning district, etc.) We expect this work to generate useful relationships between planning level variables and GSI costs, which will then be explicitly incorporated into the StormWISE model (i.e., embedded into the model's benefit functions).

StormWISE extensions. Benefit functions representing direct runoff reduction benefits and co-benefits are incorporated simultaneously in the StormWISE model to produce a multiobjective triple bottom line analysis that generates trade-off curves showing, for example, how achieving desired levels of high-priority benefits can require decision makers to accept reductions in other, lower priority benefits, when the investment budget is fixed. Feedback obtained from our community advisory board will help us prioritize benefits, which will facilitate the development of GSI implementation strategies that reflect the values of the communities that are served.

REFERENCES

Burns, P. & Flaming, D. (2008). "Water Use Efficiency and Jobs," Economic Roundatable.

Branas, C. C., Cheney, R. A., Macdonald, J. M., Tam, V. W., Jackson, T. D., & Ten Have, T. R. (2011). "A difference-in-differences analysis of health, safety, and greening vacant urban space." *American Journal of Epidemiology*, *174*(11), 1296–1306.

Clark, C., Adriaens, P., & Talbot, F. B. (2008). "Green roof valuation: a probabilistic economic analysis of environmental benefits." *Environmental science & technology*, *42*(6), 2155-2161.

Conway, D., Li, C. Q., Wolch, J., Kahle, C., & Jerrett, M. (2008). "A spatial autocorrelation approach for examining the effects of urban greenspace on residential property values." *The Journal of Real Estate Finance and Economics*, *41*(2), 150–169.

Crompton, J. L. (2001). "The impact of parks on property values: empirical evidence." *Journal of Leisure Research*, *33*(1), 1–31.

Crompton, J. L. (2005). "The impact of parks on property values: empirical evidence from the past two decades in the United States. *Managing Leisure*, *10*(4), 203–218."

Foster, J., Lowe, A., & Winkelman, S. (2011). "The value of green infrastructure for urban climate adaptation." *Center for Clean Air Policy*, *February*.

Getter, K. L., Rowe, D. B., Robertson, G. P., Cregg, B. M., & Andresen, J. A. (2009). "Carbon sequestration potential of extensive green roofs." *Environmental science & technology*, *43*(19), 7564-7570.

Garrison, N., Kloss, C., Lukes, R., & Devine, J. (2011). "Capturing rainwater from rooftops: an efficient water resource management strategy that increases supply and reduces pollution." *National Resources Defense Council*, 1-25.

Gómez-Baggethun, E., & Barton, D. N. (2013). "Classifying and valuing ecosystem services for urban planning." *Ecological Economics*, *86*, 235-245.

Hadka, D. and P. Reed (2013). "Borg: an auto-adaptive many-objective evolutionary computing framework." *Evolutionary Computation*, 21(2), 231-259.

Hartig, T., Mang, M., & Evans, G. W. (1991). "Restorative effects of natural environment experiences." *Environment and Behavior*, *23*(1), 3–26.

Heckert, M., & Mennis, J. (2012). "The economic impact of greening urban vacant land: a spatial difference-in-differences analysis." *Environment and Planning A*, *44*(12), 3010–3027.

Hewes, W.. (2008). “Creating Jobs and Stimulating the Economy through Investment in Green Water Infrastructure,” American Rivers, Inc.
Kuo, F. E., Bacaicoa, M., & Sullivan, W. C. (1998). “Transforming inner-city landscapes: trees, sense of safety, and preference.” *Environment and Behavior, 30*(1), 28–59.
Kuo, F. E., Sullivan, W. C., Coley, R. L., & Brunson, L. (1998). “Fertile Ground for Community: Inner-City Neighborhood Common Spaces.” *American Journal of Community Psychology*, *26*(6), 823–851.
Maas, J., Verheij, R. A., Groenewegen, P. P., De Vries, S., & Spreeuwenberg, P. (2006). “Green space, urbanity, and health: how strong is the relation?” *Journal of Epidemiology and Community Health, 60*(7), 587–92.
McGarity, A.E. (2012). "Storm water investment strategy evaluation model for impaired urban watersheds." *J. Water Resour. Plann. Manage.,* 138(2), 111-124.
McGarity, A.E. (2013). "Watershed systems analysis for urban stormwater management to achieve water quality goals." *J. Water Resour. Plann. Manage.,* 139(5), 464-477.
McGarity, A.E. and McGarity, M.Z. (2013). “Benefit functions for optimizing watershed investments to improve water quality.” *Proceedings of the World Environmental & Water Resources Congress*, Environmental and Water Resources Institute, American Society of Civil Engineers, Cincinnati, OH, 2013.
Mitchell, R., & Popham, F. (2007). “Greenspace, urbanity and health: relationships in England.” *Journal of Epidemiology and Community Health*, *61*(8), 681–3.
Phillipson, J., P. Lowe, A. Proctor, and E. Ruto (2012). “Stakeholder engagement and knowledge exchange in environmental research,” *Journal of Environmental Management,* 95(1): 56-65.
Rosenfeld, P. (1992). “The potential for transdisciplinary research for sustaining and extending linkages between the health and social sicences.” *Soc Sci Med*, 35(11), 1343-1357.
Stratus Consulting, Inc. (2009). “A triple bottom line assessment of traditional and green infrastructure options for controlling CSO events in Philadelphia’s watersheds,” prepared for City of Philadelphia Water Department.
Sullivan, W. C., Kuo, F. E., & DePooter, S. F. (2004). “The Fruit of Urban Nature: Vital Neighborhood Spaces.” *Environment and Behavior, 36*(5), 678–700.
Troy, A., & Grove, J. M. (2008). “Property values, parks, and crime: A hedonic analysis in Baltimore, MD.” *Landscape and Urban Planning*, *87*(3), 233–245.
Yao, Liang, et al. "Effective green equivalent—a measure of public green spaces for cities." *Ecological Indicators* 47 (2014): 123-127.
Wise, S., et al. "Integrating valuation methods to recognize green infrastructure’s multiple benefits." *Center for Neighborhood Technology, April*(2010)

ACKNOWLEDGEMENT

This publication was made possible by USEPA grant 83555501. Its contents are solely the responsibility of the grantee and do not necessarily represent the official views of the USEPA. Further, USEPA does not endorse the purchase of any commercial products or services mentioned in the publication.

Table 1. Community benefits/concerns identified in the first Advisory Board meeting

Category	GSI Benefit/Cost Concerns			
Eco-Environmental	1	Improving water quality	5	Reducing greenhouse gas (GHG) emission
	2	Reducing runoff	6	Increasing habitat area for native species
	3	Increasing groundwater recharge	7	Increasing biodiversity
	4	Reducing soil erosion		
Social-economic	1	Reducing flood impacts	9	Increasing community amenities
	2	Improving air quality	10	Creating green jobs
	3	Saving water	11	Increasing access to recreational uses of receiving water
	4	Saving energy	12	Enhancing environmental education
	5	Reducing heat stress	13	Enhancing equality
	6	Improving aesthetics	14	Inconvenience to community
	7	Increasing food access	15	Causing safety concerns
	8	Increasing property value	16	Increase expanse due to GSI installation and maintenance

Table 2. Top-10 Important Benefits/Costs With Scores and Commonly Used Metrics

Rank	Benefit/Cost	Avg. Score	Commonly used metrics[a]
1	Improving water quality	3.93	TSS: kg/y, TP:kg/y, TN:kg/y; Avoided Cost:$/y
2	Increasing community amenities	3.71	Hedonic Pricing: $/y; Willingness To Pay:$/y
3	Reducing inequality	3.50	Area of green space: m^2/person
4	Reducing runoff	3.43	m^3/y
5	Creating green jobs	3.43	Job-y, $/y
6	Improving aesthetics	3.29	Willingness To Pay:$/y
7	Increasing property value	3.07	$/y
8	Reducing flood impacts	3.00	Willingness To Pay:$/y; Avoided Cost: $/y
9	Improving air quality	2.93	NO_2:kg/y; SO_2:kg/y;O_3:kg/y; PM_{10}: kg/y
10	Reducing heat stress	2.93	Excess Mortality/y; ℃

Source: a. Own elaboration based on literature (Stratus Consulting Inc., 2009; Wise et al., 2010; Gómez-Baggethun and Barton, 2013;Yao et al., 2014)

Table 3-1 Co-benefit Ranges for GSI

Rank	Benefit/Cost	Co-benefit Ranges		
		Constructed Wetland/Rain Garden/Bioretention	Pervious Pavement /Impervious Removal	Rain Barrels/Cistern
5	Creating green jobs	12.5-13.1 job-year/1M$[a]	12.5-13.1 job-year/1M$[a]	N/A
9	Improving air quality	NO_2:0.18-0.5kg; SO_2:0.1-0.31kg[b]; PM_{10}:0.08-0.16kg; O_3:0.07-0.14kg[b]	N/A	N/A
10	Reducing heat stress	Positive but without reliable data	Positive but without reliable data	N/A
12	Increasing access to recreational uses of receiving water	247,200$/Ha[b]	N/A	N/A
14	Saving Energy	Electricity:48-268 kWh/tree[b]; heating:333-3,519MJ/tree[b]	N/A	Save energy from preventing water treatment and distribution
15	Reducing GHG emission	102-413 kg-CO_2/tree[b]	N/A	N/A
18	Saving Water	N/A	N/A	Annual rainfall*0.8[c]

Table 3-2 Co-benefit ranges for GSI

Rank	Benefit/Cost	Co-benefit Ranges	
		Green Roof	Riparian Buffer Filter Strip
5	Creating green jobs	19.7 job-year/1M$[d]	12.5-13.1 job-year/1M$[a]
9	Improving air quality	0.27 kgNO_2/m^2/y (Variance: 0.17)[e] NO_2:7-40%;PM_{10}:11-60%[e]	NO_2:0.18-0.5kg; SO_2:0.1-0.31kg[b]; PM_{10}:0.08-0.16kg; O_3:0.07-0.14kg[b]
10	Reducing heat stress	Positive but without reliable data	N/A
12	Increasing access to recreational uses of receiving water	N/A	$47,200/Ha[b]
14	Saving Energy	Electricity:3.3 kWh/m^2 [e] Heating:4.9-30kWh/m^2 [e]	Electricity:48-268 kWh/tree[b]; Heating:333-3,519MJ/tree[b]
15	Reducing GHG emission	0.336-0.413kg/m^2 [f]	102-413 kg-CO_2/tree[b]
18	Saving Water	N/A	N/A

Source: Own elaboration based on literature (a. Burns and Flaming, 2008; b. Wise et al., 2010; c. Garrison et al., 2011; d. Hewes, 2008; e. Clark et al., 2008; f. Getter et al., 2009)