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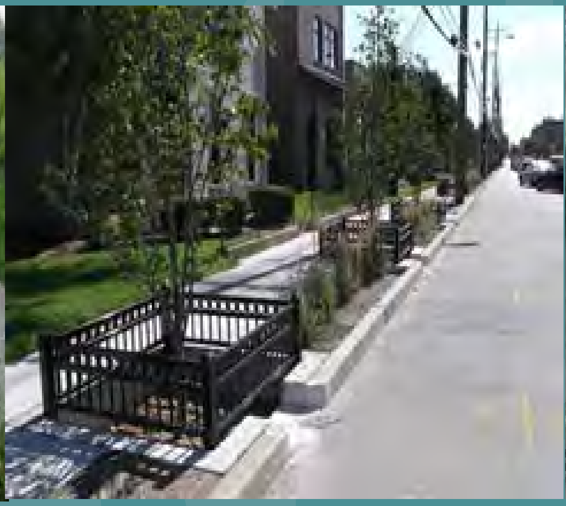
Green Infrastructure for Stormwater Control: Gauging Its Effectiveness with Community Partners


Office of Research and Development
Water Supply and Water Resources Division

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Green Infrastructure for Stormwater Control: Gauging its Effectiveness with Community Partners

Summary of EPA GI Reports

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ABSTRACT

This document is a summary of the green infrastructure reports, journal articles, and conference proceedings published to date. It is our intention to update this summary as we have more information to share and when relevant publications are completed. The Environmental Protection Agency's Office of Research and Development has an ambitious research agenda to continue quantifying the performance of green infrastructure during the next five years. This report contains the synopses of the significant findings, lessons learned, and guidance to communities based on a number of research efforts that included one roof downspout disconnection, three green plus one conventional roof, two rain garden and bioretention, and two permeable pavement research efforts across eight EPA regions. Some of the research addressed water quality changes, such as bacteria, chlorides, solids, nutrients, and metals through individual storm control measures. Others studied the aggregate hydrologic response from a collection of green infrastructure stormwater control measures over areal spaces of one to 100 acres over a period of one to seven years. One study focused on the impact of development due to the conversion of farm to suburbs for ten years. In addition to the green infrastructure performance studies, twelve sites were systematically characterized for disturbed urban soil infiltration rates. While this is the most comprehensive summary of the Office of Research and Development's research efforts to date, the findings of the research for the next five years will greatly increase our ability to apply green infrastructure.

DISCLAIMER

The U.S. Environmental Protection Agency, through its Office of Research and Development, funded and managed, or partially funded and collaborated in, the research described herein. It has been subjected to the Agency's administrative review and has been approved for external publication. Any opinions expressed in this document are those of the author(s) and do not necessarily reflect the views of the Agency, therefore, no official endorsement should be inferred. Any mention of trade names or commercial products does not constitute endorsement or recommendation for use.

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LIST OF ABBREVIATIONS

ASCE	American Society of Civil Engineers
BACI	Before-After-Control-Impact
BMP	Best Management Practices
CATE	Cities and the Environment
CN	Curve Number
CRADA	Cooperative Research and Development Agreement
CSO	Combined Sewer Overflow
CSPA	Clarksburg Special Protection Area
DEP	Department of Environmental Protection
DOI	Digital Object Identifier
EEC	Edison Environmental Center
EISA	Energy Independence and Security Act
EO	Executive Order
EPA	Environmental Protection Agency
ET	EvapoTranspiration
GI	Green Infrastructure
HSPF	Hydrological Simulation Program Fortran
JAWRA	Journal of the American Water Resources Association
KCMO	Kansas City Missouri University
KCWSD	Kansas City Water Services Department
LID	Low Impact Development
LiDAR	Light Detection and Ranging
mm	millimeter
MSD	Metropolitan Sewer District
NPDES	National Pollutant Discharge Elimination System
NYC	New York City
ORD	Office of Research and Development
PA	Porous Asphalt
PC	Pervious Concrete
PICP	Permeable Interlocking Concrete Pavement
RARE	Regional Applied Research Effort
RWH	Rain Water Harvesting
SCM	Storm Control Measures
SSC	Suspended Solids Concentration
SSURGO	Soil Survey Geographical
SUDS	Sustainable Urban Drainage Systems
SUSTAIN	System for Urban Stormwater Treatment and Analysis Integration
SWMM	StormWater Management Model
TC	Total coliform
TDR	Time Domain Reflectometers
TSS	Total Suspended Solids
U.S.	United States
USGS	United States Geological Survey
UV	Ultra Violet
VELMA	Visualizing Ecosystems for Land Management Assessment
VMC	Volumetric Moisture Content
WQ	Water Quality

LIST OF ABBREVIATIONS, CONTINUED

WSUD	Water Sensitive Urban Design
WWF	Wet Weather Flow
XPSWMM	XP's StormWater Management Model

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EXECUTIVE SUMMARY

Introduction

ORD has worked with numerous U.S. communities to study how green infrastructure (GI) can be utilized to improve the performance of currently failing wastewater systems, and to understand better the co-benefits of this approach to water management and related social, economic, and environmental ramifications. The American Society of Civil Engineers (ASCE) evaluated the water infrastructure and gave the U.S. a grade of D – because most of our water infrastructure is nearing the end of its useful life.[1] Further, EPA has issued 849 combined sewer overflow (CSO) permits[2] that have aggressive deadlines to reduce CSO events that will be very expensive ($187.9B in the next 20 years) to achieve.[3] As communities develop land and alter land use, difficulties associated with managing stormwater can be expected to increase. "Gray" stormwater infrastructure is designed largely to move stormwater away from the built environment, whereas GI reduces the quantity and treats stormwater on site while delivering many other environmental, social, and economic benefits.[4] EPA recommends that communities use GI whenever or wherever it can be effective and economically advantageous for aging water infrastructure upgrades.[5] This document is a brief summary of EPA's GI-related research efforts and the results to date from these studies. More detail can be found in the references listed at the end of each summary. The research efforts are grouped by EPA Region and community. Each

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[1] American Society of Civil Engineers http://www.infrastructurereportcard.org/drinking-water/ accessed 7/20/2015
[2] EPA's Report to Congress on Implementation and Enforcement of the CSO Control Policy http://water.epa.gov/polwaste/npdes/cso/upload/csortcappsd_s.pdf accessed 7/2/2015
[3] Water Environment Federation http://www.wef.org/WaterProtectionReinvestmentAct_Summary_080112 accessed 7/21/2015
[4] http://water.epa.gov/infrastructure/greeninfrastructure/gi_why.cfm accessed 7/21/2015
[5] EPA http://yosemite.epa.gov/opa/admpress.nsf/3881d73f4d4aaa0b85257359003f5348/5390e840bf0a54d785257881004f96d1!OpenDocument accessed 7/20/2015

summary introduces the collection of papers, a brief description of the research performed, the research questions asked, and insight from the results of the research.

To manage stormwater in densely-populated and developed areas, civil engineers have focused on gray infrastructure to manage stormwater and efficiently move it offsite. They have sized and designed gray infrastructure (e.g., pipes, tanks, pumps, etc.) for centuries and have become very comfortable with such technologies. However, the U.S. has far less engineering experience with GI technologies as compared to traditional ”gray” infrastructure and there has been a push to utilize “green” technologies because they can be less impactful to the environment and may be economically advantageous to communities (i.e., lower installation and maintenance costs). Moreover, GI may be less disruptive to the hydrologic cycle because the intent often is to infiltrate the stormwater rather than move it offsite. Individual GI stormwater control measures (SCMs)[6] (e.g., disconnection of roof down spouts, rain gardens, green roofs, detention ponds, permeable pavement, etc.) have only been analytically studied for the last twenty years and studies measuring the aggregated response of many SCMs over large areas and for multiple years are extremely rare. The overarching goal of EPA’s GI research is to quantify the reduction in stormwater runoff and resulting changes in water quality and other environmental, economic, and social benefits, and to obtain engineering cost and design data.

EPA is examining the costs of design, installation, operation, maintenance, and replacement for GI with the intent to develop objective data that communities can use when

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[6] Storm Control Measures (SCMs). Many EPA documents use the term “Best Management Practice (BMPs)” for GI and Low Impact Development (LID). There has been some reluctance from the regulated community, academics, and even regulators to continue to use the term owing to the fact that the specific term “Best” implies a high level of expected performance. Some have referred simply to stormwater management practices. The National Research Council proposed the term stormwater control measures (SCM). However, as the Clean Water Act (CWA (1977) specifically refers to “Best Management Practices,” BMPs will be the legal name until the CWA is either amended or superseded. EPA web pages still refer to BMPs.

considering implementation of GI. To help communities make this decision, EPA is developing models, such as SWMM, VELMA, and HSPF, and Decision Support Tools, such as the National Stormwater Calculator, to predict the performance of GI. Communities rely on these models and tools to help them make what can be multibillion dollar decisions. For example, Kansas City, MO designed its $10 million 100-acre Middle Blue River pilot on SWMM predictions and, based on the performance of this 100-acre pilot, it will design its $2 billion, 20-year consent decree sewer upgrade.[7] EPA's stormwater modeling tools are very sophisticated, but EPA will continue to develop and improve some of these models through validation using field data at large spatial scales in an effort to assist communities in making sound decisions.

Presented in Table 1 are ORD GI projects with completed publications (i.e., reports and journal articles). ORD intends to update this document as more information becomes available when additional results are published. Some of ORD research sites such as Cincinnati, Cleveland, Detroit, Louisville, Edison, and Camden, are still active.

GI can be applied to new or retrofit instillations. The U.S. is a demographically and geographically diverse country, and as the map (Fig. 1) and the tables (Table 1 and 2) demonstrate, EPA has just started to examine the performance and effectiveness of GI under all the different demographic and geographic conditions throughout the U.S. Eventually, EPA hopes to provide information useful to communities of all sizes (i.e., population and area) and in all climatic regimes.

[7] Kansas City Water Services Department (KCWSD). 2013. Final Report Kansas City Overflow Control Program Middle Blue River Green Solutions http://www.burnsmcd.com/Resource_/PageResource/Overflow-Control-Program-Assistance/Final-Report-Kansas-City-Overflow-Control-Program-Middle-Blue-River-Basin-Green-Solutions-Pilot-Project-2013-11.pdf

Table 1. EPA has a number of community-based research efforts, each utilizing different GI SCMs, and of various sizes, in an attempt to quantify changes to stormwater runoff due to GI.

Number of Individual SCMs Evaluated Per Location						
Location	Dis-connection	Rain Gardens	Green Roofs	Bio-Retention	Permeable Pavement	Tree + Infiltration Planters
Edison, NJ		2	1[8]		3	
New York, NY			1			
State College, PA			6			
Clarksburg, MD[9]						
Louisville, KY					14	32
Cincinnati, OH	166	82			2	
Cleveland, OH[10]		12				
Detroit, MI						
Austin, TX	1					
Kansas City, KS		78		51	2	
Denver, CO			1			

[8] The Edison Roof was not a green roof but a conventional roof. ORD characterized the water quality of the roof runoff of a conventional roof for comparison to a possible future green roof.
[9] Role of Urbanization
[10] Demolished Building

Table 2. EPA has a number of community-based research efforts, each utilizing different GI SCMs, and of various sizes, in attempt to quantify changes to water quality in stormwater runoff.

Water Quality Parameters Studied						
Location	Dis-connection	Rain Gardens	Green Roofs	Bio-retention	Permeable Pavement	Tree Planters
Edison, NJ[8]		Nutrients	Nutrients, Metal		Chlorides, Nutrients, Metals, Total Suspended Solids	
New York, NY			Nutrients			
State College, PA			Nutrients			
Clarksburg, MD[11]						
Louisville, KY					Nutrients	Nutrients
Cincinnati, OH		Nutrients Metals, PAHs, Total Suspended Solids, E. coli				
Cleveland, OH[12]						
Detroit, MI						
Austin, TX	Bacteria					
Kansas City, KS		Nutrients, Metals, Total Suspended Solids		Nutrients, Metals, Total Suspended Solids		
Denver, CO			Nutrients			

[11] Role of Urbanization
[12] Vacant lots

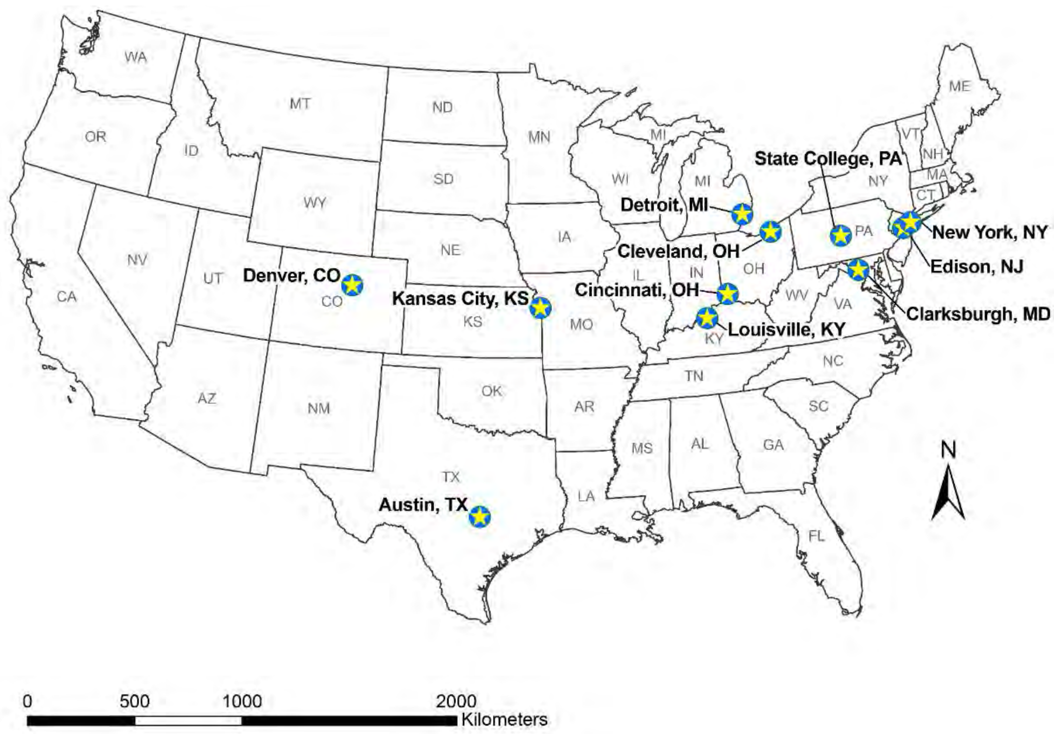

Figure 1. Map of EPA ORD green infrastructure research sites as of 2015.

Infiltration

A major site-specific property of GI often is the ability to infiltrate water. EPA's National Stormwater Calculator uses the USDA's SSURGO Soil database[13] to look up the infiltration rates of soils but this database contains undisturbed soils. However, many urban soils have been disturbed, altered, or relocated and most urban soils have been compacted which reduces their ability to infiltrate water. To understand how soil in urban systems perform when used in GI implementation, each of the major soil orders in the continental U.S. and Puerto Rico have been characterized. To date, EPA has systematically measured the infiltration rates and

[13] http://www.ncgc.nrcs.usda.gov/products/

characterized the soils in 12 cites (Portland, ME; Camden, NJ; Atlanta, GA; New Orleans, LA; Detroit, MI; Cleveland, OH; Cincinnati, OH; Omaha, NE; Junction City, KS; Phoenix, AZ; Tacoma, WA, and San Juan, PR). In addition to these cities, EPA has measured the urban soil infiltration rates at many of their research sites, including Edison, Cincinnati, Louisville, and Kansas City. ORD has studied GI sites located in densely urban, suburban, and more natural sites.

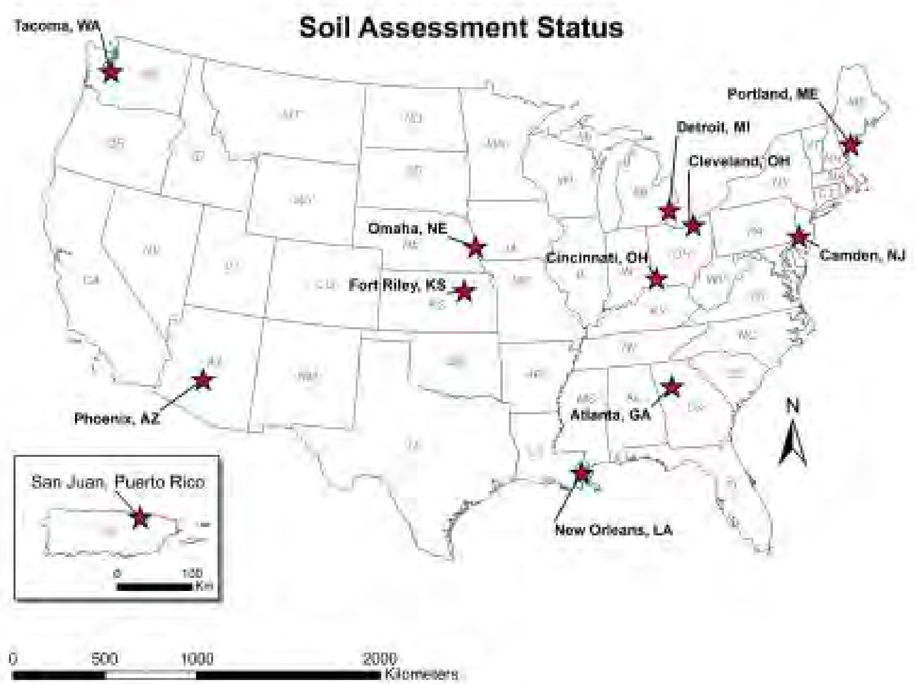

Figure 2. Twelve cities, representing each of the major soil orders, were sampled to characterize altered urban soils.

Hydrology

Most of the GI research efforts studied the hydrology of specific types of low impact development (LID) SCMs, such as green roofs or permeable pavement. Much of the data collected to date can be used to determine the maximum amount of rain specific SCMs can completely infiltrate, and, conversely, what it cannot. Furthermore, these data can be used to calibrate and validate the SWMM LID modules to help figure out when and where the models work best and caveats to consider when using the models. The Cincinnati, Louisville, and Kansas City GI research efforts have investigated the performance and effectiveness at a watershed scale by examining the response of numerous LIDs rather than focusing on the performance of one individual type of SCM.

Water Quality

The Edison, Cincinnati, Louisville, and Kansas City research efforts investigated nutrient effects but also metal and total suspended solids reductions through permeable pavement, rain gardens, and bioretention SCMs. Most of the GI water quality (WQ) data collected at municipalities have significant variance in the inlet, outlet and percent removal event mean concentrations. Statistical analyses of these data are often hampered by the fact that only a few samples could be collected or where experimental replication is not feasible or within budget. The Edison data set has higher numbers of samples with statistically comparable values for chloride, metals, and nutrient data.

Place-based

Place-based field research requires a time commitment as collaborations are established, baseline measurements are recorded, GI is installed, and storm events are monitored. Given adequate time, these studies can be used to quantify the performance and effectiveness of GI and used to improve models and help communities make decisions. Working with municipalities offers many opportunities for synergistic monitoring and advancement of GI implementation for

EPA. However, there can be coordination challenges when construction schedules are delayed and Federal contracts end.

The field-based research efforts performed to date have been very insightful, but are just beginning to examine all of the variation and diversity of stormwater management conditions in the U.S. EPA is gaining a better understanding of the intricacies of stormwater management and that there is not a one-size-fits-all solution.

Guidance for stakeholders and decision makers

GI research is a long-term, complicated, and expensive undertaking and EPA is working intensely to understand better how the different types of GI perform under different environmental settings and to provide a better estimate of expected results from its use. Stakeholders and decision makers need to understand that there are different levels of performance and effectiveness that can be achieved from GI and that there are solutions that can be implemented at multiple spatial scales and in multiple configurations. Ideally, EPA will provide case studies as examples for communities of similar social, economic, demographic, and geographic characteristics to help them identify options for dealing with stormwater management. Communities need to recognize that GI provides a number of ecosystem services that are not restricted solely to stormwater management and they should consider these as well when deciding which GI SCMs to use. Although many of the challenges and resulting solutions are generalizable, each community deals with issues that may be unique to them and they must use the best available information to address and resolve these issues.

Future needs (i.e., new questions, where our knowledge is lacking, etc.)

Although EPA is gaining a better understanding and appreciation of GI for stormwater management, quite a few knowledge gaps need to be filled to provide information that is more useful for communities. Because the U.S. is so diverse and the number of GI SCMs are great, EPA needs to determine how repeatable the performance and effectiveness of certain practices are in different climatic regimes. Specifically, much of the EPA GI research has been in the eastern U.S., in wet (i.e., mesic) climates. EPA ORD has not examined arid or semi-arid regions nor does EPA have an understanding of the benefits and drawbacks of infiltrating more stormwater. There could be water quality and water quantity effects and these need better understanding. Ideally, EPA will provide models that have been fully validated and that clearly express the strengths and weaknesses of different GI types, and where they work best so communities can use the information to make sound decisions and better manage their systems. This will require additional research in areas of the country that have largely been ignored. The issue is further complicated by a changing climate and resulting nonstationarity (i.e., past climate conditions are not a predictor of future climate conditions) and EPA research needs to help communities prepare for an uncertain future.

Community Access/General Interest

One of the more problematic issues any new concept or practice faces is the evolution of the terminology associated with it. As the topic of watershed drainage and its connection to stormwater management is increasingly discussed by researchers and decision-makers alike, new, multi-worded terms can muddle communication and slow development. Another area with room for improvement lies in the lack of integration between urban design and the developing field of urban ecology. Traditionally, environmental consultants, who generally do not conduct scientific research, are providing outdated and non-site-specific information to city planners, designers, and engineers. This leaves out important ecological-specific research an urban ecologist could provide. Thirdly, there are many socio-economic and political barriers and benefits to GI as an alternative to gray infrastructure-based stormwater management. These papers address the complexities and opportunities regarding the increased interest and implementation of GI systems as sustainable solutions to stormwater management.

The scope of the papers listed in this section is conceptual and broad, meant to encompass the challenges and potential opportunities of implementing any kind of GI into any type of urban environment. Case studies in Cleveland and Milwaukee are provided as examples to help explain how stakeholders can overcome barriers to GI application. Questions of how to translate new and often localized terminology for use in larger scale applications, and ways to integrate urban ecological research directly into the planning process were also asked.

As the topic of watershed drainage develops and evolves and GI becomes a more standardized practice, it is important for end-users of this information to understand the terminology and exactly what is being discussed. The ecological implications of urban development are also an important product of both urban and GI design and should involve direct urban ecological research. It is also essential to note that it is still possible for stakeholders to see the value of GI, and to implement GI as a method of stormwater management, even in the face of a combination of financial, administrative, political, and technical challenges.

Due to a conscious effort to use GI as a tool for the mitigation of stormwater overflows, communication, stakeholder involvement, and accuracy of ecological impact assessments are integral to laying a promising foundation for the future of GI methods.

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Keeley, M, A Koburger, D Dolowitz, D Medearis, D Nickel, and WD Shuster. 2013. Perspectives on the use of green infrastructure for stormwater management in Cleveland and Milwaukee. *Environmental Management* 51:1093-1108.

Summaries of Specific Research Efforts and References

Region 2 - Edison, NJ

The Edison Environmental Center (EEC) is a U.S. EPA facility in Edison, New Jersey.[14] This site acts as a test bed for equipment and techniques before implementing them in field settings where EPA has less control over the location. With ownership of the facility, EPA can construct experimental GI SCMs to test different design features and include replication to increase statistical power. There are four GI systems at EEC from which research results have recently been published: permeable pavement systems, bioinfiltration areas, rain gardens, and cisterns.

In a retrofitted one-acre parking lot, EPA installed three common permeable pavement types [permeable interlocking concrete pavement (PICP), pervious concrete (PC), and porous asphalt (PA)] in 140-ft long head-to-head parking rows designed to receive run-on from the upgradient impervious hot-mix asphalt driving lane. A primary goal of this research was to evaluate the effect that permeable pavement type had on the infiltrate water quality composition and hydrologic response when all three were exposed to the same conditions and rainfall events.

Eight journal articles and one EPA report have been produced on GI research conducted at the Edison Environmental Center (EEC) with most publications describing results associated with the permeable pavement systems. Hydrologic performance outputs have evaluated surface infiltration capacity, surface clogging dynamics, and evaporation. Surface infiltration capacity was statistically different by pavement type (PC – 4,800 cm/h; PICP – 2,100 cm/h; and PA – 150

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[14] This facility provides an added level of safety and control for research activities. There is no concern for vandalism or theft, and areas can be blocked to conduct tests on pavement surfaces.

cm/h), but each could sufficiently infiltrate runoff from the most extreme rainfall intensity if the surface was not clogged. Based on visual observations, surface clogging occurred as sediment from the drainage area was transported with run-on onto the permeable pavement surface and blocked the pore space.

Embedded soil moisture sensors [time domain reflectometers (TDRs)] in the open-graded aggregate below the permeable pavement surface documented this observation through remote monitoring techniques. A water balance of captured infiltrate from lined permeable pavement sections was calculated, and it showed that evaporation from permeable pavement systems was measurable, albeit small (about 5% on an annual basis), and that the PC surface had more evaporation than the other two surfaces.

Published water quality performance reports are limited to chloride, but results associated with other sampled stressors are in press (nutrients and pH) or under production (metals and semi-volatile organic compounds). Chloride concentrations in the infiltrate approached 10,000 mg/L for the rain event that immediately followed a snow event where de-icing salt was applied. Chloride persisted in the infiltrate year round, and it remained above the chronic toxicity threshold for freshwater aquatic life (230 mg/L) into April. A power regression with cumulative rainfall since the previous storm event best described the chloride flush through the permeable pavement system.

A portion of impervious asphalt from this parking lot and the roof from an adjacent building drain into six bioinfiltration areas that were constructed side-by-side with three different ratios of drainage area to bioinfiltration surface area to test the effect of size on hydrologic performance. Embedded soil moisture sensors in the six bioinfiltration areas with three different sizes demonstrated that infiltration was concentrated near the inlet. These results, in combination with meteorological observations and plant size measurements, demonstrated that shrubs closest to the inlet correlated with larger growth patterns than the shrubs farther from the inlet primarily because the closer shrubs received substantially more runoff. Runoff provides a source of water and nutrients and both are essential for plant growth.

A set of eight mesocosm[15] rain gardens were constructed with a partial factorial design to test whether any of the four design treatments (size, presence of a carbon source layer, vegetation type, and drainage configuration) influenced nitrogen fate in underdrain effluent. Collected stormwater runoff from a parking lot at the neighboring community college was used to simulate two event sizes. Lastly, a cistern was installed to provide water for cooling water tower usage and other non-potable uses. The rain water capture and use research was not designed with replication but was a research opportunity to monitor use from a system specifically installed to address Section 438 of the Energy Independence and Security Act of 2007 (EISA) and the presidential Executive Order (EO) (no. 13148, "Greening the Government through Leadership in Environmental Management" issued 4/21/2000) to improve environmental performance.

The eight mesocosm rain gardens illustrated that the presence of an internal water storage zone significantly reduced combined nitrate and nitrite mass, but it significantly increased ammonia quantity. Overall, there was no significant difference in total nitrogen quantity for the presence or absence of an internal water storage zone, and the additional carbon source layer did not have a significant effect on nitrogen removal.

The use of collected roof runoff and condensate recovery led to a substantial reduction of potable water used for cooling tower makeup water during the warmer months. There was an average annual 8.3% decrease in potable water usage, in addition to measures to decrease potable

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[15] Four were 4255 L in volume and the other four were 2785 L.

water usage previously instituted. The primary source of contamination in roof runoff appears to be atmospheric, as rainwater concentrations were correlated with most observed constituents in the roof runoff. There were some building material components (i.e. copper gutters and galvanized sheet metal), which contributed to the significantly larger observed copper and zinc runoff concentrations, respectively.

As guidance for stakeholders and decision makers, site-specific conditions will govern maintenance frequency for permeable pavement systems. The permeable pavement site at the EEC, with a limited sediment supply, has been in operation for more than 5.5 years without needing maintenance to alleviate surface clogging. Surface clogging begins at the upgradient edge (impervious surface/permeable pavement interface) and progresses downslope, so this mechanism should be considered when selecting locations to manually test surface infiltration rates for considering when maintenance is needed. The surface of the PC has demonstrated significant unraveling, however, this observation has not been included in a publication or report. When bioinfiltration areas are oversized, it increases the likelihood that vegetation planted farthest from the runoff source will experience water-deficit stress, which could limit growth, cause mortality, or necessitate additional maintenance (i.e., irrigation and fertilization), so bioinfiltration design should consider plant placement and species selection relative to the proximity of the runoff source.

Future needs associated with this research include: (1) exploring the fate of stressors as water percolates to groundwater, (2) evaluating fate of microorganisms in permeable pavement systems, (3) determining an efficient method to identify where manual surface infiltration tests should be conducted in order to evaluate maintenance needs, (4) finding more suitable uses for harvested rainwater, and (5) evaluating long-term water quality data from the permeable pavement research site to determine if there are seasonal effects of changes with age.

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Region 2 - New York, NY

This Region 2 Regional Applied Research Effort culminated in an ORD final report on the topic of green roofs (EPA 2014). This report documents the quantity and quality of runoff from a suite of urban green roofs located in New York City (NYC). An overall research goal was to assess green roof performance on actual urban rooftops, which have lower and more typical runoff dimensions to drains and are subject to more realistic urban environmental conditions (i.e., light, wind and rain shadows), as opposed to test plots at academic research campuses or laboratories. The urban green roofs were located throughout NYC representing three of the five boroughs (The Bronx, Manhattan, and Queens). All of the areas monitored drained to combined sewers, so reductions in roof runoff theoretically should help reduce CSO's.

This report presents analysis of water benefits from an array of observed green and control (non-vegetated) roofs throughout NYC. Water quantity and water quality were measured in the runoff of green and control roofs. The sites were located on a variety of buildings and represent a diverse set of available extensive green roof installation types, including vegetated mat, built up, and modular tray systems. Plant types on individual roofs were also different.

This work confirms that deploying green roofs on existing buildings can reduce the negative impacts of urban wet-weather flow (WWF), including water quality and water quality impacts in an urban environment. Findings for water quantity performance demonstrate that the modular tray system captured the lowest percentage of precipitation among all green roof systems for storms 0-20 mm in depth but was the highest for storms above 30 mm. Multi-year predictions indicated that on an annual basis, the built up system will retain the most rainfall, then followed by the modular tray system, and then the vegetated mat systems. The Natural Resources Conservation Service curve number (CN) method could not capture observed relative differences between the retention performances of the built up, modular tray and mat systems in different storm categories. Individually, the vegetated mat systems had 62% and 42% overall rainfall retention respectively, whereas the built up system had 56% and tray system 59%. The estimated long term rainfall capture of the system was between 37-60% for vegetative mats, 49-66% for built up, and 47-61% for trays.

Water quality monitoring indicated that the green roofs neutralized the acid rain as the pH of runoff from green roofs was consistently higher than that from the control roofs and precipitation with observed average pH's equal to 7.28, 6.27, and 4.82 for the green roofs, control roofs and precipitation, respectively. In general, observed nitrate and ammonium concentrations were lower in green runoff than in control roof runoff, with the exception of runoff from the built up system, which had higher nitrate concentrations than the control roof runoff. Overall, total P concentrations were higher in green roof runoff than control roof runoff. Micronutrients and heavy metals were detected either at very low concentrations or not at all.

While there appears to be more chemical constituents present in green roof runoff than control roof runoff, there is an overall reduction in the volume of runoff from green roofs. Thus, the total mass of nutrient runoff from green roofs is less than that from non-vegetated roofs. As a result, the water quality benefits of green roofs are favorable in urban environments. The projected annual mass loading per unit rooftop area of nitrate, ammonium, and total phosphorous discharging from all five green roofs was considerably less than that from their respective control (non-green) roofs, due to the ability of green roofs to retain precipitation. Thus, green roof implementation could improve urban stormwater and subsequently urban receiving water quality if achieved at large areal scales. The green roofs of this study were all built on existing structures, so results of this study could be used for further retrofitting of existing structures with green roofs.

The continued monitoring of the urban green roofs that were part of this effort (funded as a Region 2 RARE award) will provide additional data needed to understand the evolving performance of urban green roofs with age, as well as the role of seasonality in green roof hydrology. Other recommendations for further study include undertaking relative cost-benefit analysis of green roofs versus other stormwater management technologies, more research experiments considering driving factors for water control such as substrate depth and water holding capacity, and continued studies that will optimize design with respect to maintenance and performance.

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Region 3 - Clarksburg, MD

This work is from the Clarksburg Monitoring Partnership, a collaborative research effort in the Clarksburg Special Protection Area (CSPA) in Montgomery County, Maryland. This effort is a partnership among the U.S. EPA; the U.S. Geological Survey, Eastern Geographic Science Center (EGSC); and the Montgomery County Department of Environmental Protection (DEP) along with other research partners. This ongoing research is focused on the use of high-resolution mapping of urban development using repeat acquisitions of digital orthoimagery and Light Detection And Ranging (LiDAR) data, high resolution mapping of SCMs and Best Management Practices (BMPs), streamflow and precipitation monitoring, and in-stream and in-pipe biological and water quality assessments.[16]

[16] EPA http://www.epa.gov/esd/land-sci/clarksburg01-05.htm.

This research is meant to evaluate the effectiveness of the County's Phase II BMPs implemented as a part of the Chesapeake Bay Watershed Implementation Plan for the National Pollutant Discharge Elimination System (NPDES) stormwater rules for municipalities with less than 100,000 people.[17] This research uses a Before-After-Control-Impact (BACI) study design to evaluate BMP performance over time during the construction (sediment control) and post-construction (stormwater control) phases of urban development.

The CSPA is one of four Special Protection Areas in Montgomery County. Clarksburg is a rapidly developing area where the County is undergoing urbanization in a "town center" pattern; concentrating development in a relatively small area of high density residences, businesses, services, infrastructure, and amenities while maintaining intact riparian buffers, agriculture, and forest patches to the greatest extent possible. The County uses adaptive management; where lessons learned from one development are applied to later development plans.

The Phase II BMPs investigated in the research are a mixture of gray infrastructure[18] and Green BMP Treatment Trains and are found in areas of higher development density whereas GI is more prevalent in areas of lower density development. Distributed BMPs are used to retain and infiltrate stormwater runoff rather than centralized retention basins.

In spite of the best efforts of the County, monitoring results in the first watershed developed in the CSPA show a major impact from the development during the construction phase. Lessons learned to date include the need for greater sediment control and more rapid

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[17] http://www.mde.state.md.us/programs/Water/StormwaterManagementProgram/Pages/Programs/WaterPrograms/sedimentandstormwater/storm_gen_permit.aspx.
[18] http://water.epa.gov/infrastructure/greeninfrastructure/gi_what.cfm

conversion of BMPs from construction phase to post-construction phase during the development process. Future development plans also call for both reducing the intensity of development and limiting development in headwater stream areas to try to protect water quality and stream biota (see Annual Reports listed below). Future monitoring will reveal the extent to which water quality and stream biota recover towards pre-construction levels in areas already built-out and whether the adaptive management implementation of previous lessons learned will help to mitigate the impacts of future development. Our plans are to maintain the monitoring work long enough to see changes that occur during long time scales.

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Region 3 - State College, PA

This Region 3 RARE research culminated in an ORD final report on the topic of green roofs (Berghage et al. 2009). The work for this research was carried out by the Penn State Green Roof Center of The Pennsylvania State University at University Park, PA. Specifically, this research investigated the design specifications and materials of green roofs used as stormwater control devices. This research was meant to gather field performance data from side-by-side structures to provide performance data for stormwater control by green roofs for both water quantity and quality. Six small-scale buildings were tested in agricultural fields which allowed for unobstructed wet weather data collection. Additionally this research explored evapotranspiration (ET), drought limitations, and long term maintenance needs due to exposure to acid rain. For these additional studies, controlled test bed systems were located in the Penn State Horticultural Science greenhouses while additional testing of media acidification was conducted in the laboratory.

The experimental design used small-scale buildings exposed to the local weather in an attempt to gather data of variance for effects of different roof type and to determine whether statistically significant differences could be described for any given rain event. Key parameters monitored included real time flow and grab sample pollution assessment. The grab samples were analyzed for conductivity, turbidity, pH, nutrients, and trace metals. In a controlled environment (i.e., greenhouse test bed systems), weighing lysimeter studies were conducted to obtain background information and to demonstrate the differences in water storage, and retention and detention characteristics of the media, with and without the presence of plants, and drought studies. The laboratory study used accelerated aging to determine the effects of acid rain on the length of life for the roofs.

Collected field data indicated that a 3.5 – 4 inch deep green roof can retain 50% or more of the annual precipitation in the Northeast. Replicated data from this study provided estimates of expected differences in performance from identical green roofs. Green roof runoff reduction was consistent during the warm summer months (almost no runoff) but was variable during winter months when runoff from the buildings varied in some storm events from 80% for one building to 100% for others. Flow rates were reduced in runoff from green roofs until the systems were saturated at which point runoff flow roughly equaled the rate of precipitation input.

Establishment of plants on Green roofs (first year only) in Region 3 may require supplemental irrigation. Plants increase the transport of moisture through the soil medium when compared to unplanted medium. This finding will need to be incorporated into green roof modeling. Pennman-Monteith ET prediction equations can describe water loss from planted green roofs.

Field water quality data (e.g., pH, conductivity, color, and nitrate) from green versus non-green roofs were measured and compared statistically. Results demonstrated that green roofs may reduce certain pollutants (e.g., acid precipitation and nitrate), but that it may increase loadings directly related to these planted systems (e.g., phosphorous, potassium, calcium, and magnesium). The laboratory test of the pH buffering capacity of the planting media suggest that the green roof media can buffer acid precipitation for approximately 10 to 15 years, after which it may be necessary to amend the media with lime to maintain the pH buffering capacity.

Green roofs can be incorporated with other GI SCMs and should be included in a municipal stormwater plan. For suburban or agricultural areas, additional green roof runoff treatment may be as simple as directing the downspouts to grass-covered areas (vegetated filter strips or swales) or collecting green roof runoff in rain barrels to be used for irrigation, but this may not be practical for urban areas where there is limited room for stormwater controls. For urban areas that have combined sewers, green roofs should be viewed as a benefit due to the volume reduction to the combined system and the delay in time to peak.

Directly discharging green roof runoff to a receiving water is not recommended due to the increased levels of phosphorous, potassium, calcium, and magnesium. Due to variability in results, a conclusion from this study was that continued sample collection and analysis is warranted. Further testing of materials used for green roof construction and planting should be conducted to determine loadings coming from roofs as well as other constituents from atmospheric deposition and building materials for standard roofing. Modeling loadings for green roofs for watershed management requires additional monitoring with full-scale roofs or multiple roofs in an urban setting. The drought studies indicated some potential limitations without the use of irrigation.

Green roofs need to be tested in other climates so that further design specifications on plant mixtures, media depth and amendments, and potential irrigation requirements can be determined. Other climatic conditions should also include year-to-year or long-term studies, as it seems very likely that in dry years the green roof runoff would be far less than in wet years. Additional weighing lysimeter studies should be conducted to identify more plant species suitable for green roofs, especially varieties that are drought resistant and require minimal nutrient supplements. The effects of green roof runoff discharge on receiving waters or the potential for additional treatment of green roof discharge were not addressed, and these should be addressed in future studies.

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Region 4 - Louisville, KY

The Louisville and Jefferson County Metropolitan Sewer District (MSD) entered into a consent decree with U.S. EPA, U.S. Department of Justice, and Kentucky Department for Environmental Protection to limit CSOs. In one of the combined sewer systems, CSO Basin #130, a GI approach was determined to be more cost-effective than the gray alternative to meet the CSO targets outlined in MSD's long term control plan. EPA-ORD entered into a Cooperative Research and Development Agreement (CRADA) with URS Corporation and MSD to monitor and evaluate the individual performance and collective effectiveness of GI practices installed in this basin. The basin is 17 acres of mixed residential and commercial areas in the Butchertown section of Louisville, Kentucky, and the design included: 14 permeable pavement systems, 28 tree boxes, and 4 infiltration planters installed along the public right-of-way.

During the design and planning stages, the municipality (MSD) hoped the monitoring and research program could address: (1) how often maintenance is needed for the permeable pavement surfaces, (2) the lifetime of the system before complete replacement is needed, (3) if implemented at other locations across the city, should the GI design or placement strategy change to improve performance, and (4) if the design meets the CSO frequency and volume reduction targets. These concerns are shared by many communities, so our research attempted to address these knowledge gaps.

To address the first three concerns, a series of embedded sensors (soil moisture, water level, temperature) within the SCMs to study the infiltration and exfiltration dynamics of the system and evaluate how they changed with age. Most of the GI practices were not installed until 2013, so the fourth concern is still under investigation.

Based on monitoring results from the first two permeable pavement strips that were installed in December 2011, three journal articles have been published to date. One article highlights how installing soil moisture sensors [time domain reflectometers (TDR)] in the open-graded aggregate below the pavers can be used to monitor remotely the progression of surface clogging. This installation proved to be a useful monitoring technique to address the question about maintenance frequency. The second article highlighted the results from multiple pressure transducers installed in wells along the length of the system. Analyzing the rates at which water accumulated and drained provided insight on how infiltration and exfiltration processes changed with time. With respect to the exfiltration rate, there was a significant reduction after the first few events and through the first thirteen months. The decrease was attributed to fine sediment on the double-washed aggregate.

Attempts to model the hydrologic performance of this system in EPA SWMM using the measured water levels to calibrate the model were made, but this task demonstrated that the treatment of exfiltration by this model did not accurately represent exfiltration processes for a long, narrow, and deep geometry. Exfiltration was treated as a constant flux on the bottom area only, which is a similar method as in other common hydraulic models. In this system, the water drawdown rate decreased considerably with less water because the hydraulic head and exposed sidewall area were smaller. Alternate ways to model the lateral exfiltration processes were pursued, and a unit process model was developed and reported in the third paper to include and quantify lateral exfiltration. The unit process model also included a function to represent changes in surface infiltration through clogging based on the results from the embedded sensors that measured the progression of surface clogging.

As a result of this research, guidance for stakeholders and decision makers can be provided for permeable pavement placement, remote monitoring strategies to predict maintenance needs, construction materials that have a negative effect on performance, and the benefits of a specific system geometry. Surface clogging is accelerated when sediment and organic material are present in the drainage area, so in an effort to limit the maintenance frequency, permeable pavement systems should not be sited in areas with unstable drainage areas and surrounding deciduous vegetation. Soil moisture sensors (TDRs) installed in the open-graded aggregate of storage gallery proved to be an effective remote monitoring technique to determine maintenance needs. The fine particle size material (a.k.a., fines) present in double-washed aggregate (about 2% by mass) resulted in significant reductions in exfiltration rate during the first 13 months of monitoring. While this is clean by industry standards, the demand for these applications is not large enough to reduce the fines percentage, so a reduction in vertical exfiltration capacity should be considered in systems with deep aggregate layers. Even though the subsoil at the first two monitored sites was clayey and the average infiltration rates were 0.08 and 0.38 cm/h, the storage gallery and trench nearly drained completely during the time between typical events because of the specific geometry of the system – long, narrow and deep. In this type of geometry, most of the exfiltration was determined to be lateral through the exposed sidewalls.

Future needs associated with this research topic are to: (1) explore lateral exfiltration in more depth, (2) evaluate the collective effects of GI on sewer flow rates on a larger scale, (3) evaluate whether the decrease in exfiltration rate continues with time and whether it is hydrologically meaningful, and (4) investigate the interaction of the exfiltrating water with existing groundwater.

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Region 5 - Cincinnati, OH

Consent decree settlements for violations of the Clean Water Act increasingly include provisions for redress of combined sewer overflow activity through hybrid approaches that incorporate the best of both gray (e.g., high-rate treatment plants, storage tunnels) and green techniques (e.g., plant-soil systems like rain gardens, green roofs, pervious pavement systems). Research was undertaken to help determine the most cost-effective, least-invasive method for introducing GI into local communities where stormwater management is an issue. One six-year study assessed the potential impact of distributed GI placed on a number of residential lots within the same watershed. Various water quality and stream biota measurements were taken three years before and three years after the GI technologies were applied, and the results were compared to see if stormwater management at the parcel level can provide effective mitigation of combined sewer overflows. The resulting papers focus on the economic, social, and environmental factors surrounding the implementation of GI at the residential parcel level as a tool for stormwater management.

Many of these studies were conducted within the Shepherd Creek Watershed of Cincinnati, Ohio. The central motivating question was whether stormwater management at the parcel level is an effective strategy in mitigating sewer overflows and promoting stream health. Researchers gauged the willingness of the community to participate in a GI installation program– namely a reverse auction for the planting of rain gardens and the introduction of rain barrels on residents' properties. The Shepherd Creek study found that the GI implemented in this watershed did contribute to ecosystem services such as flood protection, water supply, and increased water infiltration. It also provided benefits to the local residents, and reduced the need for larger, more expensive centralized retrofits.

If this strategy is found to be a viable way to manage stormwater runoff and a similar program attempted elsewhere, it may be beneficial to note a few key factors. First, while there was indication that education alone may be enough to motivate residents to install GI, research determined an auction promoted more participation than education alone, and at a cheaper per unit control cost than a flat stormwater control payment plan. Second, a relatively small monetary incentive can successfully entice homeowners to accept stormwater management technologies on their property. Third, as participants share their experiences, neighbors may become more willing to trust parcel-level stormwater management programs such as the one conducted in Shepherd Creek.

The majority of GI research in Cincinnati evaluated infiltration-based stormwater management strategies, but researchers also studied the distribution of urban trees and associated impacts on stormwater runoff. Trees complement infiltrating GI by intercepting incoming rainfall and preventing it from contributing to stormwater runoff. Researchers found that public trees in the Cincinnati area provide substantial stormwater benefits, but these benefits vary significantly according to community forestry practices at the municipal level. Proactive management of public trees can override other drivers of unequal tree distribution within cities such as race or income.

In general, management of environmental systems is complicated by uncertainty in the constituent factors and processes that comprise an ecosystem. Regardless of the scale of investment in environmental management, uncertainty remains. Uncertainties in the efficacy of GI for CSO control arise from non-linearity in fluxes among the different parts of the hydrologic cycle and spatial and temporal thresholds in potential ecological response. These studies point to the need for further research to identify the minimum effect thresholds and restoration trajectories for retrofitting catchments to improve the health of stream ecosystems.

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Region 5 - Cleveland, OH

Each of these papers address one or several dimensions of the role of GI in sustainable urban stormwater management. Current consent decree settlements for violations of the Clean Water Act increasingly include provisions for redress of combined sewer overflow activity through hybrid approaches that incorporate both gray (high-rate treatment plants, storage tunnels, etc.) and green techniques (plant-soil systems like rain gardens, green roofs, pervious pavement systems, etc.). The overall questions that addressed are: 1) can GI be integrated into an urban setting, 2) how to design, monitor, and maintain the GI, and 3) can GI performance for stormwater management, and ecosystem services provided be assessed?

Through 2017, the GI retrofit of a neighborhood in Cleveland, Ohio (Slavic Village Community Development Corporation area) will be studied. Ongoing hydrological and ecological monitoring provides feedback on the impact of GI implementation. This work centers on managing the urban landscape for water conservation and storage, developing a role for community engagement and renewal, and moving forward a comprehensive management strategy for the stabilization and restoration of urban ecosystems. One important aspect of this work is that it is conducted in an environmental justice community. Attempts to account for these unique social and economic factors into the GI implementation process to achieve overall integration with environmental management will be made. To this end, the research is dependent upon collaboration with the Cleveland Botanical Garden, Slavic Village Development Corporation, Northeast Ohio Regional Sewer District, the City of Cleveland, Region 5, and Ohio State University.

It is possible to develop effective integrated green approaches at the site scale to improve the integrity of local hydrologic cycles, reduce runoff that reaches the sewer system, and reduce risk of combined or septic sewer overflows. The specific management approach includes rain gardens and using specific landscape hydrologic measurements (made in 2010, 2011 by ORD) to determine the utility of vacant lots to act as passive GI. These data can be used to prescribe management for these lots at a level which will make them both cost effective and provide detention for stormwater abatement.

In general, management of environmental systems is complicated by uncertainty in the constituent factors and processes that comprise an ecosystem. Regardless of the scale of investment in environmental management, uncertainty remains. Uncertainties in the efficacy of GI for CSO control arise from non-linearity in fluxes among the different parts of the hydrologic cycle and spatial and temporal thresholds in potential ecological response. Further, rapidly-changing social dynamics of a diverse, post-industrial urban setting under financial austerity contribute political and social uncertainty. Adaptive management provides a framework that explicitly accounts for these sources of uncertainty, and a recent paper (Shuster and Garmestani 2015) details our collaborative efforts to date in Cleveland, Ohio.

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Region 5 - Detroit, MI

Although the importance of urban soil interpretation has been recognized for many years, anthropogenic soils have been delineated as simply urban- or made-land on most soil survey maps. There is a significant lack of information regarding the composition of these soils and how they have been altered over time. It is important to gain better understanding of these soils so that currently unused spaces like vacant lots can be revitalized and used as natural resources for urban agriculture, GI, etc. The paper referenced in this section argues that anthropogenic soils found on vacant urban land can be mapped, even at the scale of a single lot.

The soil survey took place on a <0.1 ha vacant lot in Detroit, Michigan. The lot was formed circa 1998 by the demolition of a wood-frame home from the 1920s in an urban residential setting. The research set out to conclude whether or not there is a mappable pattern of anthropogenic polypedons[19] against the alternative that the distribution is random, as well as provide an answer to the possibility of piecing together the history of urban soils and reclaiming them to suit current stormwater management needs. The type of GI used would be determined once the composition and content of the soil was known.

The results suggest that anthropogenic soils on vacant urban land are mappable, even at the scale of a single vacant lot. The soils approximated an anthrosequence, a related group of profiles whose characteristics differ mainly because of anthropogenic activity. This anthrosequence can be used to characterize the map unit composition of native soil-urban land complexes found on vacant property produced by building demolition. However, a more complete picture of urban soils via Order 1 surveys would help define the characteristics of anthrosequences in other urban settings and inform decisions regarding the implementation of

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[19] polypedon **-** Two or more contiguous pedons, which are all within the defined limits of a single soil series.
pedon **-** A three-dimensional sampling unit of soil, with depth to the parent material and lateral dimensions great enough to allow the study of all horizon shapes and intergrades below the surface.
soil series - The basic unit of soil mapping and classification, comprising soils all of which have similar profile characteristics and developed from the same parent material.
All above definitions from Micahel Allaby. A Dictionary of Ecology. 2004. *Encyclopedia.com.* http://www.encyclopedia.com.

GI, or other revitalization projects, allowing a city and its community members to reclaim unused vacant lots and give them a purpose.

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Region 6 - Austin, TX

Water scarcity is being felt in parts of Region 6 due to the historic drought conditions and an increasing population. Alternative water sources, such as harvested rainwater, are becoming more important and Region 6 has seen an increase in the number of potable rainwater harvesters. There is also growing interest in the U.S. regarding rainwater harvesting systems (RWH) that incorporate minimal treatment. Treatment can be expensive, and both residential and commercial rainwater harvesters might be interested in minimal-treatment systems because of the associated savings. Many rainwater harvesters also wish to avoid the use of chemicals, such as chlorine, that add off-flavors or odors to the water. EPA will require data about (1) risks associated with using untreated or minimally treated rainwater produced commercially or residentially, and (2) risks will depend upon exposures occurring during the ultimate use of the rainwater such as irrigation, drinking, or other indoor household usage (e.g., laundry, bathing).

It is commonly thought that microbiological quality of harvested rainwater poses a greater potential human health hazard as compared to the physical/chemical quality. The objectives of this study were to: 1) identify the composition of the microbial community in untreated or minimally treated harvested rainwater and 2) quantify the impact of typical residential treatment (e.g., filtration and disinfection) on the microbial community.

Six residential RWH systems, located in close proximity to one another (within a 1-km radius) in the central Texas area, were selected for this study. Site 1 performed batch-chlorination in the cistern, sites 2-5 used ultraviolet (UV) light, and site 6 had no disinfection. Sites 1-5 used their treated rainwater for potable (e.g., drinking) and non-potable uses (e.g., laundry), and site 6 used the water only for non-potable purposes. All the UV sites (sites 2-5) had either roof-wash filters (which are placed between the gutters and the first cistern such that collected water is filtered before entering the cistern) or recirculating filters (which are sand filters through which the cistern water is occasionally passed). In particular, site 5 operated its recirculating filter once per day. Four sites had first-flush diverters, which divert a fraction of the initial rainfall to a separate system (e.g., pipe or bath) because the first-flush tends to have higher contaminant concentrations as compared to subsequent volumes of harvested rainwater. Each of the tested systems had two filters between the cistern and tap, but the nominal pore size varied.

RWH systems that are located geographically close to one another will not necessarily have similar water qualities in their cisterns. Neither will those systems necessarily yield similar treated water quality, even if they have similar treatment processes in place.

Although *Escherichia coli* and *Eenterococci* generally are preferable to total coliform (TC) as indicator bacteria in environmental applications, none of these appears to be a proper indicator for the microbiological quality of harvested rainwater. TC, *E. coli*, and Enterococci were often absent from the treated rainwater, even though substantial concentrations of the potential human pathogens *Legionella pneumophila*, *Myobacterium avium*, *M. intracellulare*, *Aspergillus flavus*, *A. fumigatus*, or *A. niger* were present.

The observed log-removals of HPC, *L. pneumophila*, *M. avium*, *M. intracellulare, A. flavus*, *A. fumigatus*, and *A. niger* by filtration and UV disinfection were less than expected based on previous laboratory studies. A careful study of the performance of commercially available UV lamps for residential-scale disinfection is needed. Operators of individual, residential RWH systems might require additional operation and maintenance training to achieve reliable treatment of rainwater, such that the quality is similar to that of community water systems.

Federal water quality regulations do not exist for potable RWH systems at individual residences in the U.S. Consumers of harvested rainwater might incur health risks by indoor domestic use of harvested rainwaters, if those waters are not suitably treated. For individual residences, disinfection with ultraviolet (UV) light is the most common disinfection strategy (70%), while chlorination is used in a smaller number of systems (8%). With respect to filtration, most of the potable RWH systems surveyed used cartridge filters (48%) or activated carbon filters (39%). However, the treatment efficacy of individual RWH systems is not well documented, especially for the removal of potential human pathogens, such as *L. pneumophila*, *Mycobacteria spp*., and *Aspergillus spp*., and more research is needed in these areas.

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Region 7 - Kansas City, MO

In 2010, Kansas City, MO (KCMO) signed a consent decree with EPA on CSO. The City decided to use adaptive management in order to extensively utilize GI in lieu of, and in addition to, gray structural controls. KCMO installed 130 GI SCMs—primarily bioretention units—in a hundred acre-pilot; one of the largest retrofitted areas in the U.S. in 2012. EPA's Office of Research and Development (ORD) partnered with KCMO to conduct extensive monitoring to quantify the performance of the pilot area. The study focused on the long-term monitoring efforts to quantify GI performance at two scales: site scale (individual SCMs) and pilot (100 acre) scale.

Site-scale elements of the GI research included stormwater monitoring systems at eight individual SCMs (rain gardens, bioretention cells, and smart drains) in the pilot area. Parameters measured by deployed monitoring systems included inflow, infiltrated volume, bypassed flow, and drawdown times. In addition, a subset of SCMs is being monitored for water quality (loading reduction) parameters including particle size, bacteria, nutrients, and metals. EPA also collected sewershed flow data before and after GI installation, and performed evaluations of land use, soil infiltration, drainage areas, and individual bioretention unit performance. The titles of the comprehensive reports written on this study are listed in the references.

This work was performed in the Marlborough neighborhood along the Middle Blue River in Kansas City, MO. This historically African-American community was established in 1945. The neighborhood requested that the streets be lined with curbs and gutters to prevent standing water that had traditionally been present after heavy rains. KCWSD installed the curbs and gutters as well as relined the aging sewer system. Both of these actions resulted in higher sewer flow than before the research started. KCWSD installed 67 rain gardens, 5 bioretention cells, 2 cascades, 1 bioswale, 11 curb extensions with rain gardens, 24 curb extensions with below grade storage, 19 bioretention with below grade storage, 1 gravel parking space, 4300 linear feet of porous concrete, 1100 linear feet of pervious paver sidewalk, and 90 pervious sidewalk/infiltration galleries. In addition to the GI installed, KCWSD installed larger underground pipes with an additional storage volume of 288,000 gallons which is directly connected to the sewer system.

However, in spite of system upgrades which resulted in higher sewerflow, ORD measured a 32% decrease in sewerflow before versus after GI installation which is consistent with the SWMM model results presented by KCWSD. KCWSD predicted that the peak flow would reduce by 76%. ORD is interested in seeing the resultant drop in CSO. While these data are extremely variable, water quality analyses showed around a 50% reduction in all measureable parameters TSS, SSC, turbidity, nitrate, and phosphate.

This was a challenging effort. There were numerous entities involved in the research: EPA ORD, EPA Region 7, Kansas City Water Services Division, EPA Contractors Tetra Tech, University of Missouri–Kansas City, University of Alabama–Tuscaloosa, KCWSD Contractor Burns and McDonald, KCWSD Contractor URS, Corporation, KCWSD's GI Designer. The research started in 2008 and ORD finished collecting data in 2013. The design portion of the research effort was two years longer than anticipated and there was a drought in 2012, right after the GI was installed resulting in another year for measurement. Many of the original EPA ORD, EPA Region 7, KCWSD, and contractors who started the research retired before its conclusion. This was a field scale effort which experienced many problems typical for a practical application:

1. Originally, it was intended to compare the 100-acre GI pilot to an 87-acre control area under the same rain fall conditions. There were many problems with the measurement of sewerflow in the control area and it was not possible to get useable results. The analyses presented in this report were based on before and after results for the pilot area.

2. Before GI was installed, KCWSD relined the sewers in the pilot areas which resulted in an increase sewerflow, which was not expected.

3. The pilot area Marlborough neighborhood requested that KCWSD install curbs and gutters to prevent standing water from remaining on homeowner's lawns. The installed curbs and gutters directed more stormwater into the sewers than before the GI was installed.

4. Once all GI was installed in 2012, Kansas City suffered a drought. ORD extended the research period for another year beyond its original intention.

5. The water quality sampling equipment from one of the five individual BMPs selected for analysis was accidently destroyed by the solid waste collection system.

The soil infiltration was much higher than expected and the BMPs worked extremely well. The fact that BMPs had little overflow resulted in a smaller than anticipated dataset to analyze water quality. However, in spite of system upgrades which resulted in higher sewerflow, ORD measured a 32% decrease in sewerflow before versus after GI installation which is consistent with the SWMM model results presented by KCWSD. KCWSD predicted that the peak flow would reduce by 76%. ORD is interested in seeing the resultant drop in CSOs.

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Region 7 - Omaha, NE

Many cities with CSO controls often experience pollution of streams, lakes, and other natural bodies of water when, in a rain event, the system is overwhelmed and is forced to discharge untreated wastewater through CSOs. This research looks at the combined potential of the best of both green and gray infrastructure methods in retaining and/or slowing the movement of stormwater before it adds to the CSS. A hybrid approach with green and gray infrastructures playing to their respective strengths may also allow for downsizing or elimination of some ageing gray infrastructure CSO controls. This paper details a field deployment to Omaha, NE in order to characterize soil taxonomic and hydraulic properties of vacant lots, park land and other transitional and mostly abandoned areas in order to assess their potential for the installation of GI.

Parcels, mostly vacant lots and parks, were selected for assessment by City of Omaha wastewater officials in areas where the local sewershed may benefit from additional detention capacity. This research sought to determine the soil taxonomic and hydraulic properties of urban soils in the greater Omaha area, as well as their potential to be used as an effective stormwater management tool. Types of GI that would be considered here include any infiltration-based GI such as rain gardens, in combination with gray infrastructure such as cisterns.

In conducting this and related research it has been found that obtaining site specific soil data is an important first step before any decisions are made as to what can be done to the green space. The site specific soil characteristics are often very different from what is described on generalized, regional tables and interpolated datasets. This is especially true in highly disturbed urban areas where soils were either not mapped or only minimally so.

The beginning of more research to come, this study supports the idea that a hybridized system utilizing both green and gray infrastructure methods with the goal of reducing sewer overflows is the most efficient and cost-effective alternative to managing stormwater runoff both in the short and long term. Incorporating GI techniques, such as rain gardens, into a stormwater management plan not only lessens the stress on the current, ageing infrastructure, but is overall a more sustainable and aesthetically pleasing option.

Looking ahead, the issue of maintaining these GI SCMs once they are installed, needs to be addressed. While municipal budgets are often stretched and there is little time for inspection, post-construction monitoring to determine if the GI works effectively and appropriate operation and maintenance should be conducted to ensure design effectiveness and otherwise guide corrections. This field protocol will be a model for other deployments and soil assessment studies in looking for suitability for the implementation of future GI research.

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Region 8 - Denver, CO

This Region 8 RARE research culminated in an ORD final report on green roofs (EPA 2012). This green roof research was performed in an applied urban field condition of the rooftop of EPA Region 8 Headquarters in downtown Denver, CO with supplemental plant and drought studies performed at Colorado State University in Fort Collins, CO. Due to the porous and well-drained nature of the typical growing medium used in extensive green roof systems, the success or failure of an extensive green roof is primarily dependent on a plant species' ability to grow in the media. These challenges are intensified for extensive green roofs on buildings in areas characterized by high elevation and semi-arid climate as typified by the environment of the Front Range of Colorado. Success of an extensive green roof is primarily dependent on plant species' ability to survive the low moisture content of the growing medium. Plants adaptable to dry, porous soils are primarily used in extensive green roof applications. Although Sedum species, which are succulents, have dominated the plant palette for extensive green roofs, there is growing interest in expanding the plant list for extensive green roof systems, especially using native species.

Prior to this study, green roof plants had not been scientifically tested for long term survivability and adaptability in the Front Range of Colorado. The low annual precipitation, short periods of snow cover, low average relative humidity, high solar radiation (due to elevation), high wind velocities, and predominantly sunny days all add up to challenging growing conditions for many species of plants. Plant studies of individual plants, mixed plantings and drought studies were performed. Amendments (i.e., zeolite), to traditional green roof media was tested to see if this benefited the green roof plants. Additionally, overwinter damage to the initially installed drip irrigation system allowed for comparative performance to overhead drip irrigation system.

The plant studies revealed, plant cover increased for all six species during the first growing season. Subsequently, one species was removed from analysis in the second season due to the low overwintering rate (12.5%). Four of the five remaining species also exhibited decreased plant cover due to winter dieback, but survived through the second season.

In terms of plant cover, five of the six species evaluated in this study appear to be appropriate for use in extensive green roof applications. In the mixed study of eight species, at the end of the study, the two native species that had higher plant cover than the others. Similar to the individual plant studies, there were overwintering declines though competition may have also determined success and reduction of species plant cover.

Four growing media amendments were evaluated based on plant taxa growth performance. The greatest increase in plant cover from the addition of zeolite was seen in mixtures with 33% and 66% zeolite.

In the drought study, fifteen plant taxa were evaluated for response to gradual and long-term drying of the porous extensive green roof growing medium; despite differences in dry down, the succulent species maintained viable foliage for over five times longer than the herbaceous species. Additionally, the revival rates of the succulent species were nearly double those of the herbaceous species.

Volumetric moisture content (VMC) data were collected throughout the study and the overhead rotary irrigation system delivered a more consistent amount of water throughout the green roof as measured by instantaneous VMC. Less irrigation was applied in the second year with the spray irrigation than in the first year with the drip irrigation system. Year to year, for the months July through September, there was 10% more rainfall in the second year (i.e., 97 mm compared to 88.1 mm), but there was 32% less irrigation required (i.e., 200 mm compared to 270 mm). Overall, the overhead rotary irrigation increased biomass and plant cover.

Due to the success of some native species in these experiments, the use of native plants for green roofs should be pursued though finding adequate supplies may be an issue. In the arid west, green roofs will most likely require supplemental irrigation. Due to the quick draining nature of the green roof media and shallow rooted nature of most green roof plants (especially during establishment), drip irrigation should not be used for green roofs.

Based on the diverse effects observed in this study due to changes in irrigation regime and interaction effects with zeolite amendments, future studies should look at root growth in addition to top growth of plants. The low overwintering success or eventual die-off of several species in the study and overall winter dieback of most of the observed species may be an indication of desiccation of roots due to limited snow cover. An additional limited irrigation regime during winter months may improve plant survival in green roofs in arid regions. Additional studies should be performed with other zeolite mixture ratios, additional native plant species and mixture of species should be tested. Due to the need to irrigate in the arid west, determining the cost effective benefits of green roofs beyond stormwater management needs to be qualified for this GI practice to be more accepted in this area of the country.

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Region 9 - Phoenix, AZ

Many cities with CSO often experience pollution of streams, lakes, and other natural bodies of water when, in a rain event, the system is overwhelmed and is forced to discharge untreated wastewater through CSOs. By studying the soil morphology and correspondent hydrologic data in the Phoenix area, this research was aimed at assessing the potential for residential parcels and desert parks to be used as a tool in managing stormwater flows and mitigate untreated runoff. This paper details a field deployment to Phoenix, AZ the purpose of which was to characterize soil taxonomic and hydraulic properties of Aridisol pedons found in desert parks and residential parcels, as well as a few dual-purpose park-stormwater retention basins in order to assess their stormwater retention potential.

This research effort looked at two sites located in the outlying native Sonoran Desert that have not been subject to direct anthropogenic disturbance, four residential lots representing a range of neighborhoods and landscapes, and three stormwater retention basins that also serve as recreational fields and feature turfgrass that is maintained and utilized throughout the year. This study sought to determine whether the Aridisol soils found in the greater Phoenix area are effective for retaining stormwater, especially those whose soil structure has been affected by anthropogenic change. Specifically, the focus was on the use of retention basins and other infiltration-based GI.

The resulting hydropedological data indicate that the infiltration performance of retention basins is low, probably due to the development of finer surface soils and compaction. Taken as an aggregate, these findings also suggest that residential yards may have sufficient infiltration capacity to detain the runoff volume that they produce. Proper maintenance and clearing of accumulated, fine-textured sediments within any retention basin used for the purpose of stormwater management may result in an increase in infiltration and overall a more efficient and impactful system.

Our limited number of hydropedological assessments indicate a potential for stormwater management via infiltration into urban Aridisols, although further study is needed to develop finer scale mapping of soil hydrology in this arid conurbation.

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