GREEN INFRASTRUCTURE

Lessons from Science and Practice

Cary Institute of Ecosystem Studies

SYRACUSE UNIVERSITY

SCIENCE POLICY EXCHANGE
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EXECUTIVE SUMMARY

Green infrastructure is an emerging engineering approach used to address stormwater and water quality challenges in urban areas using cost-effective technologies, which also provide environmental, social, and economic benefits. Green infrastructure can decrease water inputs to sewers, wastewater facilities, and surface waters by increasing the available storage across the urban landscape. The extent to which water is detained in the structure, removed through evapotranspiration to the atmosphere or infiltration to groundwater underlies substantial differences in function and performance among different green infrastructure designs.

Despite the growing interest in green infrastructure for stormwater management, information is limited on its design, implementation, operation and performance. The approach is still relatively new and, although it is being widely adopted, there are few studies in the peer-reviewed literature that report and contrast the performance of different green infrastructure technologies. To begin to address green infrastructure information needs, we: (1) gathered and analyzed water quantity and quality performance data for green infrastructure technologies that are commonly used for stormwater management from the peer-reviewed literature and a large national database; and (2) administered a survey to municipal officials on factors that may affect decisions related to green infrastructure adoption for stormwater management.

We found from available literature and data that there is considerable variability in the retention of stormwater quantity and quality across green infrastructure technologies and across storm events. In general, bioretention cells (mean 90% retention) and green roofs (mean 73% retention), and to a lesser extent porous pavement (mean 58% retention), are technologies that promote stormwater loss through a combination of enhanced evapotranspiration or infiltration. In contrast, other technologies are less effective at removing water (swales with mean 27% retention; detention ponds with mean 8% retention; media filters with mean 8% removal; retention ponds with mean -2.4% retention; wetlands with mean -11% retention), but accomplish stormwater management largely by allowing for additional storage for stormwater events. Yet, average retention performance differs more by sites than by events within a given green infrastructure technology.

Based on the limited studies that exist in the literature, we found the water retention capacity of bioretention cells and green roofs can be diminished under cold season conditions, compared to warm weather conditions. This reduction in performance is variable across the studies examined and can be attributed to

changes in the functioning of green infrastructure, such as decreased evapotranspiration at lower temperatures, reduced plant water uptake, and reduced infiltration into frozen soil. Note that for certain technologies and in certain climates the quantity and intensity of water inputs can decrease during winter due to differences in seasonal precipitation and snow removal. Overall, we find that given appropriate design and operation, green infrastructure can still process stormwater effectively during winter conditions.

The effectiveness of green infrastructure in removing contaminants in stormwater depends on the contaminant of interest and the technology used. Virtually all green stormwater technologies are effective at removal of suspended solids, with mean removals ranging from 71% for bioretention cells to 33% for wetlands. We found bioretention cells, media filters, detention ponds and retention ponds retain modest quantities of total nitrogen and total phosphorus. In contrast, swales, porous pavement, wetlands and green roofs retain minimal quantities of these nutrients, with some systems releasing quantities to downstream water, likely due to the application of fertilizer to biological systems. We found little evidence of retention of chloride in stormwater structures, but generally trace metals, lead and cadmium, were effectively retained.

Based on a case study in Onondaga County NY, discussions with municipal water managers, and a survey, we found that key factors enabling the adoption of green infrastructure programs include 1) strong local leadership and entrepreneurship; 2) collaboration with multiple and diverse community groups and stakeholders; 3) learning from the experiences of other green infrastructure adopting communities; and 4) consideration of social benefits related to green infrastructure technologies. Conversely, barriers that discourage the adoption of green infrastructure programs include 1) concern about cost-effectiveness (including operation and maintenance costs); 2) lack of interdepartmental coordination and funding; and 3) inadequate technical capacity and expertise.

INTRODUCTION

Aging water infrastructure is failing to meet contemporary environmental standards in cities across the U.S. Traditional stormwater infrastructure designed for efficient flow routing and drainage capacity has resulted in increased peak flows, decreased low flows, enhanced delivery of nutrients and toxics to urban waters, and degraded downstream aquatic habitat. Many older cities still have linked storm and sanitary sewers that experience combined sewer overflows (CSOs) during wet weather conditions and expose people in densely populated areas to health risks from waterborne pathogens and toxics.

Green infrastructure (GI) has emerged as a promising alternative for reducing the cost and disruption associated with grey infrastructure replacement, for improving watershed management and water quality performance, and for providing an array of urban sustainability benefits. Green infrastructure has become a centerpiece of many urban stormwater management plans and combined sewer overflow (CSO) consent decree agreements (e.g., NYC DEP 2013, PWD 2009, MMSD 2013).

Green infrastructure uses vegetation and natural processes to capture, store, and slowly release water to the atmosphere, ground water or existing drainage systems. It can include many different technologies that are generally small scale and distributed throughout the urban landscape among neighborhoods and communities. Specific technologies vary and can range from planters, street trees and rain gardens, to porous pavement and green roofs, to bioswales, bioretention ponds and constructed wetlands. The size and distribution of these technologies in networks across an urban landscape strongly influence how effective the overall green infrastructure system works in mitigating stormwater and its impacts.

The next several years will be a critical period in the advancement of green infrastructure as cities move from planning to implementation and, ultimately, to evaluation against regulatory and legal standards. Despite its promise and the many green infrastructure studies that are underway (Zhou et al. 2009, 2010, 2011), the ability to predict the effectiveness of green infrastructure practices in diverse urban watersheds in a range of climatic and seasonal settings remains poor. This disconnect may lead to gaps between stakeholder expectations and actual system performance and stymy the diffusion of green infrastructure technology. Therefore, as with any new technology, it is critical to invest the necessary time and resources to compile and synthesize data from early adopters to improve green infrastructure design and performance.

With support from the Surdna Foundation, we conducted a literature and database review to synthesize existing information on the water quantity and water quality performance of specific green infrastructure technologies.

OVERVIEW OF GREEN INFRASTRUCTURE STORMWATER TECHNOLOGIES

Several technologies have been applied as green infrastructure for stormwater management. These technologies each have advantages and limitations, and the effectiveness of their application depends on stormwater management needs, their operating conditions relative to design conditions, and the configuration of the surrounding built, landscape and surficial environment in which they are deployed. The primary objective for the application of green infrastructure for stormwater management is for the cost-effective processing of the water quantity associated with short duration storm events (i.e., rain storms, snowmelt). In general, this objective can be accommodated by two mechanisms: by increasing in storage to retain stormwater runoff until it can be processed by the stormwater infrastructure; or by facilitating water loss by evapotranspiration to the atmosphere or infiltration to the groundwater system, thereby eliminating the need to process that stormwater runoff through wastewater treatment or by surface water discharge. Green infrastructure technologies vary in their ability to process water by these two mechanisms.

In addition to this primary objective, a secondary objective of green infrastructure for stormwater management is the potential for water quality treatment which can decrease the cost of wastewater treatment and potentially improve surface water quality. There may also be social, environmental and public health co-benefits to adopting green infrastructure in urban areas. The eight technologies for which adequate performance data exist to support analysis are described in Appendix 1. The technologies are: bioretention cells, green roofs, media filters, porous pavement, grassed swales, and constructed wetlands which are considered to be green infrastructure, and detention ponds and retention ponds which are conventional technologies generally used to store stormwater inflows for later treatment by wastewater facilities.

DATA SOURCES AND PRESENTATION

Data summarized in this report are primarily from the International Stormwater Best Management Practice database, a collection made available to the public by the Water Environment Research Foundation (WERF), Environmental Protection Agency (EPA) and Environmental Water Resources Institute (EWRI; WERF 2013). In addition, data were obtained from the peer-reviewed literature. From these sources, we compiled data from 121 sites involving 4,277 hydrologic and 35,476 water quality observations from individual storm events into an original Microsoft Access database that we created for this study.

In this report we summarize the hydrologic and water quality performance of stormwater technologies by presenting observations as runoff reduction. Runoff reduction is simply the percent decrease in the volume of water or the mass of a contaminant for a stormwater runoff event observed for an individual storm water facility.

A positive value for runoff reduction indicates the extent of removal of the quantity of water or the mass of a contaminant by the stormwater technology during an individual event. A value of 100% indicates complete removal of water or a contaminant. A value of 0% indicates no removal of water or a contaminant, or that the material entering the stormwater facility is the same as that leaving the facility. A negative value indicates that there is more water quantity or mass of contaminant leaving the facility than entering. This condition may seem counterintuitive, but can occur. For example, for some technologies groundwater can seep into the stormwater structure providing an additional water source that result in greater export of water quantity and contaminants than collected by the inlet of the facility. Also, for some facilities contaminants can enter a structure by pathways other than precipitation and stormwater run on, such as addition of nutrients during fertilizer application to vegetation or application of road salt to porous pavement.

The runoff reduction results within each figure are ordered with the best performing technology on the left and decreasing performance of technologies from left to right. These facilities are at varied locations under different landscape and climatic settings, and have varied designs and operating conditions relative to site conditions and age of the facility. As a result, the summary of performance for a given technology demonstrates considerable variability.

HOW TO READ A BOX AND WHISKER PLOT

We summarized the green infrastructure performance data by technology type using box and whisker plots of runoff reduction (Figure 1). The white line in the middle of each box plot represents the median value for all observations (half the observations are above and half are below this value). The yellow rectangular markers represent the arithmetic mean value (average). The mean values are reported in the lower right corner of the figure. The edges of the boxes above and below the median represent the values for the interquartile range (25th to 75th percentile). The lines extended from the boxes are upper and lower whiskers that extend 1.5 times beyond the interquartile range. Observations that occur outside the box and whiskers are labeled as individual points, and could be considered "outliers" in the dataset, although they are included in the calculation of the mean and median values.

The red brackets along the left hand side of the box plot represent the "shortest half", which indicates the densest cluster of data points; half of all observations fall within the red bracket. The % water volume and % contaminant load reduction datasets are negatively skewed, highly variable and bounded at 100%; as a result they do not meet criteria for using parametric methods of analysis. The "shortest half" metric helps interpret the observations without transforming the data. This is useful for identifying normal operational function: during a given storm event, there is a 50% chance that the storm event will result in a % reduction value within the "shortest half" bracket. If a technology has a very narrow "shortest half" range and a mean that falls far outside it, that likely indicates that most storm events fall within the shortest half, but the overall annual average performance is influenced by a few, infrequently occurring large events. If a technology has a wider "shortest half" bracket that encompasses both mean and median, that likely indicates that the technology performs roughly the same during events of unequal size or time interval. Note that all technologies may experience storm events (or a series of events) that exceed their capture capacity or expand their effective capture, resulting in negative values of runoff reduction.

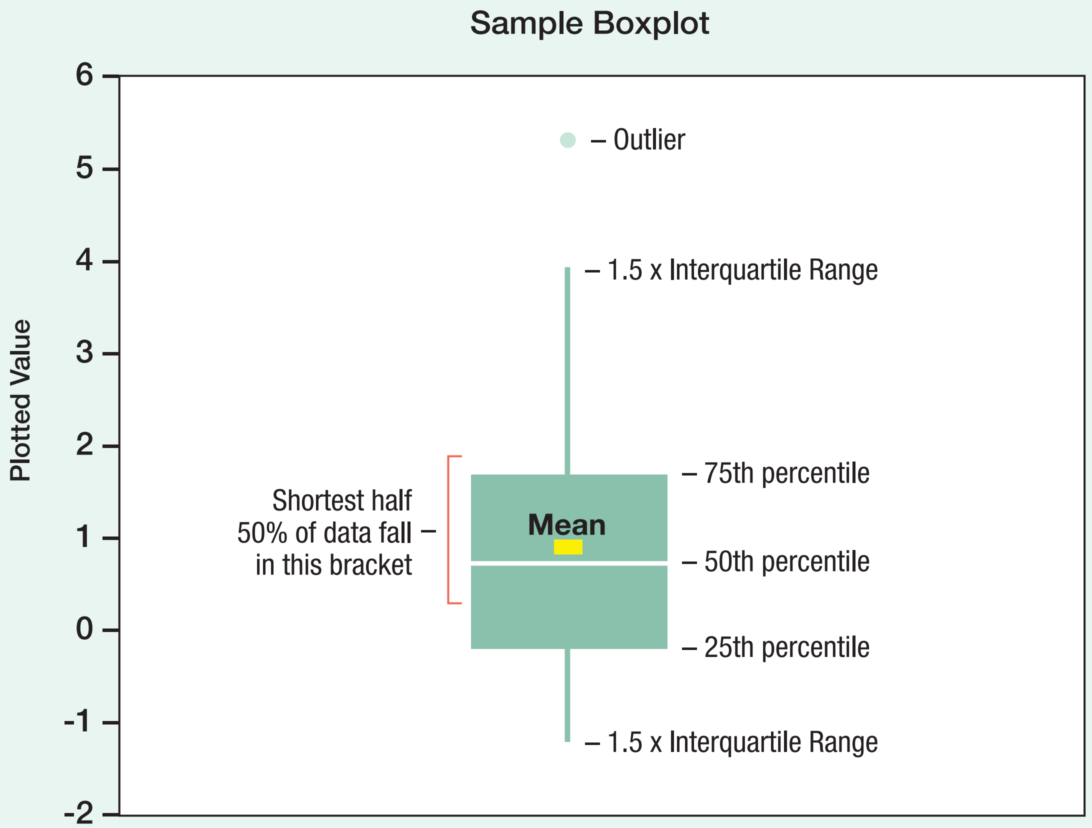
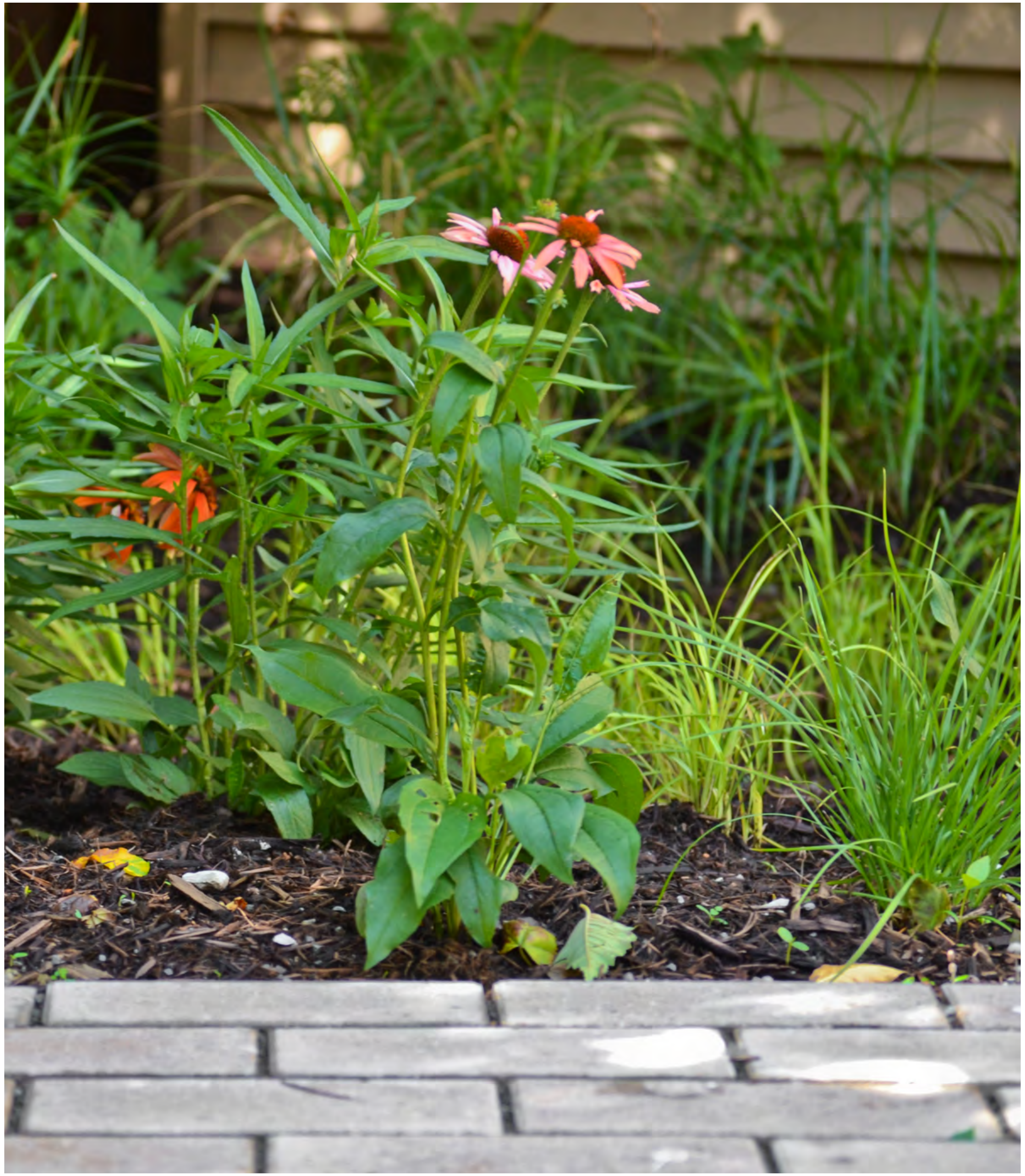


Figure 1. Conceptual diagram illustrating the features of a box and whisker plot.



SUMMARY OF GREEN INFRASTRUCTURE PERFORMANCE FOR STORMWATER MANAGEMENT

RETENTION OF STORMWATER QUANTITY

Overall, volumetric capture of stormwater was highly variable across the stormwater technologies, including green infrastructure. We present statistical analyses of runoff reduction values first using the average of events at *individual sites* (Figure 2) and then using the runoff reduction of *all events across* all sites for a given technology (Figure 3). For the first analysis, we found the average mean retention for porous pavements (72%), bioretention cells (65%) and green roofs (52%), indicate a significant capture advantage over other stormwater management strategies, such as swales (26%) and detention ponds (16%) (Figure 2).

Most technologies displayed some runoff retention observations as negative values (up to -300%), which indicates input of water to the facility from another source, such as groundwater. Given these observations, values of negative retention should be considered a normal occurrence, for some green infrastructure technologies. Wetlands, media filters and retention ponds all showed negative values of average mean retention from -11% to -12%, indicating that they are hydrologically connected to groundwater sources. These technologies are designed to delay and reduce peak runoff rather than total runoff, so are still likely to reduce combined sewer overflow impacts, but not the total water volume.

By comparison to Figure 2, the distribution of individual storm event observations (Figure 3) shows a greater range of runoff retention values. Similarly, the range in average event reduction efficacy of bioretention cells (90%) green

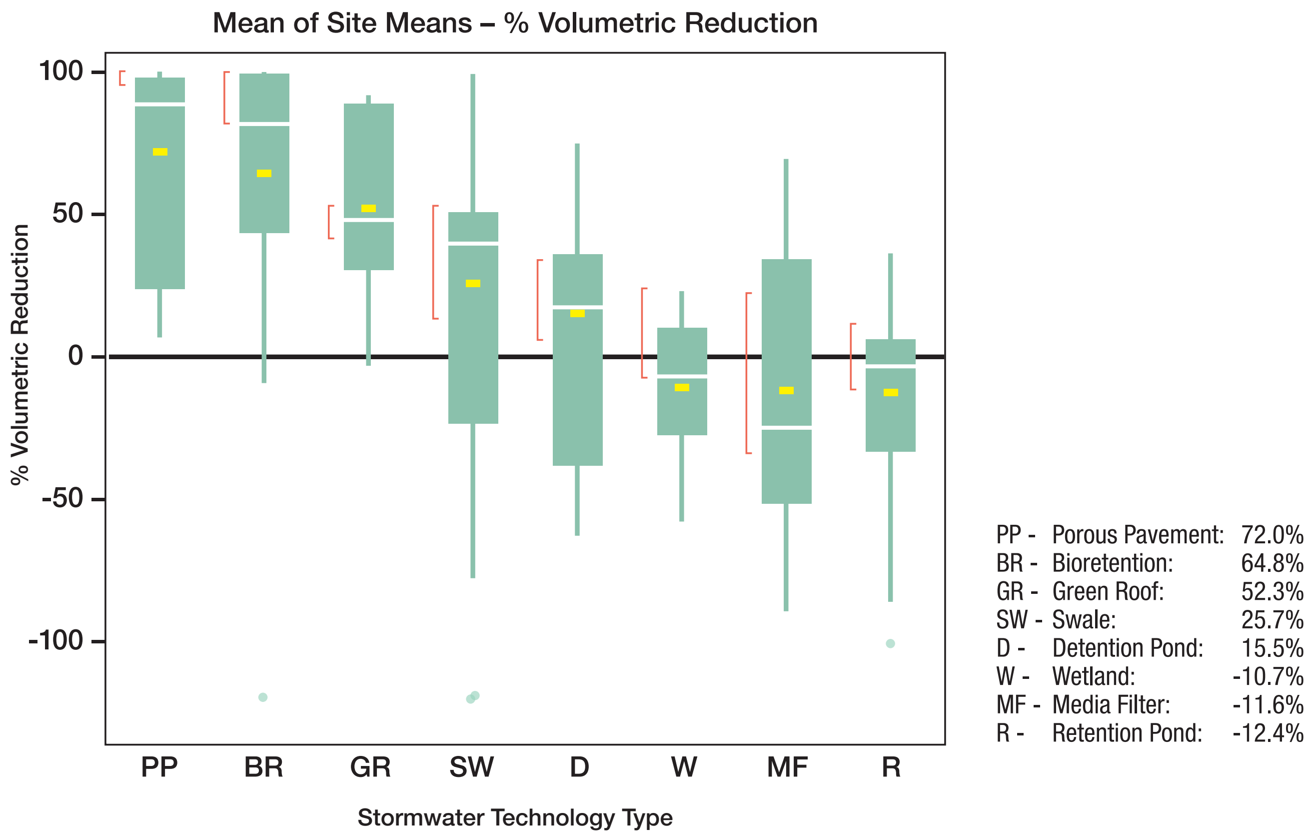


Figure 2. **Stormwater capture, loss and leakage by technology, summarized as percent volume reduction of influent water. The values in the lower left corner represent the mean performance at individual sites.**

roofs (73%) and porous pavement (58%) is greater than for the "mean of site means" analysis (Figure 2). As in Figure 2, average runoff reduction by swales (27%) is somewhat better than detention ponds (8%) and media filters (8%), whereas retention ponds and wetlands tend not to reduce total runoff volume on an average basis. It is notable that the wide range of response for individual storm event observations highlights the opportunity for good performance or failure for any of the technologies, depending on the combination of site design or capacity and precipitation/snowmelt intensity and magnitude. An important caveat is that these results may be biased by more data from sites constructed with a conservative design or by sites in climates with higher frequency, smaller events.

GREEN INFRASTRUCTURE PERFORMANCE UNDER COLD CONDITIONS

One potential barrier to adoption of green infrastructure technologies for stormwater management is concern about performance during the cold season. Although there are numerous references to the performance of green infrastructure, the number of studies on *seasonal* performance of green infrastructure technologies is limited. The University of New Hampshire Stormwater Center (UNHSC) has demonstrated the considerable potential for warm and cold season performance of well-designed and carefully operated sustainable stormwater systems (Roseen et al. 2009). Although their study was carefully conducted, the performance metrics focus on peak flow reduction and mean detention time and cannot easily be translated into runoff reduction metrics.

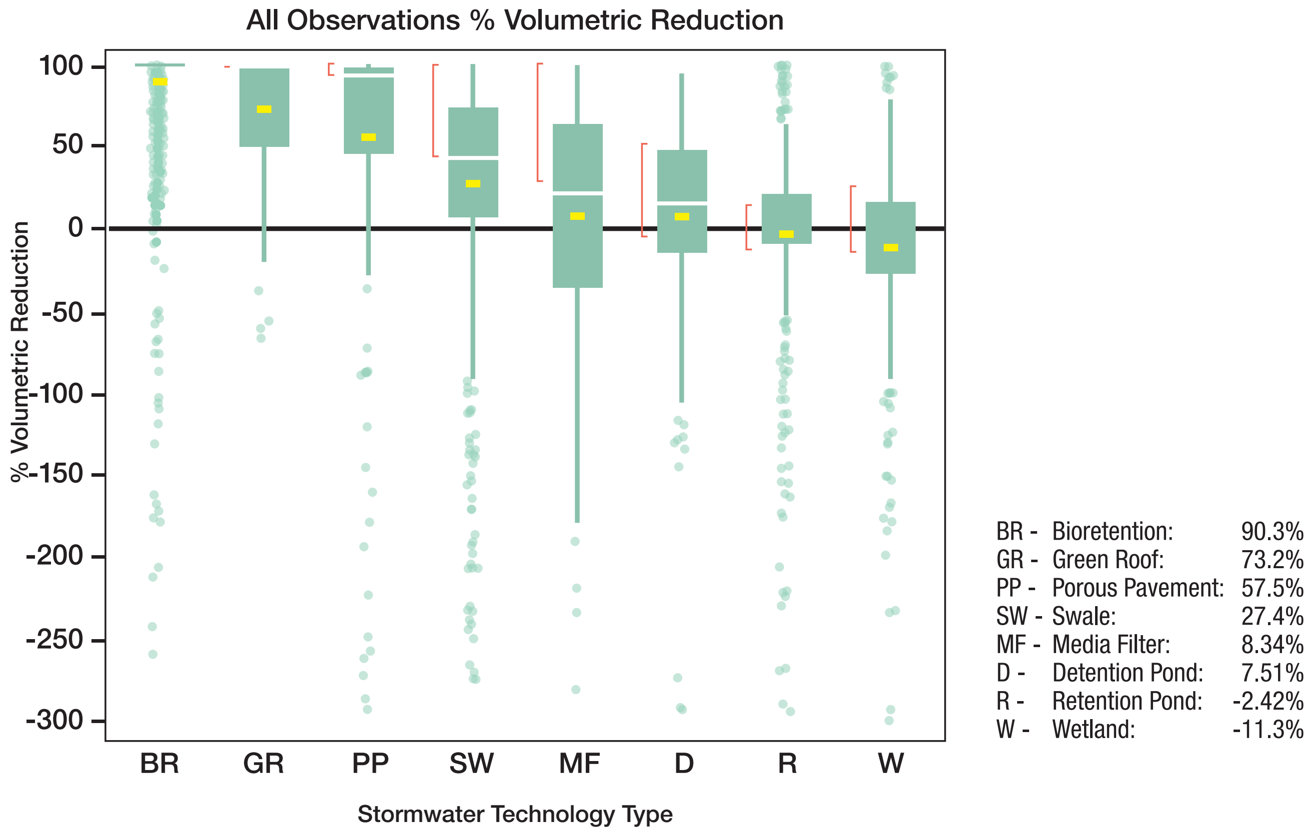


Figure 3. Summary of volumetric stormwater capture, loss and leakage by technology, summarized as percent volume reduction of inflowing water. The values shown are of performance by individual events.

In our assessment, cold climate hydrologic performance was first analyzed across site type categories for technologies with data available for summer and winter, then focused on two green infrastructure technologies, bioretention cells and green roofs. To examine the influence of seasonal variation on hydrologic performance, data from the WERF database were categorized into summer or winter based on the date of the observation (Summer: June 21 to Sept 20; Winter: December 21 to March 20; Figure 3). For the bioretention and green roof comparison, we reviewed 10 papers in the peer-reviewed literature with information on cold climate performance, in addition to the observations present in the WERF database. Observations from the literature reporting evidence of soil freezing or non-zero snow depth have been included as 'winter' observations even if they were outside this date range.

Broad seasonal comparison of the stormwater technologies in summer and winter (Figure 4) shows similar patterns in performance for summer as the mean of site means (Figure 2), but no consistent shift from summer to winter performance. Porous pavement clearly outperforms all other technologies in terms of average event runoff reduction for both summer (93%) and winter (99%) conditions. Bioretention cells perform equally well in summer (76%) and winter (74%). Only green roofs and wetlands show a significant difference between summer (53% and 7%) and winter (48% and -14%) event average retention, evident by a shift in the shortest half. Other technologies have low runoff reduction values. Improvements in winter runoff reduction across stormwater management technologies is likely a reflection of reduced water input due to snow removal, slow input rates from snowmelt, and a decrease in the likelihood of prolonged or intense rainfall during winter. Again, the variability across sites and events may obscure significant differences in performance between winter and summer for individual sites. We provide additional site-specific analyses of seasonal performance for the non-pavement technologies with greatest potential, bioretention and green roofs.

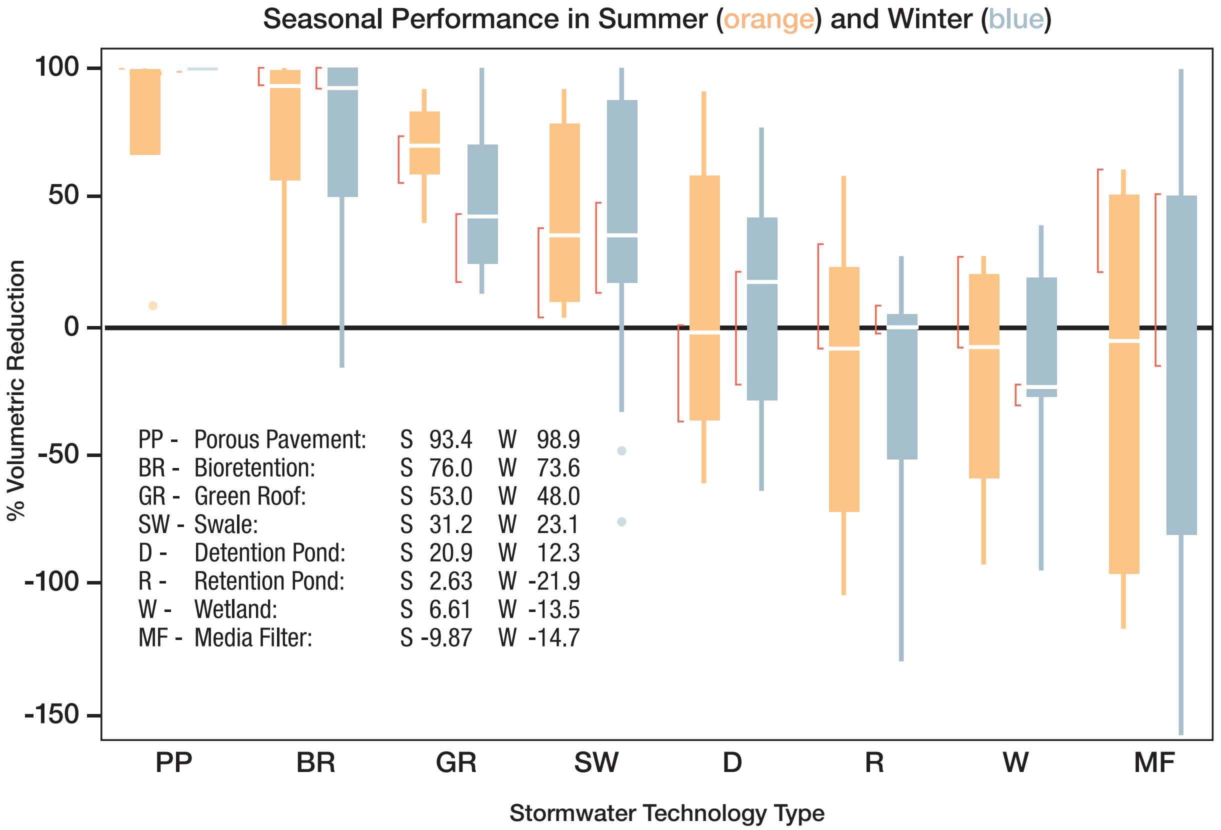


Figure 4. Summary of event based volumetric runoff reduction (retention) by technology, for summer (orange) and winter (blue) periods.

Bioretention Cell Seasonal Performance

In select bioretention cells, a decrease in runoff reduction performance is consistently observed from the warm to cold season from the three studies available in the literature, although the magnitude of the decrease in performance was highly variable across these studies and the reduction in stormwater capture was not significant (Figure 5). The variability reported in the literature can be explained by the temperature dependence of evaporation of water from surfaces and transpiration by plants and the reduction of plant activity due to seasonal dormancy. However, the effect of these seasonal changes should be considered small when compared with the overall effect of appropriate sizing and design of these systems.

The study showing the greatest retention of stormwater quantity (Khan et al. 2013) exhibited the least decrease in performance from warm to cold season, indicating that it is likely appropriately sized or oversized for the small water receiving area it serves. The other studies showed less overall retention of stormwater inflow and exhibited increasingly diminishing performance during the cold period (Hunt et al. 2008, Muthanna et al. 2008). The extreme negative retention values belie a fundamental issue in the runoff reduction analysis approach and winter maintenance of parking areas. Whereas snow removal from parking areas has the potential to markedly improve winter performance, storage of removed snow on bioretention cells can impair performance through ice development and dam formation. Negative runoff reduction values are most likely the direct outcome of the enhanced, but unaccounted for, input of water from snowmelt during rain on snow events.

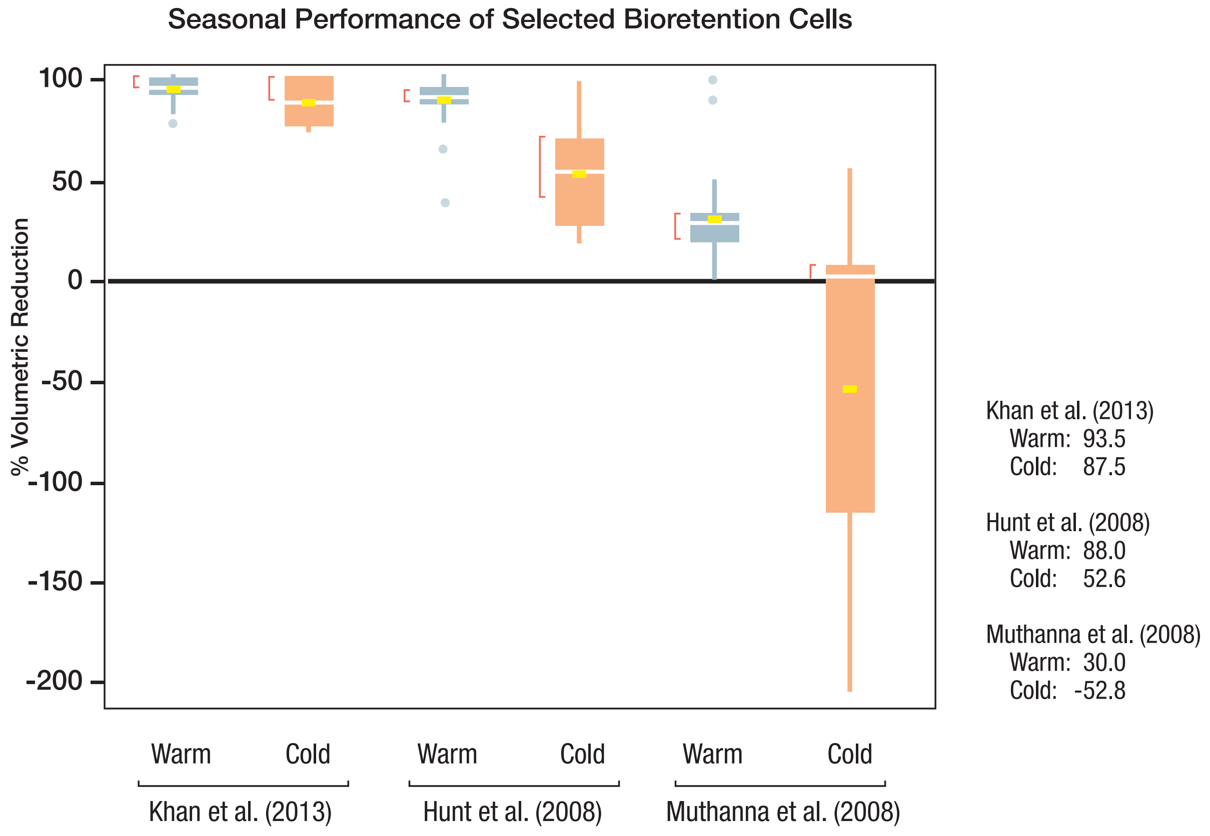


Figure 5. **Summary of volumetric stormwater capture, loss and leakage during warm and cold seasons for bioretention cells based on studies in the literature, summarized as percent volume reduction of inflowing water. The values shown are of performance by individual events.**

Green Roof Seasonal Performance

In contrast to bioretention cells, the performance of green roofs at retaining water shows a stronger dependency on event size than season (Schroll et al. 2011; Carson et al. 2013; Figure 6). However, our review of the literature shows some decrease in retention of precipitation inputs during the cold season. This is most likely due to decreased rates of evapotranspiration, ice formation in the porous growth media and melt of accumulated snow and ice during rain-on-snow/ice events. The change in mean runoff reduction performance of green roofs from warm to cold seasons was analyzed from fourteen studies in the literature and WERF database (Figure 4). It is likely that the sizing and media depth of a green roof may also influence the effectiveness of roofs during the winter. Although green roofs display reduced performance during winter months, the range in winter (shortest half 15 to 45%) still shows better operation than warm weather performance of most other studied technologies (Figure 4).

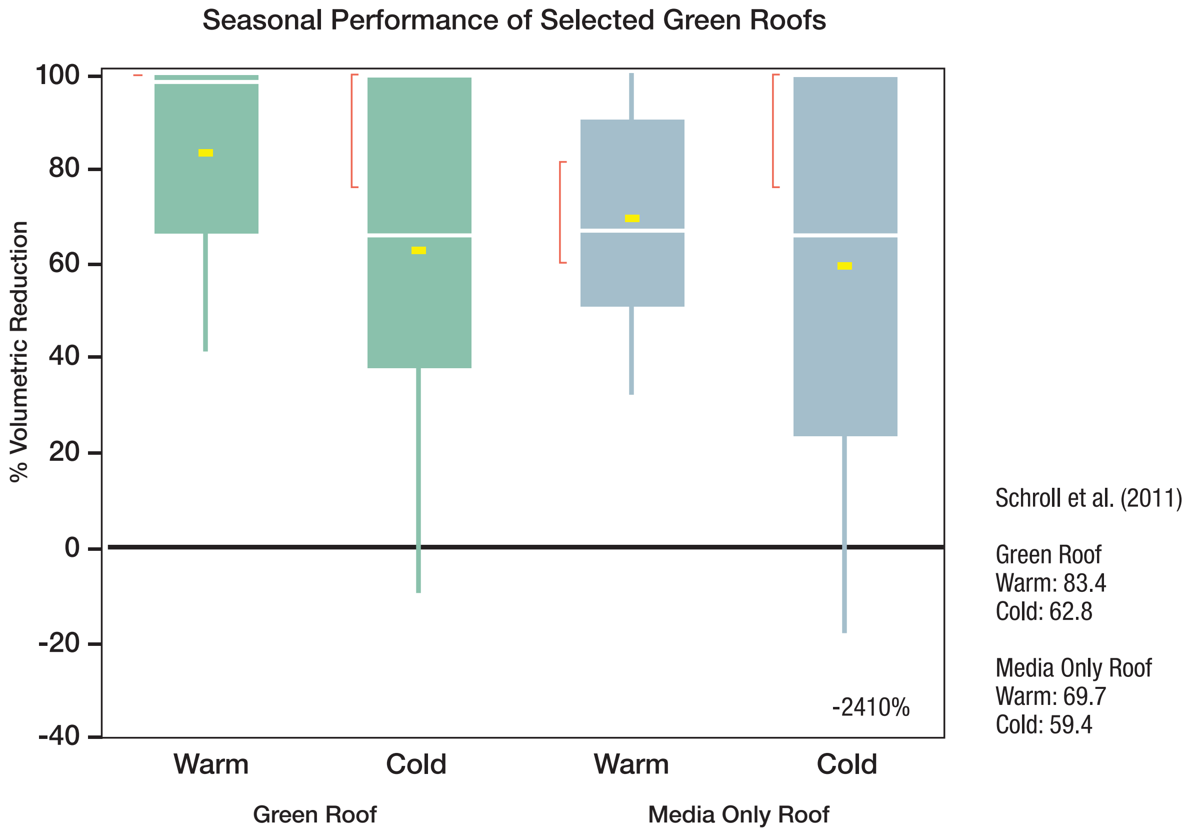


Figure 6. Representative summary of volumetric stormwater capture, loss and leakage during the warm and cold season from Schroll etr al. (2011), summarized as percent volume reduction of rainfall. Data displays performance by individual events.

APPLICATION OF RESULTS

Based on our review of current available data, we conservatively recommend that green infrastructure models should use a sliding scale bounded by the shortest half range, which represents the densest 50% of data and should give a reasonable estimate for modeling stormwater retention performance for these various technologies (Table 1).

WATER QUALITY IMPROVEMENT BY CONTAMINANT REMOVAL

Our review of literature and available data showed that green infrastructure has been investigated for the removal of a large number of water quality parameters (Appendix 1). For this report we focused on measurement of a few water quality contaminants for which there are many observations across the eight different technologies. These contaminants are of general interest to urban water managers due to their contributions to conditions of impaired surface waters. The contaminants include total suspended solids, chloride (a measure of human contamination, and road salt), total nitrogen and total phosphorus (important nutrients), and lead and cadmium (important trace metals).

Table 1. Summary of green infrastructure stormwater management performance values obtained from this study.

Technology Type		% Retention						
		Mean	Interquartile Range			Shortest Half Range		
Green roofs	**GR**	52	35	to	85	45	to	55
Rain gardens, bioretention cells, stormwater trees	**BR**	65	45	to	100	80	to	100
Grassed/dry swales and grassed waterways	**SW**	26	0	to	50	10	to	55
	D	16	-5	to	35	5	to	30
Porous pavement	**PP**	72	25	to	100	90	to	100
Wet swales and wet ponds	**R**	-12	-35	to	10	-10	to	15
	W	-11	-25	to	15	-5	to	25

SUSPENDED SEDIMENT REMOVAL

Most technologies, except green roofs, provide for removal of suspended particulates from influent stormwater (Figure 7). The two technologies that use filtration through porous media (bioretention and media filters) achieve greater mean capture rates than retention and detention ponds, which use sedimentation as the mechanism for water clarification, as well as swales, which generally use overland sheet flow to process storm water runoff. These observations are consistent with the design objective that little water entering a bioretention cell or media filter circumvents the filtering pathway. Retention and detention ponds (conventional stormwater technologies) have limited retention time during high flow periods and likely have limited opportunity for particle sedimentation and therefore less removal of suspended solids. Porous pavement is known to clog and produce sheetflow under high sediment loading, which may reflect the lower rate of suspended solids removal compared with bioretention cells and media filters. The water flow through constructed wetlands is not significantly different from retention ponds under high flow conditions, and thus they would be expected to perform similarly for removal of suspended solids. The limited runoff reduction of suspended solids from green roofs is misleading. Green roofs have very low input of suspended solids in precipitation, and the stormwater exiting these systems can mobilize some suspended solids from the soil media. This creates a low level discharge of sediment in water draining green roofs, but negative values when expressed as runoff reduction. Note that green roofs are not an important source of suspended solids to wastewater systems or surface waters.

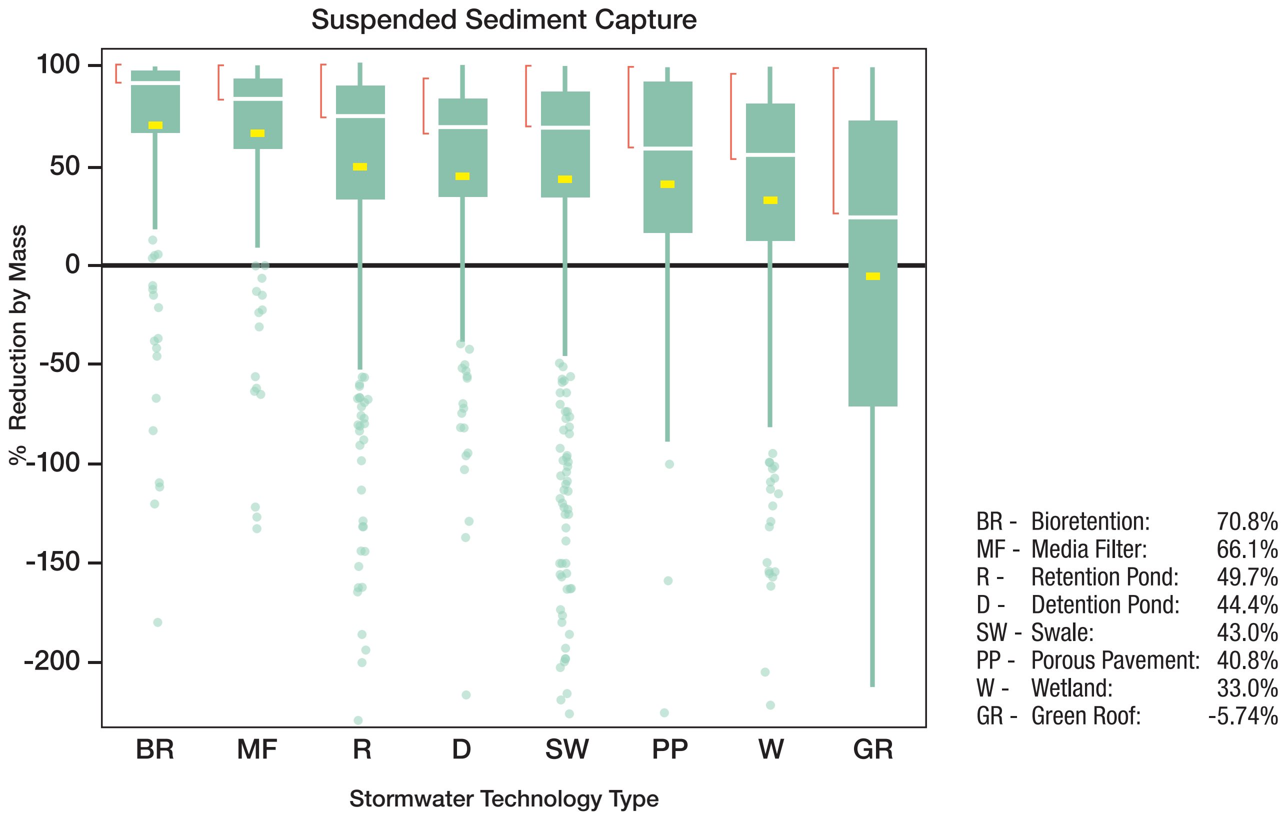


Figure 7. **Total capture, loss and leakage of the mass of suspended solids in stormwater for each technology studied.**

NUTRIENT REMOVAL

Nitrogen

There is an ongoing discussion in the green infrastructure community as to the extent to which living green infrastructure systems, such as green roofs and bioretention cells, leach nutrients to outflowing waters. Previous studies have suggested that these systems can release nutrients based on measured increases in concentration in the outflowing water compared with the concentrations in water entering the facility, rather than considering the mass inflow and outflow of nutrients. Estimates of the percent reduction of total nitrogen based on mass load of influent and effluent shows a stark contrast between bioretention and green roof systems (Figure 8). Bioretention cells effectively capture total nitrogen (mean retention 57%), whereas green roofs show a large net release of total nitrogen (mean retention -2410%). Note that data for green roofs were only available for four sites. Nevertheless this pattern of net nitrogen leaching is almost certainly due to the application of fertilizer in the green roof media during installation, pointing toward the need for better design and installation guidelines for green roofs. Note also that the nitrogen input for green roofs is largely atmospheric deposition, a relatively low input compared with values for urban runoff which supply much of the source of nitrogen for the other technologies.

Interestingly, detention ponds clearly retain a fraction of stormwater nitrogen inputs (mean retention 49%), which is not reflected in the permanently wet retention ponds (mean retention 12%) or wetlands (mean retention 16%). This difference may be due to repeated wetting and drying cycles that occur between storm events in detention ponds, allowing for nitrification and denitrification and facilitating the removal of nitrogen, or simply indicate the load of nitrogen that has infiltrated to groundwater. Wetlands and retention ponds do not exhibit the same nitrogen load capture as detention ponds likely due to a difference in soil chemistry. Swales are expected to perform in a similar manner to detention ponds and bioretention cells based on their infiltration capacity, although it is likely that the grass or sod in the swale has been fertilized, releasing nitrogen to water flowing through these facilities. There were not enough data to report on porous pavement performance for the removal of total nitrogen.

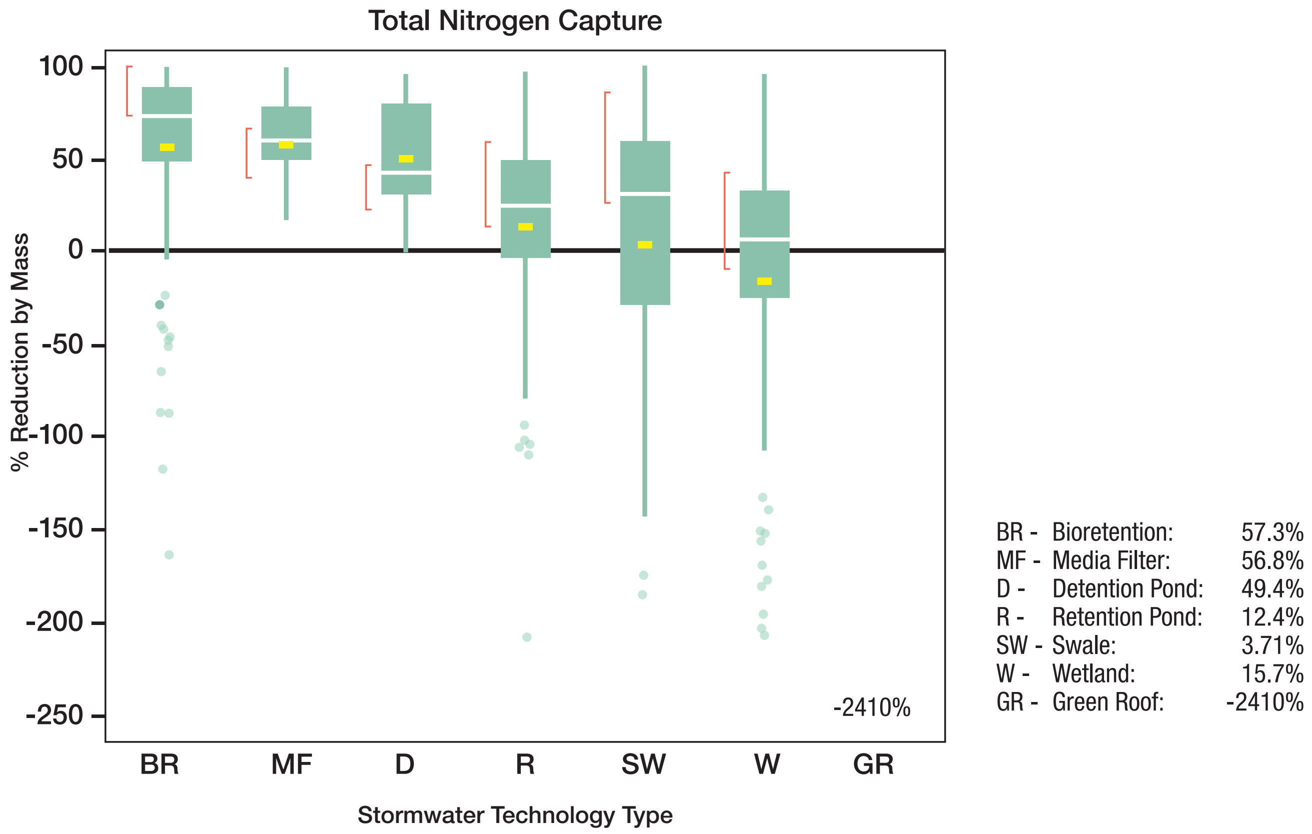


Figure 8. **Summary of stormwater capture, loss and leakage of the mass of total nitrogen by technology. The values shown are the average of performance by event observations. Note that observations are not shown for green roofs because the values of runoff retention show much greater net loss than the other technologies (mean value -2410%).**

Phosphorus

As with nitrogen, we found that phosphorus is leached from the green roofs, and also from swales (fertilizer), wetlands, and porous pavement (Figure 9). Again the release values for green roofs are misleading because precipitation typically contains low concentrations of total phosphorus. Bioretention cells (mean retention 59%), detention ponds (mean retention 13%), retention ponds (mean retention 32%), and media filters (mean retention 17%) all exhibit phosphorus retention to some degree, likely by capturing phosphorus that is associated with suspended matter. Retention ponds and bioretention cells may also capture dissolved phosphorus.

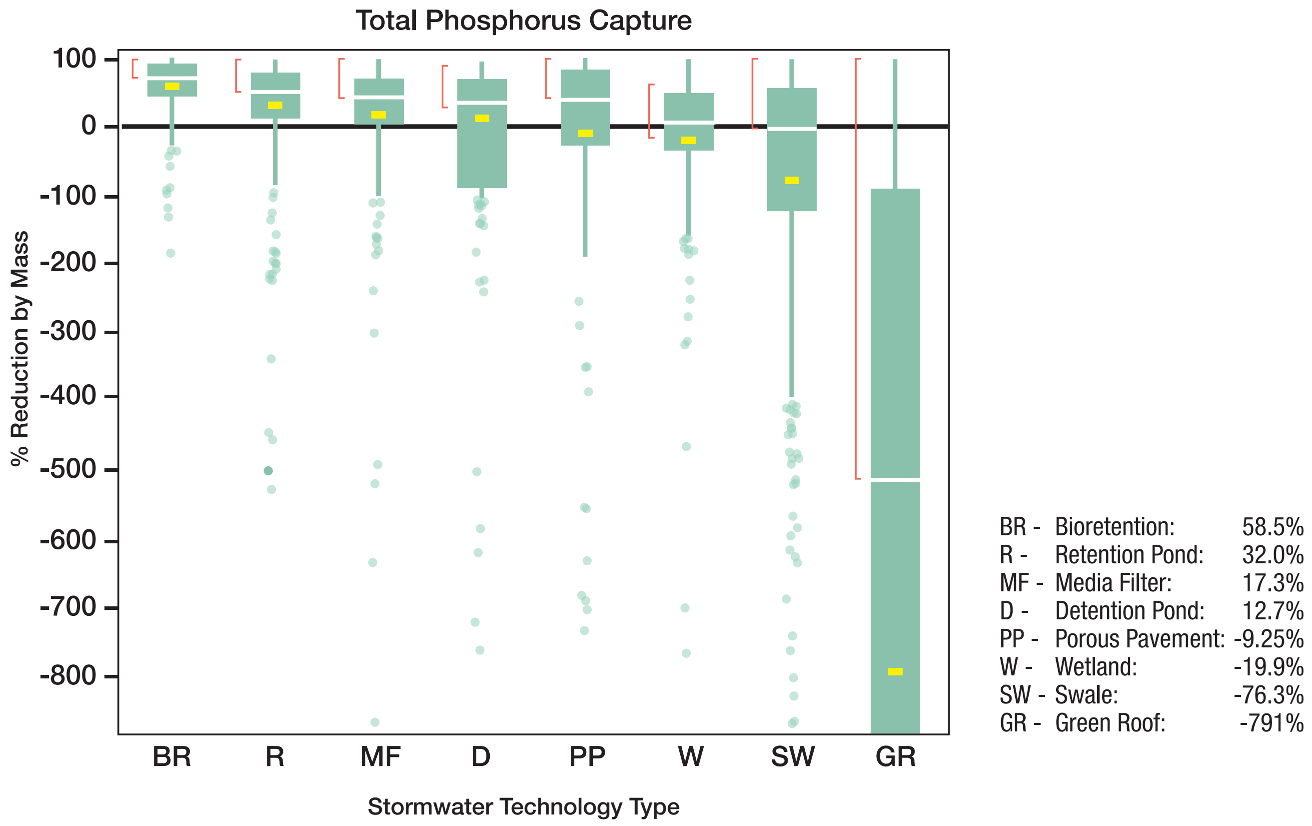


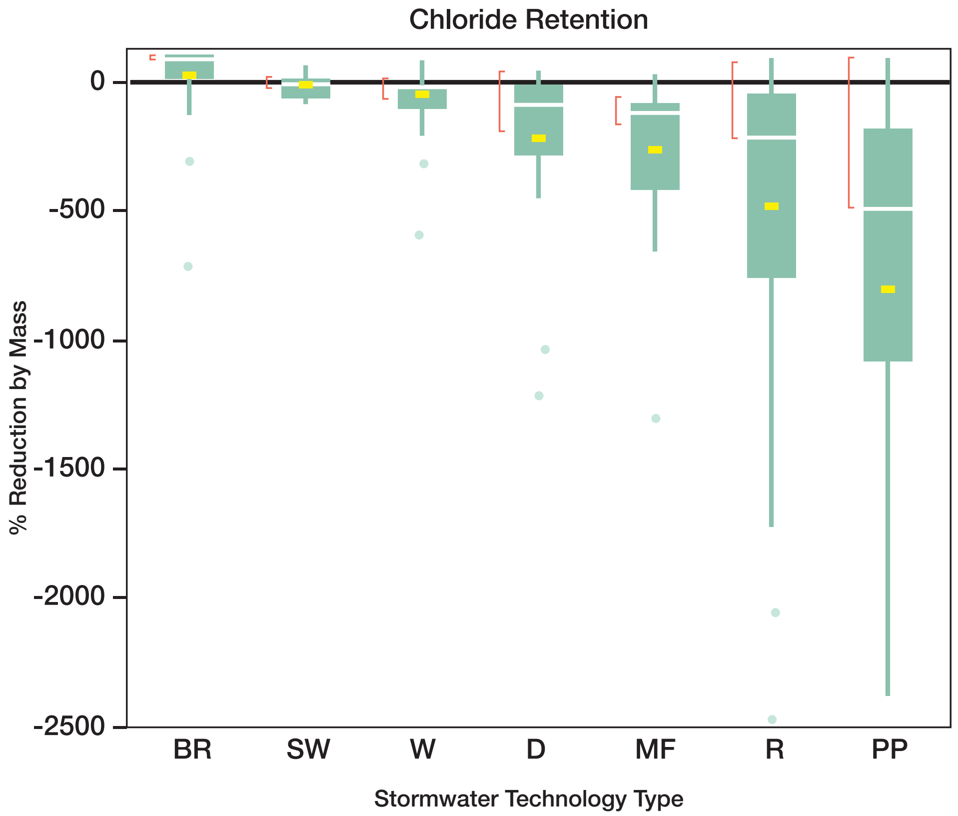
Figure 9. **Summary of stormwater capture, loss and leakage of the mass of total phosphorus by technology. The values shown are the average of performance by event observations.**

CHLORIDE

Previous researchers have noted that the accumulation of dissolved salts in living green infrastructure could result in maintenance and performance problems over the long term. However, many green infrastructure facilities receive large quantities of fresh (non-salty) water after the spring thaw, which may facilitate the flushing of accumulated salts. In general, the observations show that the technologies do not accumulate chloride (Figure 10). An apparent exception is bioretention basins, which seem to indicate moderate retention of chloride, but this pattern is based on data for only two bioretention cells. Note that in contrast to many other water quality parameters, chloride is not strongly retained by soil and plants. The net losses of chloride from detention and retention ponds, media filters and porous pavement are likely due to chloride inputs not measured in inflowing waters such as application of road salt or inputs from shallow groundwater. Note that green roofs were not monitored for chloride. Our review of the literature found few observations for sodium. We would anticipate high concentrations and loading for sodium based on observations for chloride. We would expect sodium to preferentially be retained on cation exchange surfaces associated with green infrastructure. This accumulation could result in long-term problems in system operation and maintenance. Future studies should involve analysis of sodium and its retention in green infrastructure.

TRACE METALS

All the green infrastructure technologies were relatively effective in removing lead and cadmium in influent water (Appendix 2).



BR -	Bioretention:	26.9%
SW -	Swale:	-16.2%
W -	Wetland:	-49.7%
D -	Detention Pond:	-215%
MF -	Media Filter:	-263%
R -	Retention Pond:	-480%
PP -	Porous Pavement:	-813%

Figure 10. **Summary of stormwater capture, loss and leakage of the mass of chloride by technology. The values shown are the average of performance by event observations.**

ENABLING FACTORS AND BARRIERS TO ADOPTION OF GREEN INFRASTRUCTURE

Recently there has been a notable growth in green infrastructure adoption after the U.S. EPA released an official statement in support of green infrastructure (U.S. EPA 2007). Many U.S. municipalities have embarked on wide scale green infrastructure programs while others are lagging. We conducted a literature review; a case study in Onondaga County, NY; and a survey to better understand the factors that influence decisions to adopt green infrastructure. Barriers identified through the case study and literature review are summarized in Table 2 and Appendix 3. The survey of municipal officials representing 23 communities that are currently implementing wide-scale green infrastructure plans was conducted at the second annual EPA Community Summit on Green Infrastructure on October 26-28, 2014. The survey results revealed:

1. The majority of respondents (55%) strongly agreed that local leadership efforts generally played an important role in the adoption of green infrastructure in their municipality, and that generally these efforts were linked to a collaborative organization. While several communities noted a single individual who had a key role in promoting green infrastructure strategies, many respondents (45%) disagreed that such credit could be placed on an individual.

2. The majority of respondents agreed or strongly agreed that non-government organizations (NGOs) supporting green infrastructure initiatives are present in their communities (100%) and: are generally helpful in assisting green infrastructure initiatives (92%); act as watchdogs that monitor the actions of the government (87%); and are successful in encouraging green infrastructure use among governing bodies and citizens (87%).

3. Thirty-five percent of respondents strongly agreed that a collaborative partnership exists for the development of green infrastructure projects, and 55% agreed that monitoring efforts are often shared with organizations outside of those tasked by the local government. While many respondents agreed that diverse socioeconomic groups are involved in the planning of green infrastructure initiatives (60%), the results are mixed for the involvement of indigenous groups.

4. The majority of respondents agreed that lack of interdepartmental coordination has been a barrier to green infrastructure adoption (65%). However, many respondents also felt there was not a need to utilize new engineering firms in the development of green infrastructure projects (77%); thus, local technical capacity for green infrastructure may not be a major hindrance for many municipalities. But 79% agreed or strongly agreed that operations and maintenance issues were barriers to adoption.

5. A majority of respondents agreed or strongly agreed that the consideration of social criteria (such as health and recreation benefits 91%) and the dissemination of knowledge from other green infrastructure adopting communities (96%) are critical to the development of a green infrastructure programs. The importance of social criteria may be linked to the fact the adoption of green infrastructure technologies within a framework of purposeful sustainability goals that seek to maximize welfare gains for the respective communities.

CONCLUSIONS

We offer the following conclusions from this study.

- There is considerable variation in the effectiveness of green infrastructure to reduce quantities of stormwater by site, event and technology applied. The mean decrease in stormwater inflows by site ranges from large decreases for porous pavement (72%) and bioretention cells (65%) to a negative decrease (or, increase inflows) for constructed wetlands (-11%), media filters (-12%) and retention ponds (-12%).

- Water retention may be more effective in summer than winter for bioretention cells, porous pavement and green roofs -- technologies which rely on water loss by evaporation. However, given adequate design and operation green infrastructure can perform effectively during the cold season.

- Performance for removal of contaminants from stormwater varies by technology and contaminant considered. In general, removal is effective across most technologies for suspended solids and trace metals (lead, cadmium). Removal is mixed for nutrients, with more effective removal in bioretention cells, retention and detention ponds, and media filters. This result is likely due to the removal of the particulate fraction of nutrients. Removal is less effective, based on data used in this analysis, for porous pavement, swales, constructed wetlands, and green roofs. We observed limited accumulation of chloride by green infrastructure.

- We recommend that groups developing and applying green infrastructure models use conservative performance estimates for volume reduction in order to ensure that predicted performance and actual performance are aligned. This alignment is important for appropriately managing public expectations and meeting regulatory obligations.

- Leadership efforts, collaboration with stakeholders (particularly NGOs), consideration of potential social criteria/ co-benefits, and learning from the experiences of other communities are perceived to be key enabling factors for green infrastructure adoption. Lack of interdepartmental coordination and operation and maintenance concerns are perceived to be among the greatest barriers to green infrastructure adoption.

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APPENDIX 1
Green Infrastructure Technologies Analyzed

A ***bioretention cell*** (BR), also known as a bioretention basin, biofilter or bioswale is a green infiltrative system that captures water from building and roadway runoff by interrupting the traditional urban stormwater pathway and allowing it to collect at a location upstream from the storm sewer inlet. The cells are installed by excavating a pit or trench and back-filling with a porous, low-nutrient media, such as a layer of sand-loam mix over coarse gravel, and topped with a layer of mulch. The site is planted with a variety of native or horticultural species, which are usually fertilized or given compost only during an initial establishment period. The volume of stormwater captured in bioretention cells is related to the contributing area, the size and depth of the soil media, the porosity of the underlying native soil, whether or not the site is equipped with an underdrain and/or liner (not recommended), and to a lesser extent, the types of plants used. The primary mechanisms to reduce runoff are both infiltration and evaporation.

A ***green roof*** (GR) consists of several layers of liners to protect the building structure from water damage, overlaid by a lightweight soil matrix, and planted with a variety of drought-tolerant plants, such as sedums, native or pioneer species, and occasionally, edible or horticultural plants. The volume of stormwater captured by a green roof is directly related to the roof area and depth of the soil media. The primary mechanism to reduce runoff is via evapotranspiration.

There are many different types of ***porous pavement*** (PP), including porous asphalt, porous concrete, permeable/grassed interlocking pavers, cobblestone, and other materials used for vehicle and pedestrian surfaces. Porous pavement is usually installed over layered courses of gravel or crushed stone and may include an underdrain. The volume of capture depends upon the contributing area, permeable surface area, and infiltration rate. A large fraction of the stormwater capture is diverted to infiltration to groundwater and evaporation through the surface after the storm event. Evaporation from permeable asphalt surfaces is influenced by solar radiation, permeable surface color and the planting scheme of adjacent lands.

A ***media filter*** (MF) uses a substrate to remove suspended solids and clarify water as it passes through the filter. Media filters rely on a wide variety of substrates such as sand, peat, geotextile fabric, crushed rock or glass, carbon, shredded paper, rubber pellets, and foam. Media filters, sometimes called “biofilters” because they provide microbiological habitat surface, may also be designed to remove dissolved pollutants, especially ammonia and nitrate. Most media filters have a small storage volume with limited connectivity to natural groundwater tables and therefore may impact water quality without changing overall stormwater volume.

Swales (SW), also called grassed waterways or vegetated filter strips, may be confused with bioretention cells (sometimes called bioswales). Grassed swales are generally planted with grass seed or sod and they may resemble a wide, gently sloping, shallow trench. The soil in the swale may be excavated and replaced with better-draining media replacement, or commonly, native soil that is re-graded to create a trench to facilitate stormwater collection. This type of swale is common in agricultural and transportation applications as well as residential developments to slow the velocity of flow and allow for the removal of suspended solids from runoff via overland sheet flow. Swales with sod have limited connectivity with underlying groundwater, although the amount of infiltration is highly dependent upon the underlying soil type and wetting/drying cycles. Vegetated swales are often maintained by periodic mowing (at weekly to seasonal intervals), whereas bioretention cells are usually not mowed and have much more porous soil.

Detention ponds (D) are traditional stormwater management structures designed to attenuate the peak of hydrologic discharge during a storm runoff event. They are generally grassed or sparsely vegetated, and nearly always have a piped inlet and outlet. There are subtle differences between detention ponds and swales that are related to the purpose of the structure. Detention ponds appear like a pond when they are full of water, and a grassed field with surrounding berms when they are dry. Detention ponds almost always have distinct culverts or pipes serving as point inlets and outlets, while swales typically receive water as overland flow along the length of the swale. Ideally a detention pond will fill during a wet-weather event and then slowly release the collected water over the 12 to 48 hours that follow the event, providing short-term storage but little permanent capture. ***Retention ponds*** (R) are similar to detention ponds, except they maintain permanent standing water, thus creating hydric soils and supporting a different biotic community.

Constructed wetlands (W) are frequently installed in areas adjacent to known tributaries or seasonal rivulets, or in pockets of low-lying, poorly draining soils. They may be built to replace disturbed natural wetlands after the completion of a construction project. They provide additional surface storage during wet-weather events, and may act to infiltrate stormwater or conversely, as a conduit for discharge of groundwater depending on the groundwater table. Wetlands are known to provide flood and inclement weather protection as well as nutrient removal, depending on groundwater exchange and oxidation-reduction conditions.

APPENDIX 2
Water Quality Results for Lead and Cadmium

LEAD

All the green infrastructure technologies were relatively effective in removing lead, including porous pavement and green roofs, which on average had low influent concentrations compared with other technologies (Figure A.2.1). The low concentrations of lead in input waters for green roofs and maybe porous pavement are likely due to lower concentrations in atmospheric deposition, compared to other stormwater sources.

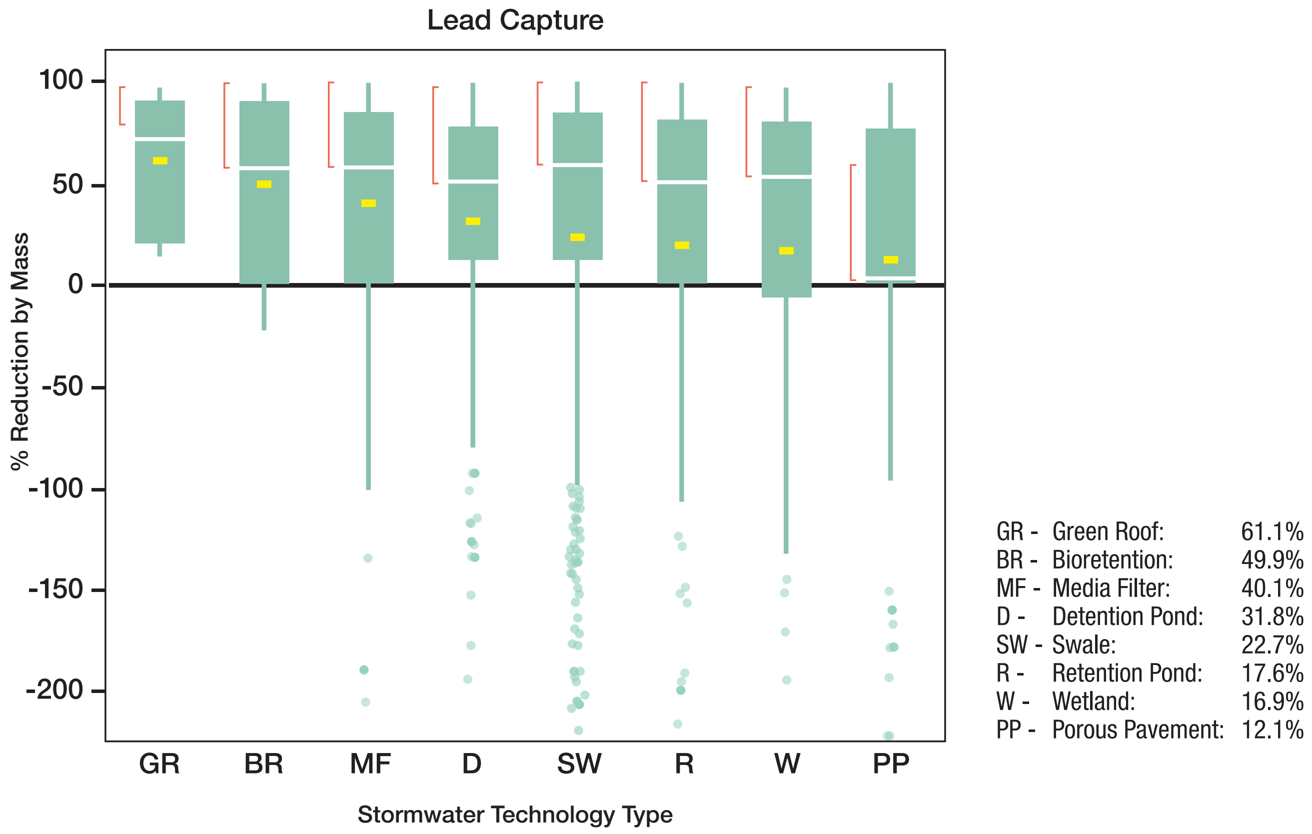
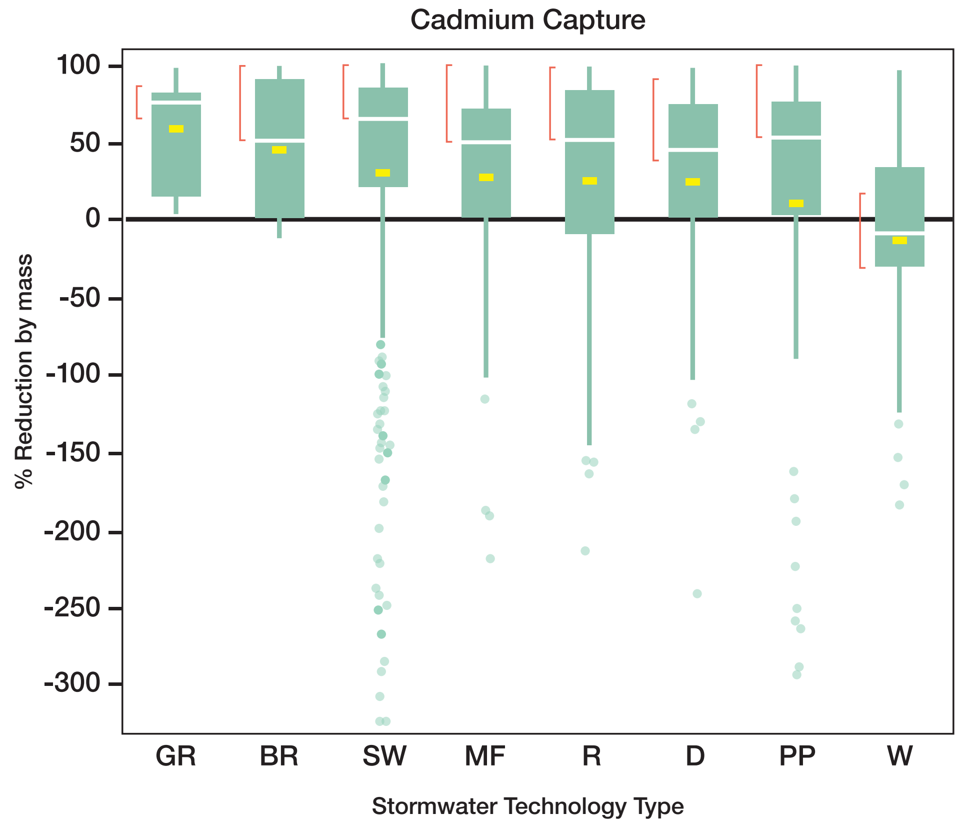


Figure A.2.1. Summary of stormwater capture, loss and leakage of the mass of lead by technology. The values shown are the average of performance by site observations.

CADMIUM

Cadmium was also generally retained effectively by all technologies except for constructed wetlands (Figure A.2.2). The relatively poor performance of constructed wetlands might be explained by the reducing environment of permanently wet soils. The anoxic conditions in wetland ecosystems can create conditions that allow mobilization of cadmium and other trace metals.



GR -	Green Roof:	59.4%
BR -	Bioretention:	46.5%
SW -	Swale:	29.2%
MF -	Media Filter:	28.2%
R -	Retention Pond:	24.8%
D -	Detention Pond:	24.2%
PP -	Porous Pavement:	12.8%
W -	Wetland:	-12.2%

Figure A.2.2. **Summary of stormwater capture, loss and leakage of the mass of cadmium by technology. The values shown are the average of performance by site observations.**

APPENDIX 3.
Barriers to Adoption

A review of barriers identified in various research efforts related to green infrastructure adoption and implementation is provided in Table A.3.1. Original research efforts (as opposed to synthesis reviews) were considered, including case studies and workshop analyses that focused on green stormwater infrastructure or low impact development technology adoption; thus, barriers to developing sustainable urban water systems were not included. Note that much of the barrier identification literature relies on the solicitation of experts' perceptions of barriers in combination with a researcher's familiarity of barriers previously identified[1]. Many studies focused on barriers facing municipal leaders as well as barriers facing individual actors and other institutions, such as community residents and engineering firms. Categorization of the barriers is based loosely on the social-ecological systems framework (Ostrom 2009; McGinnis and Ostrom 2011). While some studies ranked the severity of various barriers experienced by communities, these results are not expressed in Table A.3.1.

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[1] For example, barriers identified by Roy (2008) consists of a synthesis of the literature and compilation of the authors' ideas

Table A.3.1. **Summary of barriers to adoption of green infrastructure.**

Category	Barrier	Sources
Actors	**Leadership and entrepreneurship** · Political, community and industry	(Godwin et al. 2008); (Madden 2010); (Flynn and Davidson 2015)
	Community involvement, partnerships, and outreach	(Ruppert and Clark 2009); (Stockwell 2009);(Clean Water America Alliance 2011); (Montalto et al. 2013); (Flynn and Davidson 2015)
	Knowledge of system and technologies · Awareness · Mental model of watershed system and infrastructure effects · Cultural preferences · Disparity among public, private, and government actors	(Lassiter 2007); (Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Earles et al. 2009); (Ruppert and Clark 2009); (CH2MHill 2010); (Hammitt 2010); (LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Siglin 2012); (Montalto et al. 2013); (Flynn and Davidson 2015); (Baptiste, Foley, and Smardon 2015)
	Trust and reciprocity among stakeholders	(Montalto et al. 2013); (Flynn and Davidson 2015)
	Past experiences	(Montalto et al. 2013); (Flynn and Davidson 2015)
	Socioeconomic attributes	(Montalto et al. 2013); (Flynn and Davidson 2015); (Baptiste, Foley, and Smardon 2015)
	Number of actors · Human capital constraints	(Oregon Environmental Council 2007); (Earles et al. 2009);(Stockwell 2009); (CH2MHill 2010); (Flynn and Davidson 2015)

Table A.3.1. Summary of barriers to adoption of green infrastructure (continued).

Category	Barrier	Sources
Governance	**Regulatory rules and structure** · Federal, state and local · Codes and ordinances · Water rights	(Lassiter 2007); (Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Brown, Farrelly, and Keath 2009); (CH2MHill 2010); (Earles et al. 2009); (Ruppert and Clark 2009); (Stockwell 2009); (LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Flynn and Davidson 2015)
	Funding issues · Program funding o Incentives · Cost-effectiveness o Life cycle costs o Operation and maintenance costs	(Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Brown, Farrelly, and Keath 2009); (Earles et al. 2009); (Ruppert and Clark 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010);(LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Siglin 2012); (Flynn and Davidson 2015)
	Interdepartmental coordination	(Roy et al. 2008); (Brown, Farrelly, and Keath 2009); (CH2MHill 2010); (Hammitt 2010); (LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Flynn and Davidson 2015)
	Property rights/Land ownership	(Brown, Farrelly, and Keath 2009); (Earles et al. 2009); (Clean Water America Alliance 2011); (Siglin 2012); (Montalto et al. 2013); (Flynn and Davidson 2015)
	Operation and maintenance · Apportioned responsibility · Compliance · Demands of decentralized projects	(Lassiter 2007); (Oregon Environmental Council 2007); (Hammitt 2010); (Brown, Farrelly, and Keath 2009); (Earles et al. 2009); (Ruppert and Clark 2009); (CH2MHill 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Montalto et al. 2013);
	Repertoire of norms and strategies · Perceived risk · Resistance to change · Disparities between institutions	(Lassiter 2007); (Oregon Environmental Council 2007); (Roy et al. 2008); (Earles et al. 2009); (Ruppert and Clark 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010); (LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Siglin 2012); (Flynn and Davidson 2015)
	Geographical scale of governance system	(Stockwell 2009)

Table A.3.1. Summary of barriers to adoption of green infrastructure (continued).

Category	Barrier	Sources
Engineering and Technology	**Technical capacity and expertise**	(Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Earles et al. 2009); (Ruppert and Clark 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010); (LaBadie 2010); (Madden 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Flynn and Davidson 2015)
	Research support · Performance uncertainty · Safety	(Alexander and Tomalty 2002); (Lassiter 2007); (Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Earles et al. 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012);
	Project implementation · Planning and review process · Challenging designs · Design standards and codes	(Oregon Environmental Council 2007); (Godwin et al. 2008); (Roy et al. 2008); (Earles et al. 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010); (LaBadie 2010); (Clean Water America Alliance 2011)
Urban Watershed System	**Biophysical characteristics (particularly regarding site selection)** · Available space · Landscape · Soil type · Climate	(Lassiter 2007); (Oregon Environmental Council 2007); (Earles et al. 2009); (Stockwell 2009); (CH2MHill 2010); (Hammitt 2010); (Clean Water America Alliance 2011); (Olorunkiya, Fassman, and Wilkinson 2012); (Siglin 2012); (Montalto et al. 2013)
	Existing stormwater infrastructure	(Earles et al. 2009); (Madden 2010); (Siglin 2012); (Montalto et al. 2013); (Flynn and Davidson 2015)

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Photo Captions

Inside front cover: Three constructed wetlands at the Olentangy River Wetland Research Park, on the campus of the Ohio State University in Columbus, OH. Photo: William Mitsch, Florida Gulf Coast University.

Page 1: A bioretention cell or vegetated swale designed to capture runoff from the 690 overpass in Syracuse, NY. Photo: Caitlin Eger, Syracuse University.

Page 2: Onondaga County's Harbor Brook constructed treatment wetlands at the end of its first planted season (Syracuse, NY). Photo: Caitlin Eger, Syracuse University.

Page 6: Purple coneflower (Echinacea purpurea) in rain garden with permeable pavers in a neighborhood in Chicago, IL. Photo: Center for Neighborhood Technology (https://flic.kr/p/og7eQS).

Page 10: Spring seedums on the Syracuse Center of Excellence green roof in Syracuse, NY. Photo: Amanda Westerdahl, Syracuse Center of Excellence.

Page 14: Permeable pavers and rain gardens, West Union, Iowa. Photo: Conservation Design Forum, via the Center for Neighborhood Technology (https://flic.kr/p/oq98XY).

Page 19: Paving/grating detail of new tree along Centennial Mall, approaching the State Capitol in Lincoln, NE. Trees are supported below ground by the Silva Cell system, which also allows the trees and soil to manage stormwater on-site. Stormwater enters the system through the pavers and grating shown here. Photo: Lyndsey Haag, DeepRoot (https://flic.kr/p/orP3VP).

Page 21: Native species from the Gadway sandstone pavement barrens planted on the Gateway Building of the SUNY-ESF campus in October 2013 (Syracuse, NY). Photo: Caitlin Eger, Syracuse University.

Page 22: A detention basin in Seattle, WA, during installation. Photo: Turner Construction Company.

Page 25: Recently mown residential grassed swale in Montgomery County, MD. Photo: Montgomery County Department of Environmental Protection.

Page 32 and 33: Because it sits atop a parking garage and rail yard, Chicago's Millennium Park is considered the largest green roof in the world. Lurie Garden at Millennium Park – Chicago, IL. Photo: Center for Neighborhood Technology (https://flic.kr/p/o1nqXY).

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