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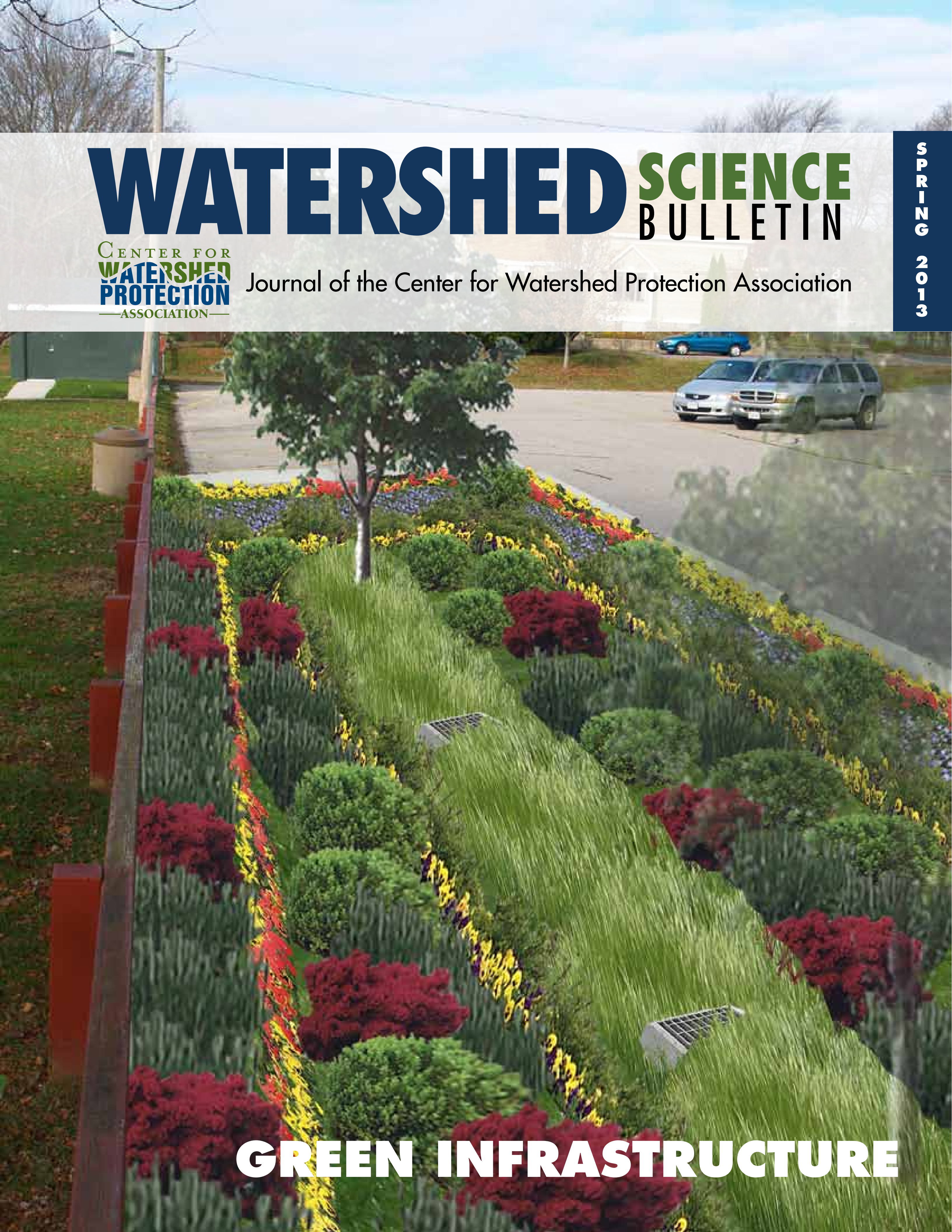

GREEN INFRASTRUCTURE

Volume 4, Issue 1

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From the Editor’s Desk

This issue of the Bulletin focuses on the use of green infrastructure in urban watersheds and how its implementation has gone beyond water quality improvements to enhance community involvement and provide greater ecological function to our urban areas. For the purposes of this issue, we define green infrastructure broadly to include landscape-scale natural features and site-scale practices, such that we may consider the full range of its applications. For example, green infrastructure in the field of conservation planning refers to the network of natural lands across the landscape, such as forests, wetlands, stream corridors, and grasslands, while its applications in engineering include practices ranging from impervious cover reduction to stormwater best management practices, such as bioretention.

Green infrastructure strives not only to improve water quality and aquatic ecosystems, but also to positively affect social and economic aspects within communities. To this end, innovation in design, from community planning to stormwater management, is key to solving many issues facing urban areas today. Green infrastructure in its many forms is part of the solution, and contributors to this issue provide examples of the type of innovation that is happening in watersheds throughout the United States at a regional or watershed scale.

In This Issue

Mayer and others provide a detailed analysis of a stream restoration project in Baltimore County, Maryland, to identify factors that limit the removal of excess nitrogen in degraded urban streams. The case study demonstrates how monitoring before and after a restoration is central to the identification of the nutrient contributions from instream processes and restoration and management actions to enhance nitrogen removal.

Moving from the reach scale to the watershed scale, **Wood and others** compare two modeling approaches to select the most cost-effective best management practices in a subwatershed of the Charles River. The regulatory driver behind the project required a process that was technically and scientifically sound and had buy-in from the local jurisdiction. The lessons learned from their experience are likely to be applicable to urban watersheds elsewhere that strive to find a balance between pollutant load reductions and cost.

In the Vignettes section, a series of case studies highlight the role of green infrastructure in the redevelopment of brownfields and its multiple benefits beyond stormwater pollutant load reduction. **Gray and Green Approaches To Address Combined Sewer Overflows in Northeast Ohio** highlights Project Clean Lake, through which the Northeast Ohio Regional Sewer District adopted a “triple-bottom-line” approach to reduce stormwater loadings to its combined sewer system. Brownfields and vacant properties in areas targeted for urban revitalization are priority sites for green infrastructure. **The Green Renewal of Milwaukee’s Menomonee Valley** describes a community-based effort, whereby local input on the area’s vision and goals resulted in a design to redevelop a blighted industrial district using green infrastructure that include stormwater management and local amenities, such as a trail system. A green infrastructure approach is used to green an urban corridor to restore the ecological function and resilience that connects two water resources—the Mississippi River and Bayou Bienvenue in New Orleans, as described in **Groundwork New Orleans: Developing a Green Slice Watershed Habitat Corridor**. The vignette, **The Role of Stream Restoration in Green Infrastructure**, describes an urban stream restoration as an example of how an urban, channelized stream can be transformed into a meandering channel, providing water quality improvements and other ecosystem services.

In the Ask the Experts section, we ask practitioners and researchers how their communities are using green infrastructure to address combined sewer overflows.
With this issue, we aim to help inform watershed and stormwater practitioners about how green infrastructure, in its many forms, can fit into their programs to protect and restore watersheds.

Neely L. Law, PhD, Editor-in-Chief

Effects of Stream Restoration on Nitrogen Removal and Transformation in Urban Watersheds: Lessons from Minebank Run, Baltimore, Maryland

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Abstract

Stream restoration is an important green infrastructure tool that may improve water quality and protect watershed function and services. Runoff from impervious surfaces and leakage from sewage infrastructure, septic systems, agricultural ditches, and tile drains creates excess nitrogen (N) in groundwater, surface water, and coastal waters, which is detrimental to human and ecosystem health. Degraded urban streams suffer from altered hydrology and biogeochemistry that can impair a stream's capacity to process and remove excess N in stream water. This case study of Minebank Run in Baltimore, Maryland, found factors that limit the removal of excess N in degraded streams and identified restoration and management approaches that enhance N removal. We found three stream restoration strategies that can greatly improve N removal capacity: (1) increasing hydrologic residence time, (2) increasing hydrologic connectivity between the stream channel and floodplains, and (3) increasing organic carbon availability to foster denitrification "hot spots." The findings suggest that combining approaches—such as prioritizing nonpoint N source reductions in watersheds and integrating green infrastructure with stream and floodplain wetland restoration approaches, which reduce peak flow, increase hydrologic residence time, and supply organic matter (e.g., maintaining riparian zones)—will be the most efficient way to enhance N removal and protect ecosystem services in urban streams.

Introduction

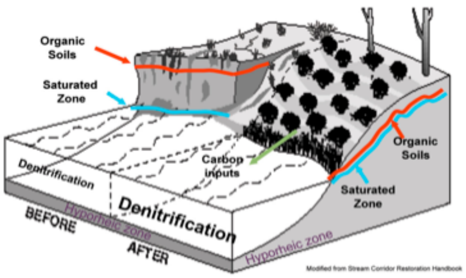
In many watersheds, the rapid expansion of urban land use has coincided with increases in eutrophication, hypoxia, and toxic algal blooms in surface and coastal waters (Freeman et al. 2007; Kaushal et al. 2008). Urbanization can dramatically impact watershed health through increased runoff from impervious surfaces, changes in sediment delivery, and increased pollutant and nutrient loads from nonpoint sources (Mayer et al. 2010). In addition, urban streams have a decreased capacity for the retention of nutrient loads as a result of channelization and hydrologic disconnection between streams and floodplain wetlands and riparian zones (Paul and Meyer 2001). Stream restoration can be an important green infrastructure tool that improves water quality and protects ecosystem function and services, but designs and outcomes at the reach scale can vary (Kaushal et al. 2008; Sivirichi et al. 2011).

Channel incision and bank erosion caused by increased runoff are major contributors to a suite of degradation effects, collectively termed the *urban stream syndrome* (Gift et al. 2010; Walsh et al. 2005). The consequences of urban stream syndrome are decreased water infiltration, lower water tables, dry aerobic riparian soils, and a decreased hydrologic connectivity among groundwater, riparian zones, and streams (Gift et al. 2010; Kaushal et al. 2008). These changes alter biogeochemical processes that are critical for removing excess nutrients, like nitrogen (N), from urban watersheds (Mayer et al. 2010).

N is an important nutrient for aquatic ecosystems; however, in excess, it is detrimental to human health and ecosystem function (Mayer et al. 2007). Anthropogenic inputs, such as fossil fuels, fertilizers, and sewage, increase N loads in watersheds and estuaries, cause pollution of groundwater, and increase eutrophication in surface waters (Vitousek et al. 1997). N can be attenuated by uptake and assimilation into plant, algal, and microbial biomass; over time, however, it will be released back to the environment through decomposition. The only process that can remove N from surface waters and groundwater is denitrification, a microbially mediated process that transforms nitrate (NO_3^-) to gaseous forms (N_2) under anaerobic conditions (Tiedje 1982). Consequently, a primary goal of our research was to find ways to optimize denitrification within stream restoration projects as a way to remove excess N.

Laboratory studies have shown that most bacteria use oxygen (O_2) in respiration to produce energy for growth. However, when dissolved O_2 (DO) levels are low (i.e., in *anaerobic* conditions), many different species of bacteria, referred to as *denitrifiers*, can use NO_3^- in place of O_2 for respiration (Tiedje 1982). Using NO_3^- instead of O_2 in respiration requires a specific set of specialized enzymes that reduce NO_3^- (available and mobile) to N_2 via respiration to make energy. However, these specialized enzymes are activated only when DO concentration is low (Tiedje 1982). So the primary factor controlling denitrification (the reduction of NO_3^- to N_2) is DO concentration.

O_2 is supplied to the water and sediments by the diffusion of atmospheric O_2 across the air–water interface and through photosynthesis of aquatic plants and algae. The solubility of O_2 is a function of water temperature, salinity, and atmospheric pressure. DO can be used up through respiration by plants, animals, and microbes, thereby generating the anaerobic conditions needed for denitrification. Once these anaerobic conditions are set, denitrification rates are then often limited by NO_3^- or carbon (C) availability (Tiedje 1982). NO_3^- is not typically limited in degraded streams, but C can be limited as a result of a lack of vegetation or a disconnection from the watershed that supplies C as organic matter.



Modified from Stream Corridor Restoration Handbook

Figure 1. Hypothetical effects on biogeochemistry of stream restoration that addresses heavily incised streambanks. Modified from Federal Interagency Stream Restoration Working Group (FISRWG). 1998. Stream Corridor Restoration: Principles, Processes, and Practices. GPO Item No. 0120-A, SuDocs No.A 57.6/2: EN 3/PT.653. ISBN-0-934213-59-3.

Potential of Stream Restoration To Remove N

The riparian–stream interface has a strong influence on stream biogeochemical cycling and ecology. This interface creates dynamic gradients of DO, N, and organic C as groundwater and stream water mix. Thus the riparian–stream interface is an active location for biogeochemical reactions such as C metabolism, nitrification, and denitrification (Figure 1; see also Jones and Holmes 1996).

In healthy undegraded streams, hydrologic connectivity between the landscape and stream at the riparian–stream interface can facilitate the mixing of N, organic matter, and denitrifying microbes in the subsurface, fostering “hot spots” for N removal via denitrification (Hedin et al. 1998; Kaushal et al. 2008). Denitrification occurs in such hot spots when heterotrophic bacteria consume O_2 and create anoxic conditions in the groundwater, thereby causing facultative anaerobic bacteria to switch to using N (specifically NO_3^-) instead of O_2 for respiration.

However, N processing in degraded urban streams may be impaired because of increased rates of erosion and vertical hydrologic disconnectivity with groundwater tables and the stream (e.g., Groffman et al. 2002).

Case Study Purpose and Goals

In 2001, researchers from the US Environmental Protection Agency (USEPA), US Geological Survey (USGS), Cary Institute of Ecosystem Studies, and the University of Maryland began a collaborative, long-term study of the effects of stream restoration on biogeochemistry. This paper integrates the results from previous research projects (Craig et al. 2008; Doheny et al. 2007; Doheny et al. 2006; Duerksen and Snyder 2005; Gift et al. 2010; Groffman et al. 2005; Harrison et al. 2012a; Harrison et al. 2012b; Harrison et al. 2011; Kaushal et al. 2008; Klocker et al. 2009; Mayer et al. 2010; Mayer et al. 2004; Sivirichi et al. 2011; Striz and Mayer 2008) to present a comprehensive case study on N and the biological and hydrologic processes that limit the transformation of N in a degraded urban stream and how stream restoration affects N processing.

Minebank Run, a second-order stream in Baltimore, Maryland, whose headwaters originate from a storm drain, was chosen as a long-term monitoring site because the Baltimore County Department of Environmental Protection and Resource Management (DEPRM) had plans to restore and reconstruct this stream to address numerous geomorphic problems. In addition, research associated with the Baltimore Ecosystem Study, a National Science Foundation–funded urban Long Term Ecological Research (LTER) project, provided context on the wide range of stream physical and chemical conditions in the area, including a comparison with forested reference streams, agricultural streams, and diverse urban and suburban streams.

Urban development in Minebank Run watershed (which has over 80% urban and suburban land use) predates stormwater management regulations, and thus, uncontrolled runoff entering the stream was a significant water quality problem. Minebank Run exhibited the urban stream syndrome, including steep bank incision, flashy hydrology, rapid flushing of nutrients and sediments, and severe erosion (Doheny et al. 2006; Doheny et al. 2007; Striz and Mayer 2008). During storm events, Minebank Run displayed instantaneous peak discharges up to 320 times higher than mean discharge (maximum storm of 39.36 cubic meters/second versus a maximum mean of 0.12 cubic meters/second) (Doheny et al. 2006). This flashy hydrology precluded subsurface interaction, especially during storm events when Minebank Run functioned like a conduit, carrying pollutants to the Chesapeake Bay. Minebank Run was also characterized by streambed aggradation and degradation, altered biogeochemistry at the riparian–stream interface (or *hyporheic zone*), damage to sanitary and bridge infrastructure due to sediment scour and floods, and altered hydrology that increased the risk of erosion and incision from even minor storm events (Doheny et al. 2006; Doheny et al. 2007; Striz and Mayer 2008).

At a reach scale, the project team reconstructed Minebank Run using a combination of approaches, such as natural channel design (Rosgen 1996), soil bioengineering measures, aquatic habitat features, and more experimental approaches using low connected floodplains for stormwater management (Duerksen and Snyder 2005; Sortman 2002). Overall, DEPRM's restoration design was intended to mimic natural valley and floodplain morphology, including step-pool and pool–riffle sequences, stable meander patterns, and stormwater management in headwater reaches with adequate space for floodplain reconnection. While the restoration approach was primarily intended to address severe channel erosion, we hypothesized that restoration could also affect the geology, biology, hydrology, and biogeochemistry of the system (Mayer et al. 2004).

We use results from the Minebank Run stream restoration research project to identify factors that limit the processing of N in degraded streams and quantify the change in denitrification due to restoration. From successes and failures, we also identify restoration and management approaches that are likely to enhance N processing based on long-term monitoring.

Methods

The Importance of Organic C for NO_3^- Removal

This study investigated the relationships among streamflow, water table elevation, groundwater NO_3^-, dissolved organic C (DOC), DO, and chloride (Cl^-) at Minebank Run by comparing restored and degraded stream reaches. The project team measured denitrification potential, root biomass, soil organic matter, groundwater chemistry (including C and N), stream discharge, and water table elevations at riparian sites, restored and degraded stream reaches at Minebank Run, and nearby reference streams. We determined denitrification potential by an *in vitro* measure of denitrification enzyme activity in the soil (Mayer et al. 2010; Groffman et al. 1999), measured root biomass by dry weight (Gift et al. 2010), determined soil organic matter by the loss-on-ignition method (Gift et al. 2010), determined groundwater chemistry using standard methods (Mayer et al. 2010), measured stream discharge via USGS stream gauges (Mayer et al. 2010), and determined water table elevations using piezometers (Mayer et al. 2010).

The Influence of Groundwater Tables and Hydrology on NO_3^--N: Setting the Proper Oxidation–reduction Potential for Denitrification

To assess the impact of hydrology on N transformation, we collected groundwater from the stream channel and streambank at the riparian–stream interface and measured the oxidation–reduction potential (ORP), DOC, NO_3^-, Cl^-, stream discharge, and water table elevations (for methods, see Mayer et al. 2010). ORP is a measurement of the tendency of a compound to accept or donate electrons. In general, the more oxidized (aerobic) a sediment becomes, the more positive the ORP. Alternatively, the more reducing (anaerobic) the sediment, the more negative the ORP and the greater the likelihood that denitrification will occur.

The Importance of Surface Water Velocity for N Uptake

This study measured NO_3^- retention and sediment denitrification potential in two similarly designed restored streams and two degraded unrestored streams in Baltimore, Maryland. We define N retention as a measure of a system's capacity to process N pollution through uptake by plants and algae or removal of N by denitrification. The project team measured NO_3^- retention in a restored reach of Minebank Run using a ^{15}N stable isotope surface water tracer test (Klocker et al. 2009). We measured sediment denitrification potential using methods described above (Groffman et al. 1999).

The Importance of Groundwater Residence Time for N Retention

We compared *in situ* denitrification rates between hydrologically connected (low-bank, low-incision) and disconnected (high-bank, highly incised) sites at the riparian–stream interface within restored and unrestored reaches (see Kaushal et al. 2008 for details). We determined *in situ* denitrification rates using a N isotopic tracer test (Addy et al. 2002) in groundwater sampled from piezometers positioned to quantify spatial and temporal variability (Kaushal et al. 2008).

The Use of Urban Alluvial Wetlands as Sinks for Excess N

The project team compared *in situ* denitrification rates and mass removal of NO_3^- among two relict oxbow wetlands, three constructed wetlands, and two forested reference wetlands. We determined *in situ* denitrification rates as described above (also see Addy et al. 2002) from groundwater, surface water, and stream water collected from piezometers (Harrison et al. 2011). We also determined the mass of N removal—the total mass of NO_3^- removed per cubic meter of water flow through the hyporheic zone (e.g., Kaushal et al. 2008)—by estimating the percentage difference or change in the mass of N entering a stream reach and leaving a stream reach using the mass balance approach (e.g., Sivirichi et al. 2011).

Results and Discussion

The Importance of Organic C for NO_3^- Removal

N flux and uptake in urban streams is strongly influenced by organic C flux and availability (Groffman et al. 2005). However, it is unclear how these C and N processes are affected by the disconnected hydrology of degraded streams or by restoration approaches (e.g., the use of geomorphic structures), both of which may result in unique urban stream biogeochemistry (Kaye et al. 2006). The objective in this study was to determine the importance of the riparian–stream interface in N processing and identify conditions that favor N transformation in stream channels and banks.

We found that denitrification potential and microbial biomass C were higher in riparian–stream interface sediments than in deep floodplain sediments (Mayer et al. 2010), suggesting that the riparian–stream interface is important for responding to and processing C and NO_3^-. Thus, restoration approaches that increase C supply to riparian–stream interface sediments could increase the denitrification capacity of the stream ecosystem.

Stream features (pools, riffles, vegetated and unvegetated gravel bars, and organic debris dams) that contain high levels of organic matter have the highest denitrification potential (Groffman et al. 2005). However, high and flashy storm flows at Minebank Run limited the accumulation of organic matter in these features, resulting in a lower denitrification potential than that of nearby streams. Nevertheless, results showed a strong positive relationship between root biomass and soil organic matter and between soil organic matter and denitrification potential (Gift et al. 2010). Thus, deep-rooted vegetation may help maintain an active denitrification zone in restored riparian areas.

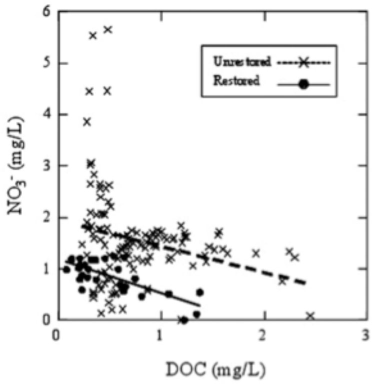


Figure 2. Relationship of NO_3 – to DOC in groundwater of the hyporheic zones of the restored and unrestored stream reaches

Groundwater chemistry showed an inverse relationship between NO_3^- and DOC over time (Figure 2) as well as a positive relationship between NO_3^- and DO. This means that

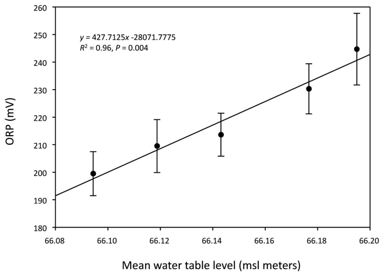
(1) where more DOC is available, one is likely to find less NO_3^- in the groundwater and (2) denitrification is probably occurring in poorly oxygenated groundwater where DO is used up via microbial respiration. However, this trend was strongest in the subsurface environment of the restored reach (Kaushal et al. 2008), indicating that the restored subsurface more consistently provided this favorable environment (i.e., more DOC and less DO). The improved denitrification potential may be a function of the restored hydrologic flow paths and increased concentration and/or availability of DOC. Stream structures that accumulate organic matter, like debris dams, and plant roots in riparian areas can help supply DOC for denitrification. In fact, a recent Minebank Run study showed that oxbow wetlands with high primary productivity serve as a good source of DOC, have a high denitrification potential, and could be useful features to incorporate into stream restoration projects where N mitigation is a goal (Harrison et al. 2012a). However, features that maintain anoxic conditions in the subsurface may mobilize phosphorous or produce methyl mercury, and if denitrification does not proceed to completion, N oxides, which are potent greenhouse gases, may be produced (Harrison et al. 2012a).

The Influence of Groundwater Tables and Hydrology on NO_3^--N: Setting the Proper Oxidation–reduction Potential for Denitrification

This study demonstrates that the riparian–stream interface plays a key role in stream N removal. Stream hydrology and geomorphic features physically define the riparian–stream interface and influence the flux of stream water into and out of it. Therefore, one must identify stream restoration efforts that promote N transformations within the riparian–stream interface yet maintain ecological and geomorphic integrity. We looked for associations between nutrient concentrations and hydrologic conditions to better understand how C, N, and Cl^- cycle along hydrology flow paths and are stored or released in the riparian–stream interface.

We found that groundwater table elevation changed in response to stream discharge, rising when discharge increased and resulting in changes in water chemistry, notably the significant increase in the ratio of NO_3^- to Cl^-. This relationship suggests that microbial processing of NO_3^- in streams occurs when groundwater elevations are low and residence times are high. Here we define residence time as the amount of time a molecule of NO_3^- spends in contact with the microbially active denitrification zone within the riparian–stream interface (e.g., Kaushal et al. 2008). However, the response to groundwater level differs between stream channel and riparian zones. Declines in water level elevation in riparian zones produce a *hydrologic drought*, reducing microbial activity and N uptake (Groffman et al. 2003), whereas a drop in groundwater level near the stream channel facilitated increased contact between groundwater and microbially active subsurface sediments.

The hydrology of the stream also affected the ORP of the subsurface ecosystem. ORP increased with water table elevation and was especially high where NO_3^- was high (Figure 3). This suggests that sediment zones associated with a high water table were oxidizing (i.e., aerobic) and therefore not conducive to NO_3^- transformations. We speculate that when stream discharge decreases and water tables drop, subsurface flow paths lead to hyporheic mixing, changes in DOC uptake, a drop in ORP, and an increased denitrification potential—a series of events that has been observed by researchers elsewhere (Baker et al. 2000; Dahm et al. 2003; Grimm et al. 2005). The response of NO_3^- transformations to water table elevation and ORP is not unique to urban streams. Similar relationships have been found in undeveloped streams (Naiman et al. 1994), agricultural systems (Molenat et al. 2008), and large rivers (Hinkle et al. 2001). Simply put, hydrology affects ORP and, therefore, N processing.



reduction potential (ORP) to groundwater elevation in the hyporheic zone at five sample dates between October 2002 and May 2004 at Minebank Run, Maryland, USA. Error bars are 1 standard error. Note: mV is millivolts and msl is mean sea level. Source: Reprinted with kind permission from Mayer et al. 2010, figure 11d. ©2010 American Society of Agronomy, Crop Science Society of America, and Soil Science Society of

The Importance of Surface Water Velocity for N Uptake

Many urban stream restoration projects are designed primarily to protect aging urban infrastructure (exposed sewer lines, etc.) and to enhance stormwater management. A goal of the Minebank Run stream restoration project was to dissipate the erosive force of stream discharge by reconnecting the stream to the floodplain and allowing overbank flow or by creating catchment basins below storm drains (Duerksen and Snyder 2005; Kaushal et al. 2008). A critical question, therefore, is whether similar stream restoration designs support ecosystem functions such as NO_3^- retention and denitrification.

This study compared N retention between restored and degraded stream reaches by determining the distance a molecule of NO_3^- travels in the stream before it is biologically consumed, a measure called the NO_3^- *uptake length*. We found a significant relationship between NO_3^- uptake length and mean surface water velocity in the four streams. The length of NO_3^- uptake increased with surface water velocity, such that the restored reaches had the shortest NO_3^-

uptake lengths and degraded streams the longest (357 m and 1,341 m, respectively; Figure 4). These results indicate that (1) at the stream reach scale, NO_3^- retention and denitrification processes could influence NO_3^- dynamics and (2) restoration practices that increase hydrologic contact with sediments by reducing water velocity may influence N cycling. The results also indicate that the potential for N retention in stream channels may be limited during storms and high-flow events. Additional work showed considerable variability in N retention within reaches at the stream network scale and suggested that monitoring needs to move beyond individual reach-scale studies (Sivirichi et al. 2011).

The Importance of Groundwater Residence Time for N Retention

We previously found that stream sediment concentrations of DOC and DO are strong determinates of denitrification in urban streams and that hydrology, stream velocity, and geomorphic structures can alter these important N processing dynamics. Hydrologic connectivity—the passage of water between aquatic and terrestrial ecosystems across space (i.e., longitudinal, lateral, and vertical axes) and time—is a key concept in the restoration of ecosystem function in urban streams. The degree and nature of hydrologic connectivity dictates downstream fluxes and transformations of energy, C, nutrients, and contaminants; connectivity also impacts watershed ecosystem functioning and services (Freeman et al. 2007; Kaushal and Belt 2012). For instance, the diversion of water through pipes reduces connectivity with the urban watershed, resulting in elevated streamflow, nutrient, and pollutant levels (Freeman et al. 2007).

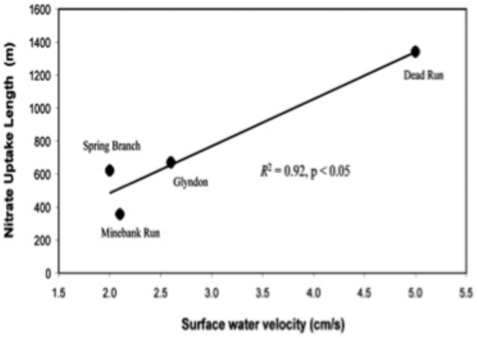


Figure 4. Relationship between stream surface water velocity and NO_3^- uptake length for four urban streams. Restored streams (Minebank Run and Spring Branch) degraded streams (Glyndon and Dead Run). Source: Reprinted with kind permission from Springer Science+Business Media: Klocker et al. 2009, figure 4b. ©Birkhauser Verlag, Basel/Switzerland 2009.

Comparing hydrologically connected (low-bank, low-incision) and disconnected (high-bank, highly incised) sites at the riparian–stream interface at restored and unrestored reaches enabled an investigation of the influence of groundwater flow and residence time on the removal of NO_3^- as well as the potential of geomorphic restoration to increase rates of denitrification. We found that hydrologically connected sites had significantly higher denitrification rates than did disconnected sites, and denitrification rates were higher at restored sites than at unrestored sites. In particular, the low-bank (connected) restored site had significantly higher denitrification rates than any other site (Figure 5). The removal of N at these sites was strongly related to hydrologic residence time (ranging from 0.5 to 9.31 days).

Our results suggest that restoration practices that improve connectivity between the stream and riparian zone can increase rates of *in situ* denitrification, resulting in substantial NO_3^- removal. In particular, restoration of low banks provided a wider channel with reduced channel incision that increased hydrologic interaction between groundwater and the upper soil horizons of the well-vegetated riparian zone. Improved hydrologic connectivity is likely to increase hydrologic residence times, alter groundwater flow paths, and increase the flow of organic C to the riparian– stream interface. The result can favor ORP conditions and metabolic activity that promote higher *in situ* denitrification rates.

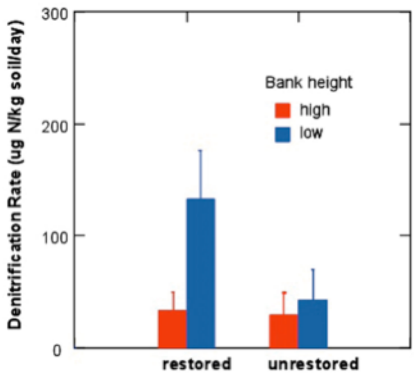


Figure 5. In situ denitrification rates at high (heavily incised) and low (less incised) streambanks in restored and unrestored reaches of Minebank Run. Source: Modified from Kaushal et al. (2008).

The Use of Urban Alluvial Wetlands as Sinks for Excess N

Wetlands provide many important ecosystem services for watershed management (Mitsch and Gosselink 2000). More recently, researchers and watershed managers have become more interested in the use of urban wetlands to mitigate N problems in urban watersheds (Craig et al. 2008; Mitsch et al. 2005). To evaluate the potential of urban wetlands for N mitigation, we measured the denitrification rates and mass removal of NO_3^- in seven urban wetlands in the Baltimore Metropolitan region.

We found no significant differences in denitrification rates between urban and forested wetlands (push–pull method, F = 0.25, *P* = 0.77; Harrison et al. 2011). In fact, this study showed that urban wetlands functioned as denitrification sinks for NO_3^- at rates similar to those of the adjacent streambank (Harrison et al. 2011). We also found that mass removal of NO_3^- in urban wetland sediments could be substantial, with the oxbow wetlands denitrifying an amount of N equal to 8% to 11% of the daily NO_3^- stream load. Overall, our results suggest that stream restoration that includes the creation of wetlands (oxbow or constructed) and increased hydrologic connectivity to floodplain wetlands can be important for increasing denitrification rates in urban landscapes (Harrison et al. 2012a; Harrison et al. 2012b). Floodplain wetlands provide the primary conditions necessary for denitrification: long hydrologic residence times, high DOC concentration/availability, and low O_2 concentrations. Thus, taking advantage of created and/or incidental floodplain wetlands may be an effective stream restoration approach for reducing downstream N pollution.

Conclusions and Recommendations

Our research at Minebank Run demonstrates some important fundamentals about ecosystem function in urban streams and the potential to use restoration to manage N pollution to protect ecosystem function. In particular, the findings show the following:

1. Urban stream ecosystems retain at least some capacity to process N.
2. Stream hydrology and hydrologic connectivity impact N processing capacity.
3. Stream restoration can improve N processing in urban streams if the restoration includes approaches that:
    a. slow down streamflow,
    b. add DOC,
    c. reconnect floodplain hydrology, and
    d. reduce watershed N inputs.
4. Variability across reaches can occur, and monitoring needs to move beyond the reach scale.

As a microbially facilitated process, denitrification is favorable only in stream sediments with low ORP (i.e., anaerobic conditions) and nonlimiting levels of NO_3^- and organic C. Factors and features that affect these nutrient dynamics will also impact the ability of stream restoration designs to remove NO_3^-. In particular, riparian soils, geomorphology, hydrologic flow paths, and geology all play roles in explaining variations in denitrification rates (e.g., Alexander et al. 2000; Stanley and Doyle 2002; Wollheim et al. 2005) and should be further evaluated for stream restoration efforts aimed at mass removal of NO_3^--N.

Our work at Minebank Run showed that stream hydrology and hydrologic connectivity have a strong impact on NO_3^- processing in urban streams. Results showed a strong relationship between mass removal of NO_3^- and hydrologic residence time as well as a dramatic improvement in denitrification rates after the restoration of hydrologic connectivity to riparian areas. Therefore, stream restoration aimed at increasing hydrologic residence time, increasing the hydrologic connectivity of the stream channel with floodplains, adding organic C, and increasing the number of denitrification hot spots may improve N processing capacity and complement comprehensive watershed management strategies. Previous work by Kaushal et al. (2011) suggests that a substantial contribution of NO_3^- entering these urban streams originates very close to the channel via sanitary sewer leaks. Therefore, the restoration of sanitary infrastructure in the stream corridor to reduce sources combined with floodplain reconnection may be a useful N management strategy.

Stream restoration is still a highly experimental field, and restoration designed to improve biogeochemical function may not necessarily recreate predisturbance conditions (Palmer 2009). Because of increased costs and regulations and broad community expectations, stream restoration must be designed to satisfy several objectives at once. For instance, although we emphasize NO_3^- removal potential in restored streams, few data are available elsewhere that quantify N retention and denitrification in restored streams (but see Bukaveckas 2007; Filoso and Palmer 2011; Klocker et al. 2009). This is a missed opportunity to quantify important water quality outcomes associated with restoration designs. Furthermore, high variability is associated with denitrification and N retention in restored streams (Kaushal et al. 2008; Klocker et al. 2009; Mayer et al. 2007); this leads to uncertainties about the magnitude and range of NO_3^- removal possible in stream restoration (Kaushal et al. 2008). Therefore, long-term quantitative studies across sites and systems, various N fluxes, and flow regimes is needed to better understand factors that contribute to variability and to provide a more comprehensive evaluation of the effectiveness of restoration practices on N removal. Although the stream restoration effort at Minebank Run was not designed for N removal, we have shown that geomorphic restorations designed to improve hydrology and reconnect with the floodplain can also help mitigate N pollution.

In summary, managing water quality requires an integrated approach at the watershed scale. Combining stream restoration with upland green infrastructure elements can improve the overall performance and effectiveness of water quality management by integrating upland, riparian, and stream components of the watershed. A combination of approaches that work together to reduce peak flow, reduce and intercept N point sources, and enhance nutrient processing in urban streams and floodplain wetlands will be the most efficient way to improve water quality and protect watershed ecosystem services.

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Building Blue in Franklin, Massachusetts

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Abstract

This study compared two methods of developing subwatershed-scale stormwater management plans to bring a small subwatershed into compliance with a nutrient total maximum daily load (TMDL) study using low-impact development (LID) stormwater treatment systems. We developed one plan using a step-wise professional judgment method and the second using an optimization algorithm set to maximize phosphorus reduction while minimizing cost. The resulting management plans offer insight into the benefits of subwatershed-scale stormwater planning efforts, and specifically the benefits of mathematical optimization in stormwater management planning. Finally, the study presents multiple accessible options for compliance with a nutrient TMDL using LID systems sited and designed to provide a host of additional public benefits, such as reduced flooding, increased groundwater recharge, decreased stress on drinking and surface water resources, and the addition of public green space.

Introduction

Like many municipalities in eastern Massachusetts, the Town of Franklin faces significant water resource challenges. Traditional development patterns and infrastructure designs have altered the environment, disrupting the natural hydrologic cycle and creating unanticipated problems that Town planners and engineers must now solve. Local aquifers, the source of all of Franklin's water supplies, are stressed in summer months, leading to outdoor watering bans and creating challenges for future growth. Baseflows in local rivers and streams, which depend on the same aquifers, often drop to levels that threaten fish and wildlife as well as recreation. Rainfall, which was once absorbed as it fell by plants or soaked into the ground to fill aquifers, is now drained rapidly off of developed impermeable land through underground pipes and culverts, creating water pollution and causing flooding and erosion. Franklin's water resource challenges are mirrored in cities and towns across the New England region and, to some extent, across the country.

Charles River Watershed Association (CRWA) has been working to understand urban hydrology for the past two decades. CRWA's mission is to preserve and protect the Charles River and its watershed, one of the most densely populated watersheds in

Massachusetts. This relatively small, 800-km^2 watershed encompasses 35 municipalities, ranging from the ultra-urban hubs of Boston and Cambridge to exurban residential communities, such as Franklin. Because so many water resource management decisions and practices take place on the local level, CRWA has a long history of partnering with watershed municipalities to conduct research, offer trainings, and implement pilot projects.

In 2005, CRWA launched the Blue Cities® Initiative, a program to develop and implement sustainable urban water resource management tools (CRWA 2009a). The goal is to identify techniques and management approaches to reengineer the built environment to make it function more like the natural environment. This work has demonstrated that sustainable solutions exist, and that by using techniques such as green infrastructure, low-impact development (LID), water conservation, and smart sewering, towns can balance their water budgets, protect their groundwater and surface water resources, and continue to grow.

The Massachusetts Department of Environmental Protection (MassDEP) and the US Environmental Protection Agency (USEPA) identified stormwater runoff as the main reason the Charles River does not meet water quality standards (MassDEP and USEPA 2007). This has led to a new set of federal regulations that will impact not only municipal governments, but also private property owners throughout the watershed. In November 2008, USEPA Region 1 (New England) issued a residual designation pursuant to the Clean Water Act stating that privately owned properties within the watershed, having certain land uses and with 0.8 ha or greater of impervious cover, termed *designated discharge sites* (1) contribute to water quality violations in the Charles River and (2) must reduce phosphorus levels in runoff from these sites to restore the Charles to a healthy ecosystem that meets all of its designated uses (USEPA 2008).

This unique regulatory step is the result of a key finding in two nutrient total maximum daily load (TMDL) studies performed on the Charles River.[i] These studies showed that stormwater runoff from 20% of the land area in the watershed—areas with high-density residential, commercial, and industrial land uses—contributes nearly 50% of the annual phosphorus load to the Charles River (MassDEP and USEPA 2007; CRWA 2011). In 2010, USEPA issued a draft general permit to pilot the new rule in three communities, one of which is Franklin; this permit has not yet been issued in final form. The rule requires designated discharge sites to reduce annual phosphorus loads from site runoff by 65% (USEPA 2010).

Finally, USEPA Region 1 also intends to issue an updated National Pollutant Discharge Elimination System (NPDES) general permit for stormwater discharges from municipal separate storm sewer systems (MS4s) in eastern Massachusetts.[ii] This will solidify the existing requirement that Franklin and 33 other watershed communities (Boston receives an NPDES Phase I permit) reduce phosphorus loads in stormwater runoff in accordance with the nutrient TMDL waste load allocations to prevent excessive nutrient pollution and the rapid eutrophication of the Charles River.

The Town of Franklin, long aware of these issues, is committed to the long-term stewardship of its natural resources and is actively seeking sustainable approaches to their management. Funded by a grant from the Jessie B. Cox Charitable Trust Fund, CRWA conducted a study to determine what would be required to restore water quality, reduce flooding and erosion, and comply with the nutrient TMDL in the Upper/Middle Charles River, Massachusetts (CRWA 2011), in a small subwatershed in the town of Franklin. For this study, the selected subwatershed served as a representative area of the town. The stormwater management options assessed were limited to certain types of constructed LID stormwater treatment systems. We sited treatment systems based on computer geographic information system (GIS) assessments, site visits, and consultations with Town officials and local engineering consultants (R. Claytor, principal engineer, Horsley Witten Group, pers. comm., 2009). Originally, we sized systems based on the project team's input and judgment and then used a commercially available algorithm to develop two watershed-scale stormwater management plans. A comparison of the two plans provided insight into techniques and strategies for achieving compliance with the Charles River nutrient TMDL.

Methods

Study Area Selection

We selected Spruce Pond Brook subwatershed as the project study area using a set of geographic criteria, field assessments, and discussions with Town staff. In the first step of the selection process, the project team analyzed data for 23 possible study area subwatersheds using a GIS. The goal was to select an area that (1) was an appropriate size for stormwater modeling; (2) included land uses and soil types representative of the town as a whole; (3) contained a mix of public and private properties; (4) included some designated discharge sites (properties that will be subject to USEPA's new stormwater permitting program, which will apply to sites with > 0.8 ha of impervious cover in industrial, commercial, or high-density residential land uses); (5) was entirely within the town of Franklin; and (6) drained to a well-defined point where water quality and flow measurements could be estimated (or measured if additional resources became available). The initial screening eliminated subwatersheds that did not match closely with the criteria above.

In addition to the quantitative criteria, we also sought to select a subwatershed that provided opportunities for implementing treatment systems that could serve as demonstration projects and address multiple water resource management challenges (e.g., stormwater quality, flooding, and groundwater recharge). We were also looking for a subwatershed that included a variety of landscapes and neighborhood types to showcase a spectrum of stormwater treatment system types and aesthetics. To assess these qualitative criteria, we conducted site visits to evaluate the small number of remaining subwatersheds. Following this assessment process, we presented the findings to the Town administrator, the director of public works, and several members of his staff to select the final study area. Town personnel provided important input regarding the municipality's plans and priorities for the various areas. The project team selected Spruce Pond Brook subwatershed as the study area because it closely matched all of the selection criteria (Figure 1). CRWA (2009b) describes the selection process in more detail.

Figure 1. Spruce Pond Brook subwatershed, Franklin, Massachusetts.

Study Area Site Description

Franklin is a residential community in the exurban area surrounding Boston. Originally developed around industrial uses driven by the availability of hydropower, the town continues to support commerce and industry today. Presently, this municipality is subject to USEPA's Phase II MS4 general stormwater permit. This Spruce Pond Brook subwatershed is a small, 2.85-km^2 subwatershed located in the southeastern corner of Franklin (Figure 1). This subwatershed has an estimated population of 4,186 people (US Census Bureau 2000) and is the drainage area of a small, first-order tributary to the Charles River. The majority of the subwatershed is developed land that is drained by underground stormwater drain pipes.

Study Area Analysis

After selecting the subwatershed, we amassed detailed site information to inform the selection, location, and design of stormwater treatment systems. The project team compiled information—such as stormwater flow patterns, underground infrastructure location, soil type, land use and zoning, land cover, property boundaries and ownership, drinking water resources (withdrawal sites and protected areas), and groundwater levels and flow patterns—into a GIS. This study also compiled materials on historical water resources and land uses, surface water quality, state water quality classifications and listings, and previous environmental studies and planning assessments of the area.

Using information on stormwater drainage patterns and property boundaries, the project team subdivided the study area into 49 drainage areas (Figure 2). We identified industrial, commercial, and high-density residential properties with more than 0.8 ha of impervious area as probable designated discharge sites and defined those as individual drainage areas. This permitting process is designed to encourage owners of these properties to treat their stormwater runoff on-site. The remaining drainage areas were defined by stormwater infrastructure and natural topography. The GIS analysis enabled the identification of one or more sites within each drainage area as possible sites for locating a stormwater treatment system. We prioritized sites with fast-draining soils (i.e., hydrologic soil group A or B) on publicly owned land, located such that the system would be able to treat runoff from a large percentage of the drainage area (i.e., the base of a large hill or confluence point in the stormwater drainage system).

The team conducted on-the-ground site assessments of 45 of the 49 drainage areas. During site visits, the field team refined drainage area boundaries and assessed the potential sites for stormwater treatment systems identified by the preliminary GIS analysis (Schueler et al. 2007; R. Claytor, principal engineer, Horsley Witten Group, pers. comm., November 2009). Field staff collected data using field forms, large-scale maps, and digital cameras. Town personnel were present at some but not all site visits. The project team compiled information into a multipage matrix and library of digital photos. We selected possible treatment system location sites for each drainage area. CRWA (2009c) provides more detailed information on site analysis.

Calculating Target Reduction Goal and Existing Pollution Loads

Figure 2. Forty-nine drainage areas for the Spruce Pond Brook subwatershed.

This study determined the target reduction goal for Spruce Pond Brook subwatershed using loading and reductions established in the Charles River nutrient TMDL studies. To calculate an overall phosphorus reduction percentage goal, we first calculated the existing load based on subwatershed land use and then multiplied loads from each land use by the TMDL target reduction percentage assigned to the respective land uses. This calculation yields a target phosphorus reduction for the study area of 59%, which is actually higher than the 54% reduction specified for the whole town of Franklin by USEPA's NPDES draft general permit for stormwater (Table 1, Figure 3). We estimated that a reduction of 17% could be achieved through nonstructural stormwater management practices, such as street sweeping, catch basin cleaning, leaf litter collection and composting, or through discontinuing the use of fertilizers that contain phosphorus. Therefore, we determined that the net target reduction goal for phosphorus loading from stormwater to be achieved through structural controls as assessed in this study was 42%.

We calculated the phosphorus load in stormwater runoff for each of the 49 drainage areas based on Massachusetts Office of Geographic Information (MassGIS 2005 land use, impervious area, and phosphorus loads previously developed by Tetra Tech (2009) specifically for the 2005 land use categories. Although these phosphorus load export coefficients were slightly different from the Upper/Middle Charles River TMDL coefficients CRWA (2011) used in the calculation described above, which were based on the 1999 land use data, they preserve the total calibrated stormwater TMDL load. This study ignored small variations in phosphorus loading across soil types. The land use–based export coefficients (ELU_n), multiplied by the pervious area (LUp_n) and impervious area ($LUic_n$) within each land use (n) in the drainage area, yield the estimated existing (TMDL base conditions) total phosphorus load for the drainage area (PL_{DA}).

$$PL_{DA} = \sum_{i=1}^{n} (ELU_{Pn} \times LUp_n) + (ELU_{ICn} \times LUic_n)$$

Table 1. Target phosphorus reduction calculation for Spruce Pond Brook subwatershed.

Land Cover/Source Category[a]	Area in Subwatershed (ha)	Existing Phosphorus Loading by Land Use[b] (kg/ha/year)	Existing Phosphorus Loading in Subwatershed by Land Use (kg/year)	Percentage Load Reduction[c]	Target Phosphorus Loading Reduction (kg/year)	Resultant TMDL Load (kg/year)
Commercial	9.48	1.70	16.1	65.0%	–10.5	5.6
Industrial	18.97	1.47	27.9	65.0%	–18.1	9.8
Higher-Density Residential	14.04	1.13	15.9	65.0%	–10.3	5.6
Medium-Density Residential	102.32	0.57	57.9	65.0%	–37.6	20.3
Low-Density Residential	25.83	0.05	1.2	45.0%	–0.5	0.6
Agriculture	3.24	0.51	1.6	35.0%	–0.6	1.1

Forest	80.69	0.13	10.5	0.0%	–0.0	10.5
Open Space (Recreational)[d]	24.80	0.03	0.9	35.0%	–0.3	0.6
Total	279.37		131.9		–77.9	54.0
Percentage						59.1%

[a] Source: MassGIS 2002. [b] As determined by TMDL. [c] As required by TMDL. [d] Includes developed landscapes and recreational park land (including impervious areas, such as tennis and basketball courts).

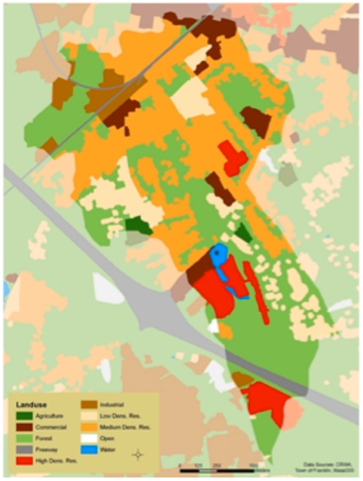

Figure 3. Land use in Spruce Pond Brook subwatershed.

Stormwater Treatment Systems

In this study, stormwater management control techniques were limited to specific structural stormwater treatment systems. We selected a stormwater treatment system for each developed drainage area from the following suite of LID treatment systems:

- infiltration chamber
- infiltration basin
- bioretention system
- green street design (using bioretention systems)
- gravel wetland

The project team selected and sited treatment systems for each drainage area based on a thorough review of existing drainage, stormwater infrastructure, soil conditions (soil profile and water table depth), existing property use, space constraints, slopes, pollutant removal efficiencies, sizing constraints, discussions with Town officials, estimated cost, and neighborhood character (MassDEP 2008; Vermont Agency of Natural Resources 2002; USEPA 1999).

Modeling Analysis

This study used a simple mathematical model to calculate phosphorus reductions. We calculated phosphorus removal based on annual curves developed by long-term modeling of treatment systems (Tetra Tech 2010), using data collected at the University of New Hampshire Stormwater Center (2007; Figure 4). As described above, we assigned a treatment system type and site within each drainage area and calculated an existing phosphorus load.

The project team determined pollutant removal based on the design storm size and the type of proposed (or existing) treatment system. Figure 4 shows an example pollutant removal curve for gravel wetlands. The pollutant removal performance curves (Tetra Tech 2010) vary slightly based on the land use of the drainage area; however, this study applied the average pollutant removal values across all land uses. We multiplied the percentage pollutant removal, based on treatment system size, by the existing annual load to give the reduced annual phosphorus load. To determine the overall phosphorus removal for the subwatershed, we summed the load removed for each drainage area and then compared it to the target load reduction.

We estimated the construction cost for each system using estimates of unit cost (in dollars per unit volume treated) and the proposed runoff volume treated by the system (R. Claytor, principal engineer, Horsley Witten Group, pers. comm., March 2010; North Carolina State University 2003). For systems proposed on private land, we also estimated the cost of purchasing the land, based on recent

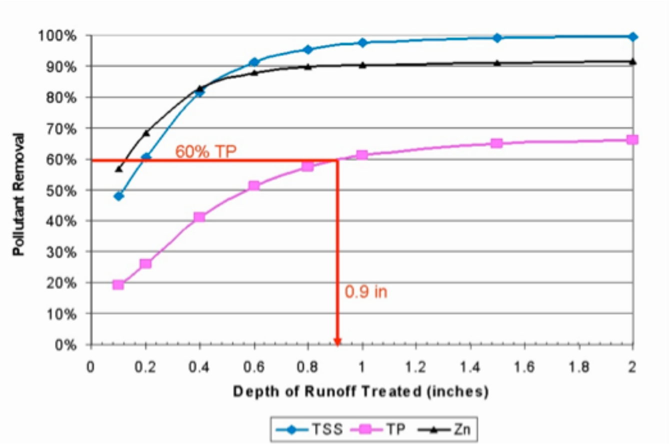

Figure 4. Example of treatment system performance curve. TP, total phosphorus; TSS, total suspended solids; Zn, zinc. Source: Tetra Tech 2010.

land sale values in Franklin, and included this estimate in the total cost.

This study examined two scenarios that differed in their methods of identifying and sizing treatment systems across the 49 drainage areas to achieve a 42% phosphorus load reduction. Based on the results of each scenario, CRWA developed two stormwater retrofit plans for each of the subwatershed's 49 drainage areas. In the two scenarios, we determined the volume of water to be treated (i.e., design storm size) by the treatment system assigned to each drainage area using a different methodology (i.e., Scenarios 1 and 2, described below). Design storm size also dictates treatment system size; therefore, the size of treatment systems within each drainage area varies between the two resultant plans. This includes treatment systems that were assigned no treatment volume, which means those particular systems would not be recommended for implementation. The overall reduction would be achieved through a combination of systems exclusive of treatment systems assigned zero treatment.

During the study area analysis, we determined possible locations and system types for each drainage area based on GIS data, site visits, and communication with Town personnel (see above). Treatment system location and type did vary between the two scenarios. As discussed above, however, the project team used two methodologies to determine which systems should be recommended for implementation and which systems were not cost-effective. In this study, determining the possible system locations and types in advance based on technical information and Town input facilitated the Town's ultimate acceptance of the final plans. However, one could also use this approach to explore scenarios in which treatment system type and location vary.

We assigned each designated discharge site a phosphorus load reduction target of 65%; this did not vary between the two scenarios. A small number of drainage areas already contained stormwater treatment systems. Existing systems constructed prior to 2000 were considered part of the TMDL base conditions; therefore, we did not count phosphorus removal by these systems toward the achievement of a 42% reduction of base conditions. For the five existing systems constructed after 2000, phosphorus removal was estimated based on the system design and *was* counted toward the target reduction total.

The optimization model described in Scenario 2 (see below) used a commercially available genetic algorithm for Excel to minimize the total construction cost by varying individual treatment system design storms with the constraint that the target phosphorus reduction of 42% must be equaled or exceeded across the subwatershed (Palisade Corporation n.d.). Optimization yields least cost scenarios using different treatment system sizes while still meeting the target phosphorus reduction.

Scenario 1: Initial Design

The project team used its best professional judgment to determine Scenario 1 treatment system volumes. In general, large drainage areas where logistical conflicts (utilities, changes to the stormwater drainage system, land ownership, and space conflicts) were minimal served as priority sites for treatment and generally were assigned large treatment volumes and systems. In drainage areas with more challenges, the project team assigned small or no treatment systems. Although we considered cost, this was not the main factor in the decision-making process. The team used an iterative process to achieve the target reduction of 42%, such that we added systems or increased their size until the reduction was achieved.

Scenario 2: Optimization

The project team created Scenario 2 through a model optimization set to minimize costs while still meeting the target for phosphorus removal of 42%. The optimization varied the design storm for the systems in each drainage area and looked for the best overall combination of treatment systems. We did not set an upper bound on design storm size (and therefore treatment system size); we set a lower bound at zero. A design storm value of zero meant that no treatment system would be proposed for that particular site. The project team reviewed optimization output to ensure that proposed systems were not too large for the proposed sites. The treatment system type for each drainage area was fixed and was the same as in Scenario 1.

During the optimization process, we allowed existing treatment systems to vary in the same manner as proposed systems; these systems were even able to become smaller or to reach zero treatment volume, which is an unlikely real-world scenario. This scenario included existing systems as a means of investigating whether retrofitting and resizing existing systems would provide a cost-effective treatment option. We subtracted the phosphorus removal value for systems present prior to 2000 operating as constructed, from the overall reduction because, as discussed above, this is included as part of the TMDL base conditions and cannot be counted toward TMDL compliance and therefore the 42% required reduction. We calculated this value (1.9% across the subwatershed) using the same methodology used to calculate removal from proposed systems using the best data available on the design of these systems (see above).

Results and Discussion

Each plan provides a reduction of at least 42% in phosphorus loading from stormwater runoff for the subwatershed, but at drastically different costs (Table 2). The Scenario 1 stormwater plan results in a 43% reduction in the phosphorus load at a cost of $4.9 million. The use of mathematical optimization reduced costs considerably; Scenario 2 results in a 44% reduction in the phosphorus load at a substantially lower cost of $3.1 million

The two plans exhibit other striking differences as well. The plan generated from the results of Scenario 2 (Plan S2) proposes stormwater runoff treatment systems for considerably more drainage areas than does the Scenario 1 plan (Plan S1). Plan S1 has 21 drainage areas receiving no treatment, whereas Plan S2 has only 8 such drainage areas (Table 2). Additionally, in Plan S2, proposed design storm sizes for treatment systems are concentrated in the low range (< 2 cm), and many more systems under this plan provide phosphorus removal in the low range (< 60% removal; Table 2, Figures 5 and 6).

Table 2. Summary of stormwater plans.

		# Drainage Areas Proposed	
		Scenario 1	Scenario 2
Treatment System Type	Infiltration Chamber	5	7
	Infiltration Basin	6	13
	Bioretention	9	10
	Green Street	4	5
	Gravel Wetland	4	6
	Total	28	41
Treatment System Design Storm (cm)	> 4	2	3
	3.01–4	2	1
	2.01–3	13	4
	1.01–2	9	19
	0.01–1	2	14
Phosphorus Removed (%)	81–100	10	13
	61–80	15	12
	1–60	3	16
Cost (Millions $)	Treatment System Cost	4.6	3
	Land Cost	0.3	0.1
	Total Cost	4.9	3.1

Unit Cost ($/ha Treated)	Total	$35,726.71	$18,378.01

The project team's initial instinct to identify prime sites for stormwater treatment systems and to maximize their treatment volume resulted in a more costly approach. In one instance, Plan S2 proposes no treatment system in a drainage area where Plan S1 proposed a considerable level of treatment. The treatment system that Plan S1 assigned for this drainage area, a gravel wetland, was chosen because of high groundwater on the proposed site. Gravel wetland systems are of medium to high cost among the treatment systems reviewed in the study. In Plan S2, benefits from this larger treatment system at a challenging site were made up for by implementing smaller, dispersed treatment systems at multiple other sites.

Plan S2 includes more systems treating smaller water quality volumes from a larger portion of the subwatershed. The treatment systems used in this study have diminishing removal efficiency rates for total phosphorus after a certain design storm size is reached. Figure 4 shows an example efficiency curve. Since most treatment systems proposed in Plan S2 have a smaller treatment volume, they fall on a steeper part of the removal efficiency curve. By employing multiple treatment systems, each treating smaller water quality volumes, the result in Plan S2 is greater aggregate phosphorus removal across the subwatershed at a similar overall treatment volume and a reduced cost per unit of phosphorus removed. This finding is consistent with the general principles of LID, which encourage smaller, on-site systems to treat the first flush of a rain event.

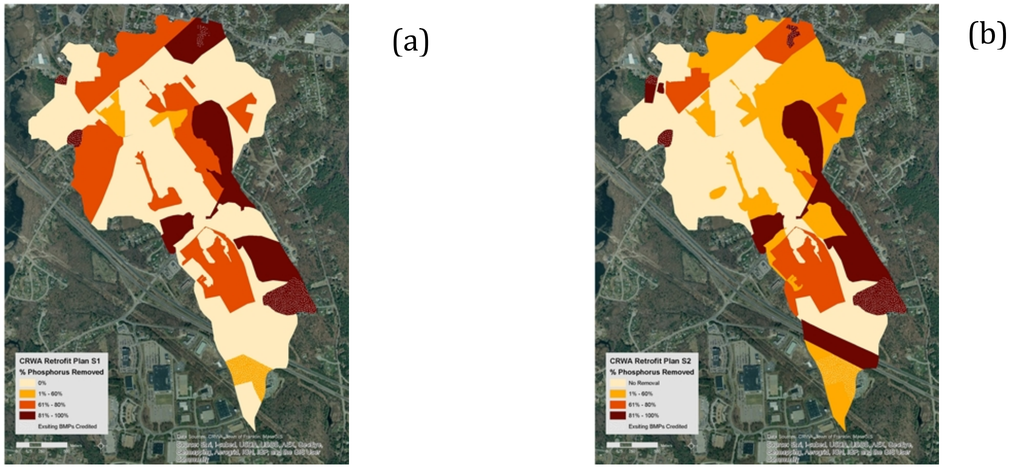

Figure 5. Percentage phosphorus removal by drainage area for (a) Plan S1 and (b) Plan S2.

Conclusions

This study provides a model for municipalities throughout the Charles River watershed by clearly presenting how a small subwatershed can be brought into compliance with the Upper/Middle Charles River nutrient TMDL using LID stormwater management treatment systems. Furthermore, the results of the study are broadly useful to demonstrate how one could design various sites to work together to achieve TMDL compliance (or to meet other water quality goals) on the subwatershed or watershed scale. The optimization model used in Scenario 2 is an extremely useful tool to obtain solutions at least cost and best reduction result.

Based on the results of this study, CRWA (2010) produced a comprehensive management plan, *Stormwater Management Plan for Spruce Pond Brook Subwatershed,* which includes Plans S1 and S2, as well as detailed conceptual designs for 12 priority drainage areas within the watershed. Conceptual designs are based on Plan S1 but provide a good starting point for designing a system of any size, as proposed in either Plan S1 or Plan S2. Figures 6 and 7 are examples of the before and after visualizations created for the proposed designs in the priority drainage areas. By developing this plan and presenting it to the Town, the municipality can act on implementation opportunities as they arise, either through regularly scheduled capital investment projects or through grant opportunities. CRWA (2010) provides more information on the planning and design phase of this project.

To date, the Town of Franklin has implemented small bioretention systems at two of the sites identified as good options for treatment in both management plans. The sites include an elementary school and an athletic field complex, both of which are highly visible in the community. These sites also serve as pilot projects to educate the community about LID treatment systems.

Moving forward, CRWA and the Town of Franklin hope to continue to implement many of the treatment system opportunities identified through this study. As this project affirms, it is technically feasible to comply with the TMDL, and doing so would help Franklin not only to meet its regulatory requirements but also to increase groundwater recharge, reduce flooding, and provide community benefits from increased “greening” and aesthetic enhancements. Nevertheless, funding adequate stormwater management on a town-wide scale, including the construction of multiple stormwater treatment systems, presents a major challenge for the Town.

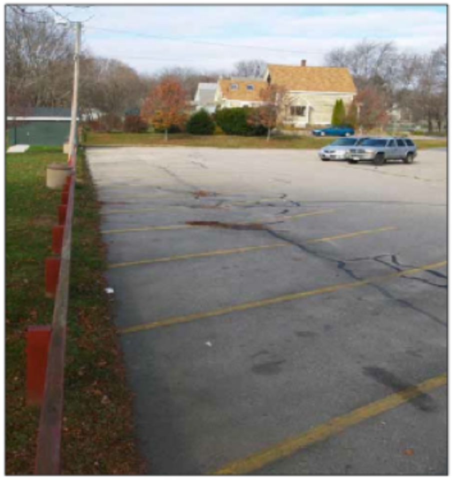

Figure 6. Existing parking lot in drainage area 4A-3. Source: CRWA 2010.

Figure 7. Proposed bioretention area for drainage area 4A-3. Source: CRWA 2010.

Lessons Learned

The project team learned many valuable lessons throughout this process. Close coordination and cooperation with Town personnel were essential in making this project a success. We worked hard to build successful working relationships with Town employees in many departments. Additionally, the project team met regularly with an advisory committee made up of representatives from planning, conservation, public works, and engineering departments and the Town administrator. We learned that it was essential to be able to clearly explain our goals and process to multiple Town employees to achieve effective buy-in and cooperation from the various departments. Finally, we had to be open and responsive to suggestions and feedback from the Town.

Site visits were integral to the success of this project. Accurate data and maps were invaluable in this process; however, ground-truthing data and gaining an on-the-ground perspective were essential elements of our existing conditions assessment and preliminary design phase. Although time consuming, this task was essential to the Town's ultimate acceptance of plan recommendations.

Last, we learned that the best locations and sizes of treatment opportunities challenged best professional judgment and that it is important to look for treatment opportunities wherever possible. The optimized model run reinforced the importance of treating runoff from all areas. Treating a large volume of water from one drainage area does not necessarily compensate for leaving other large areas untreated. In this study, the lower-cost option was achieved by proposing the treatment of runoff from more drainage areas, even at small design volumes. This may prove to be an effective strategy for meeting the Charles River nutrient TMDL.

Acknowledgments

This study would not have been possible without the significant support of many project partners. In particular, we gratefully acknowledge Jeff Nutting, Robert Cantoreggi, Bill Yadisernia, Nicholas Alfieri, James Esterbrook, and Beth Dahlstrom from the Town of Franklin; Rich Claytor and Michelle West from Horsley Witten Group; Mark Voorhees of USEPA; Tham Saravanapavan and Guoshun Zhang of Tetra Tech; and Pallavi Mande, Alexandra Ash, Danielle Mucciarone, Jordan Hanley, Hannah Carlson, Kate Rowe, and Kate Benesik, all of whom are additional, vital members of the CRWA team. CRWA would also like to acknowledge the Jesse B. Cox Trust and ESRI for financial support of this project. Finally, the authors would like to thank the article reviewers who provided valuable feedback and input that greatly improved this article.

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[i] *The two nutrient TMDL studies for the Charles River include one for the highly urbanized portion of the watershed (e.g., the last 15 km of the Charles) and a second TMDL for the more suburban middle and upper sections of the watershed. The watershed was divided into these two distinct geographic areas because of their disparate land use characters.*

[ii] *This permit was previously issued in draft form; a revised permit is expected to be issued for public comment in spring 2013.*

Gray and Green Approaches To Address Combined Sewer Overflows in Northeast Ohio

The Northeast Ohio Regional Sewer District (District) has developed, and is working to implement, a comprehensive watershed approach to address flooding, erosion, and water quality problems of Northeast Ohio and the Lake Erie basin. Central to this effort is the intersection of green infrastructure (GI) and regional stormwater management to address combined sewer overflows (CSOs). Significant opportunities for GI are available within the District on the many brownfields and vacant parcels currently held by City of Cleveland and Cuyahoga County land banks.

In 2011, the District entered into a consent decree (decree) with the US Environmental Protection Agency and the US Department of Justice that describes a 25-year plan to reduce remaining CSO discharges to less than 500 million gallons[i] (MG) annually; equivalent to 98% capture of CSO. The initial plan proposed by the District relied solely on gray infrastructure and reduced 97% of the total CSO. The 1% difference translated to the capture of an additional 63 MG that was needed to protect the State of Ohio's designation of Lake Erie as a "sensitive receiving water body." Because the cost for CSO capture increases rapidly with higher levels of CSO control, the District evaluated the use of a combined green–gray infrastructure approach to reach the targeted reductions in CSOs.

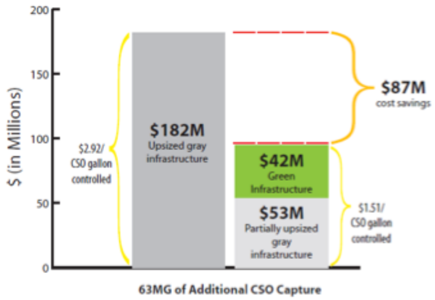

Figure 1. A comparison of costs to implement gray versus combined gray and green infrastructure to capture an additional 63 MG of CSO. MG, million gallons.

The plan, known as Project Clean Lake (http://neorsd.org/projectcleanlake.php), is estimated to cost $3 billion. The District adopted a "triple-bottom-line" approach, which takes into consideration environmental impact, cost and social impacts, to optimize the mix of gray and green practices. To capture the additional 63 MG of CSO, the decree requires the District to capture 44 MG of CSO with GI at a minimum cost of $42 million. The District will capture the remaining 19 MG with the required gray infrastructure. This saves $87 million compared to a strategy relying on gray infrastructure alone (Figure 1). The decree also includes 21 miles of deep storage tunnels to provide more than 300 million gallons of wet weather storage.

In April 2012, the District adopted a GI plan that outlines the process for locating, designing, constructing, operating, and evaluating the performance of a set of GI control measures to meet the decree requirements (http://neorsd.org/I_Library.php?a=download_file&LIBRARY_RECORD_ID=5526). A key element of the GI plan is the prioritization of brownfields and vacant properties for GI, which is expected to assist in the revitalization of targeted urban neighborhoods.

The District developed a GI index to score areas based on the potential for these areas to support and benefit from GI implementation. The District identified areas with high GI index scores as priority areas for GI implementation and candidate GI projects. Specifically, one of the variables included in the calculation of the GI index scores is “available land.” The land bank programs of both the City of Cleveland and Cuyahoga County retain a large number of parcels within the combined sewer system (CSS) area, and these parcels are a priority for runoff control landscape uses (see Figure 2).

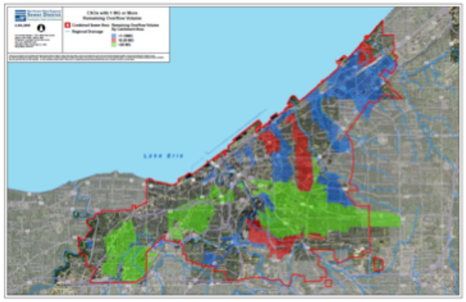

Figure 2. Map of Northeast Ohio Regional Sewer District CSS area. MG, million gallons.

The District identified 38 priority areas for GI implementation and, of these, selected 20 as candidate GI projects based on criteria that included vacant land reuse. More than half (11) of the candidate GI projects were characterized by significant reuse of vacant parcels, including brownfields.

Project Highlights

Recently, in partnership with University Circle Incorporated, Marriott Hotel, and the Snavely Group, the District embarked on a GI pilot project, which included the installation of pervious pavers at the newly built Marriott Hotel at University Circle near Case Western Reserve University. Instead of flowing into a sewer, the runoff from the hotel will infiltrate the pavers and then drain into a storage and infiltration chamber. The water will finally dispense from the chamber into the soil below. The Marriott project will eliminate about 1 MG of stormwater from the CSS.

In addition to its work on urban stormwater management for CSO control, the District is implementing its Regional Stormwater Management Program. Through this program, the District will provide stormwater management throughout its 62 communities and four main watersheds to protect and restore watershed function and provide comprehensive solutions to flooding and erosion. For example, the District will restore the West Creek in an effort known as the West Creek Confluence Stream Restoration project. Through this project, the District intends to stabilize and rehabilitate approximately 1,000 feet of stream channel and convert the available contiguous land areas into a combination of stormwater treatment wetlands and hydraulically connected floodplains. The proposed improvements will avert serious bank erosion within the project reach and will provide stormwater quality improvements for a portion of the contributing watershed, including West Creek’s confluence with the Cuyahoga River.

The intersection of these two efforts—GI and regional stormwater management—offers a comprehensive watershed approach to address the flooding, erosion, and water quality problems of Northeast Ohio and the Lake Erie basin. Additionally, the reuse of vacant land parcels for GI implementation provides opportunities to stabilize distressed neighborhoods, promote economic development, and use land bank resources efficiently.

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For More Information

For more information, contact the Northeast Ohio Regional Sewer District at 216-881-6600 or log onto the project website, http://www.neorsd.org/projectcleanlake.php.

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[i] *The Consent Decree documents specify the number in English units and subsequently all other material related to the Consent Decree uses English measurements as well.*

Groundwork New Orleans: Developing a Green Slice Watershed Habitat Corridor

Urban infrastructure and development have multiple impacts on environmental systems, including habitat displacement, nonrenewable energy use, and the reduction of natural resource quality and quantity resulting from both. Water management is a major component of urban infrastructure development and maintenance, particularly in New Orleans, where parts of the metropolitan area are below sea level and the city as a whole is surrounded by a degraded wetland system that is degrading further. Resiliency in such an environment requires learning to live with the water around us as a resource, rather than a waste, to be managed. In New Orleans, impermeable surfaces rob the groundwater of the opportunity to capture rainwater and recharge and thereby contribute to subsidence as the peaty soil on which the city was built compacts.

The City of New Orleans “watershed” is a highly modified system established on a deltaic swamp system and riverine levee–bayou complex. This is readily apparent by observing the elevation changes within the city, a product of the original natural levee and ridges from historic channels; drained swamps (and subsequent subsidence); and extensive urban modifications, including drainage systems consisting of huge pumps and canals (Figure 1). These modifications have, over time, resulted in a system that is susceptible to flooding from typical rain events (in a city that receives 165 cm of rain each year) as well as from hurricanes and tropical storms.

Figure 1. Generalized elevations in the city of New Orleans areas derived from light detection and ranging (LIDAR) imagery. The blue and green areas represent higher elevations (the Mississippi River was at 3.65 m stage during the LIDAR capture), whereas the yellows to reds indicate lower elevations, with much of these areas below sea level. Note the green ridges (Metairie and Gentilly ridges), which represent natural levees from old channels. Source: Data downloaded from Atlas: Louisiana Statewide GIS, http://atlas.lsu.edu.

The purpose of the Groundwork New Orleans “Green Slice” project is to provide an example of watershed/habitat corridor planning based in the Lower Ninth Ward of New Orleans. By developing low-impact stormwater retrofits and habitat enhancements in a corridor spanning nearly 3 km between the Mississippi River and Bayou Bienvenue and anchored at Global Green’s Holy Cross Project (a brownfield and former industrial site at the terminus of Caffin Avenue; Figure 2), the project aims to serve as a pilot for strategies that provide decreased susceptibility to flooding.

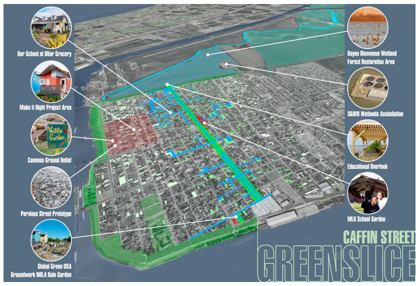

Figure 2. Green Slice map illustrating the Green Slice corridor and its connectivity to concurrent projects at the Martin Luther King, Jr.’s Charter School for Science and Technology, the Sewage and Water Board’s Wetland Assimilation Project, Make it Right, Global Green, the Department of Public Works’ Pervious Street Prototype, and other projects within the community. Credit: Ramiro Diaz, Waggonner & Ball Architects and Groundwork New Orleans.

Groundwork New Orleans intends to identify, coordinate, and develop synergies within the corridor to increase efficiency and secure additional investment. In so doing, the Green Slice project would leverage existing and planned projects and programs that support green infrastructure as well as job training, skills building, and learning. The objective of this green urban corridor proposed for development in the Lower Ninth Ward is to reduce the ecological footprint of the area by incorporating greenways, gardens, and green infrastructure while increasing storm resilience and providing a greater human-nature interface in this fragile ecology.

Development of the corridor will include sustainable design components—that is, systems in which renewable energy sources (e.g., solar and rainfall) reduce ecological inputs and provide the greatest portion of the energy use in the area. For example, the neutral ground (median) along Caffin Avenue is an ideal place to install a longitudinal bioswale (Figure 3) to (1) capture the first 2.54 cm (1-inch) of rainfall from the adjacent roadways and (2) provide a tree-lined phreatophytic corridor that enhances the ecological value of the corridor by attracting birds and other animals, increases transpiration of shallow groundwater, and reduces the heat island effect of the urbanized area. The intent is to meld the urban infrastructure into its regional ecology, creating contiguous habitat between the Mississippi River and Bayou Bienvenue that supports urban infrastructure, including jobs to support the people in the urban environment.

The US Environmental Protection Agency has awarded Groundwork New Orleans an Urban Waters Grant in support of the Green Slice Plan. The Green Slice will be designed as a demonstration and interdisciplinary research site for water management and water quality improvement, impacting local urban watersheds and developing tools for experiential learning and neighborhood-based outreach. Project implementation began in October 2012.

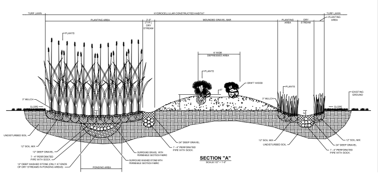

Figure 3. Typical cross-section of an engineered bioswale. Credit: J.O. Evans III and Peter Liginieres, FutureProof LLC.

For More Information

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The Role of Stream Restoration in Green Infrastructure

Federal, state, and local laws and regulations are driving new efforts to restore water quality in the Chesapeake Bay, and stream restoration is playing an important role in reducing sediment and nutrients while offering the opportunity to restore lost links in the landscape's green infrastructure. Stream restoration projects that restore both physical stream channel conditions and lost ecosystem services have the potential to provide water quality benefits as well as societal benefits, such as community gathering spaces, recreation, wildlife habitat, and marketable products (e.g., fish and forest products) as water quality goals are achieved.

In the late 1980s and early 1990s, roadway and stormwater detention pond construction in the Annapolis area by the Maryland State Highway Administration and Anne Arundel County resulted in the channelization, straightening, and riprap lining of a portion of the Western Tributary to Church Creek, a tributary of the South River in the Chesapeake Bay watershed. The channelization disconnected the stream from its natural floodplain, changed sediment transport, and affected instream aquatic habitat by eliminating the riffle pool sequence characteristic of natural streams that support healthy fisheries. In 2000, Anne Arundel County extended Admiral Cochrane Drive to Maryland Route 2; this provided the opportunity to restore the previously channelized stream to a more natural condition.

Figure 1. Aerial imagery of the stream restoration project in 2007. Source: Google Earth.

The design objective of the stream restoration was to replace the straightened, riprap-lined trapezoidal channel of limited aquatic habitat with a stable, natural stream channel characterized by a natural meander pattern and riffle pool sequence with a diverse and functional aquatic habitat. The project team followed the natural channel design approach, as described by D. Rosgen, to restore a natural meander pattern and stream profile. The design incorporated (1) log vanes, log cross vanes, and log step pools to form the stream pattern and profile and to protect the bed and banks from erosion; (2) a floodplain bench at the elevation of the bankfull discharge; and (3) bioengineering techniques, including both willow stakes and riparian zone shrub and tree planting and seeding to inhibit erosion and provide cover habitat. Figure 1 illustrates the stabilized meandering channel five years after the restoration.

The stream restoration project required five years of monitoring to fulfill a condition of the Clean Water Act Section 404 permit authorization. The monitoring program included the collection of geomorphic and biological assessment data to evaluate vertical and lateral stability, particle size distribution of bed material, water quality, the success of vegetative plantings, and changes in macroinvertebrate populations. Preconstruction geomorphic data for the restoration reach are available for comparison to post-construction data because the collection of these data is part of the design process outlined by D. Rosgen. Unfortunately, preconstruction biological assessment data are not available for comparison purposes.

Results of the five years of geomorphic data collection indicate that the restoration reach is stable. In particular, the sinuosity of the channel has remained consistent since the construction, bank height ratio data indicate that the channel is able to access its floodplain, near-bank stress within the reach is moderate to low, bank pin measurements and cross-section survey data indicate that the cross-sections are stable, and the meander width ratio data indicate that the channel is unconfined.

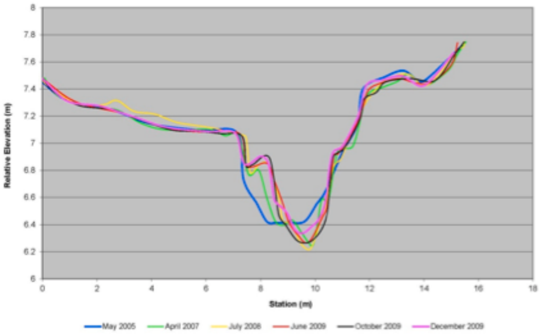

Figure 2. Pool cross-section showing adjustment.

Figure 2 shows a plot of one of the pool cross-sections with evidence of lateral channel migration from 2005 to July 2008; however, the channel has not migrated since July 2008. All other cross-sections show no evidence of migration. Visual observation revealed the presence of silt in the restoration reach, and the riffle and bar particle (pebble count) data verified this observation. The silt source was episodic and related to construction in the watershed upstream of the restoration reach. Nevertheless, the siltation did not result in channel instability.

The project team collected data on bank and riparian vegetation annually at 12 permanent sampling plots, following a Maryland Department of the Environment protocol. The vegetation sampling data demonstrated an increase in species richness from 36 species in 2005 to 59 species in 2009. Submerged aquatic vegetation occurred throughout most of the channel. The vegetation sampling also showed the presence of nine exotic species as well as climbing hempweed, a native species that grew so prolifically in the project area that it appeared to be threatening the survival of some of the planted vegetation by growing overtop of shrubs or growing up willows and weighing them down. The project team implemented a control effort to eradicate climbing hempweed and exotic species in August 2009.

To evaluate the health of the stream, the project team performed biological and habitat assessments in the spring and fall of each monitoring year, following the protocol described by M.T. Barbour and colleagues. Benthic macroinvertebrate sampling data showed a shift over time in the relative abundance of species and from more pollution-tolerant to less pollution-tolerant species. Sampling also recorded the presence of fish and frogs throughout the stream, and the habitat assessment data indicated optimal overall habitat.

Water quality monitoring data collected as part of the protocol indicated that all parameters fell within Maryland Department of the Environment standards for Use I waters, which are designated as suitable for water contact recreation and for the growth and propagation of fish, other aquatic life, and wildlife. However, conductivity steadily increased throughout the five-year monitoring period, from 230 µhos/cm in 2005 to 480 µhos/cm in 2008 (in both the spring and the fall). This could be due to the increasing urbanization in the watershed and the increased runoff carrying pollutants into the stream. Conductivity to support a diverse mix of species should range from 150 to 500 µhos/cm. While some improvement in water quality is reflected in the shift in abundance from more pollution-tolerant to less pollution-tolerant species, conductivity (coming from watershed sources) may ultimately limit the ability of the macrobenthic community in the Western Tributary to include an abundance of less pollution-tolerant species.

The monitoring data collected as part of the Western Tributary stream restoration project demonstrate success in restoring lost ecosystem services up to a point—that is, the project clearly restored the structure and function of the physical habitat. However, the water quality and macroinvertebrate data suggest that, unless more is done to manage the sources of stormwater-borne pollutants in the contributing watershed, the recovery of the biological communities will be limited. The results from this project are consistent with findings reported by B. Doll, who found that stream restoration could effectively create the necessary physical habitat to support diverse aquatic life, but that the delivery of nutrients, sediment, and other pollutants from of the contributing watershed influences the extent of achievable ecosystem recovery.

Site-based stormwater management retrofits can effectively use rooftops, porous pavements, infiltration, rainwater harvesting, and functional landscapes to remove stormwater-borne pollutants. However, these retrofits alone may require significant time (decades or more) to improve conditions in previously damaged stream channels. Local jurisdictions—including Anne Arundel County, where this project took place—must address compliance with Clean Water Act municipal separate storm sewer system permit requirements to reduce nutrients and sediment pollution in stormwater; to do so, they are increasingly combining stormwater retrofits with stream restoration. The integration of stream restoration with site-based stormwater management may offer the best opportunity to restore clean water and natural ecosystem values and functions and to provide the associated benefits to the human population.

List of Sources

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For More Information

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Contributor

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Aaron Koch

Deputy Commissioner for Sustainability, City of Chicago Department of Water Management

Aaron Koch is the deputy commissioner for sustainability in the City of Chicago's Department of Water Management. In this role, he is responsible for implementing the water sustainability initiatives outlined in *Sustainable Chicago 2015*, Mayor Rahm Emanuel's roadmap for environmental stewardship and economic development. Aaron previously served as a senior policy advisor in the New York City (NYC) Mayor's Office of Long-Term Planning and Sustainability, where he was an author of the water chapters of *PlaNYC*, Mayor Michael Bloomberg's sustainability plan, as well as the *New York City Wetlands Strategy* and the *Sustainable Stormwater Management Plan*. Aaron holds a master's in city planning from the University of Pennsylvania and a Bachelor of Science in architecture from the University of Minnesota.

Question 1: Please tell us a bit about the watershed where you work (geographical location).

I recently joined the Chicago Department of Water Management from the NYC Mayor's Office of Long-Term Planning and Sustainability. I am responsible for water sustainability policy and planning with a focus on developing a coordinated green infrastructure (GI) policy for the City of Chicago. We have strong leadership within multiple City agencies and precedence from efforts under Mayor Daley, such as the stormwater ordinance that Pete Mulvaney outlined (see above). We are now seeking to build on those accomplishments under the leadership of Mayor Emanuel and through *Sustainable Chicago 2015*, which is the City's new roadmap for environmental stewardship and economic development. Chicago is already a GI leader with approximately 360 green roofs and 175 green alleys, and we want to continue our commitment to sustainability by incorporating GI into long-term funding and capital budgets to strategically keep water out of our combined sewer system.

Question 2: How does your department define GI?

GI for stormwater management means using distributed source control measures that keep water out of our sewer system and better mimic predevelopment conditions. In *Sustainable Chicago 2015*, a key action to reduce combined sewer overflows (CSOs) and basement flooding is to create a GI plan that is embedded in the capital budgeting process.

Question 3: What is your department's experience with GI, and what reasons or decision-making processes were behind the adoption of this approach to address CSOs, whether throughout the region/area or for a specific project?

The City of Chicago has a strong track record on GI implementation. This includes well-documented efforts, such as promoting green roofs and building permeable green alleys, but also a wide variety of stormwater source controls at public sites and buildings. The City has also increased GI on private properties through the stormwater ordinance and by providing homeowners with rebates for rain barrels and trees through our Sustainable Backyards Program. All of these efforts have involved collaboration among many City of Chicago departments. In addition to the Department of Water Management, other key agencies, such as our Department of Transportation and Department of Housing and Economic Development, promote GI to keep stormwater out of our overtaxed sewer systems, but also because GI provides multiple other benefits, such as improving air quality and reducing the urban heat island effect.

Question 4: Does the adoption of a GI approach to address CSOs result in regulatory issues that differ from those associated with more conventional or traditional engineering solutions to address CSOs?

Unlike many other municipal governments, the City of Chicago does not have a consent decree for CSO reductions. But we are working with the Metropolitan Water Reclamation District of Greater Chicago as they seek to use GI as part of their consent decree. Even though the City doesn't directly face regulatory issues, GI still requires a different way of operating, such as developing different standards for design, construction, and maintenance. Also, implementing GI requires more careful coordination between and among city agencies, other stakeholders, and the public.

Question 5: Can you identify a few key challenges that you have encountered in implementing GI?

First, unlike traditional gray infrastructure, implementing GI requires a more coordinated approach within the local government and with the private sector. Second, funding is always a challenge. The federal government has significantly reduced direct funding to municipalities to meet the requirements of the Clean Water Act over time. This presents local water utilities with difficult choices about how to balance the need to invest in maintaining and replacing existing infrastructure while at the same time making new investments in GI or other stormwater management projects. This also places a heavier burden on water ratepayers. Rate increases offer one funding mechanism, but we must be mindful of how rate increases can impact our citizens, particularly in challenging economic times.

Question 6: Beyond the goal of using GI to address pollutant loadings in receiving waters, in your experience, what other community/social or economic benefits resulted from using GI?

GI provides well-documented environmental benefits, such as improved air quality, a reduced urban heat island effect, and increased quality of life. I also believe that GI can provide benefits when we engage the community in GI planning.

Question 8: What programs or assistance are available to advance the use of GI, and what criteria are used to determine what type of solution is most appropriate? Which assistance needs are being met, and which are not? Is the information getting to the practitioners?

The City of Chicago provides education to residents and the general public on GI through seminars and programming at the Chicago Center for Green Technology, which is the Midwest's most comprehensive green design educational resource for urban residents. The City also provides financial incentives through the Sustainable Backyards program for installations that meet specific criteria. Thousands of Chicagoans have participated in these programs. In 2011 alone, the Sustainable Backyards Program distributed 420 rebates to residents that resulted in the planting of over 1,200 native plants and 397 trees and the installation of 133 rain barrels and 116 compost bins. There is always a greater need for additional funding and outreach for GI education, outreach, and community-level implementation, and we will continue to explore partnerships to meet these needs.

Question 9: Can you share a “success story”? If so, who was involved (e.g., organizations, volunteers, or researchers)?

In addition to the stormwater ordinance Pete mentioned, Chicago has used a sustainable development policy that couples highly valuable land use development approvals to drive GI implementation. The City worked with the private real estate community during the creation of the stormwater ordinance and tied special land use development approvals to GI implementation, such as green roofs. Green roof GI practices are prevalent in Chicago largely because the developers wanted City special project approval or special funding and were required to comply with a “green matrix” that requires GI.

Question 10: Based on your experience with GI, what research or other work (e.g., coordination or programs) is still needed for its effective watershed management application?

This is an exciting time to work in stormwater management and GI. The federal government is following the lead of cities and embracing GI. Cities and their state and federal partners need to continue to move GI forward through additional planning, by building more projects, and through monitoring and research. However, we need additional analysis and research to better understand where we can use GI most successfully. GI is not always the cheapest option for stormwater management, and GI is not the answer for all issues and places. We need to better understand where GI makes the most sense and target GI where we can maximize our return on our investment. Also, it is important to recognize that each city should use GI based on its goals, local conditions, and vision for the future.

Suggested resources

Please read the companion “Ask the Expert” on Pete Mulvaney

City of Chicago 2012 Sewer Construction and Stormwater Management Requirements
http://www.cityofchicago.org/city/en/depts/water/provdrs/engineer/svcs/2009_sewer_constructionandstormwatermanagementrequirements.html

City of Chicago Sustainable Backyards Program
http://www.cityofchicago.org/city/en/depts/cdot/provdrs/conservation_outreachgreenprograms/svcs/chicago_sustainablebackyardprogram.html

Pete Mulvaney

Advisor, Greenleaf Advisors LLC

Pete Mulvaney started his career at the Museum of Southwest Biology, where he was exposed to the environmental and economic impacts associated with hydrologic diversions through various studies along the Rio Grande and other southwestern river systems. Pete then spent four years with the National Institutes of Health (NIH), developing experiments and publishing findings about the triggers that stimulate a tumor cell to become invasive. Pete left NIH with the feeling that preventing environmental insults was the path toward a healthy future. This principle led Pete to environmental engineering. As the Kappe Lab Scholar at Pennsylvania State University, he studied the engineering of water treatment technologies and parlayed this into consulting for HARZA Engineering (now MWH). As a team leader, Pete either led or participated in the engineering of environmental solutions to major infrastructure investments, including hydropower reservoirs in South America, major floodplain restorations along the Danube River, and the restoration of wetlands in Illinois. In 2005, Pete accepted a position as director of sustainability for the Chicago Department of Water Management, where he integrated solutions to complex issues such as stormwater policy, water conservation, and sewer operations. Since 2011, as an advisor with Greenleaf Advisors, Pete has been able to leverage his broad experience to solve complex problems with financial, environmental, and engineering acumen. Pete holds an MBA from Kellogg School of Management, Northwestern University; an MS in environmental pollution control from Pennsylvania State University; and a BA in psychology from the University of Colorado.

Question 1: Please tell us a bit about the watershed where you have worked (geographical location).

The Chicago River Watershed is quite unique. In 1900, it was “reversed” by connecting it to the Des Plaines River, which flows into the Mississippi watershed, as opposed to the Great Lakes watershed, which is its natural discharge point. This was, and remains, one of the great hydraulic engineering feats of its time, as it enabled Chicago to have clean drinking water from Lake Michigan. Over the last 100 years, this highly engineered drainage system has produced tremendous value. Today, however, the context of the river is changing, and people question what role the river has in addressing tomorrow’s concerns.

Question 2: How does your organization define green infrastructure?

In our organization at Greenleaf Advisors LLC, green infrastructure (GI) is either *inflow reductions* using landscape changes or the addition of *distributed intelligence* (like a restrictor or a smart valve) to existing infrastructure. If we include potable water in GI, this adds water reuse, resource management, etc. to the definition.

Question 3: What is your experience with GI, and what reasons or decision-making processes were behind the adoption of this approach to address combined sewer overflows, whether throughout the region/area or for a specific project?

The City of Chicago was originally engaged in GI to be a global leader by adopting and adapting best practices from other global cities. Mayor Richard Daley wanted Chicago to be a better leader and steward of water resources, and this was a major GI driver. Chicago’s “greening” efforts were less focused on solving a problem than an expression of what the City wanted to be—a world-class city with the highest quality of life to retain and attract world-class people. Chicago's green roof programs, rain garden initiatives, and Streetscape projects were all modified versions of work in other cities. Over time, we realized that GI can be implemented to solve problems, such as combined sewer overflows (CSOs) and basement flooding.

At Greenleaf, we are engaged on several fronts to improve the management of our water resources. We are involved in exciting new technologies that can improve the performance of existing stormwater storage. We are also investigating how stormwater responsibilities and costs can be distributed more broadly, and thereby stimulate market-based solutions. However, what I am most proud of is the ability to create stimulating environments where collaboration between agencies is accelerated. I feel strongly that enhancing utility management is the fastest way to improve our water resources.

Question 4: Does the adoption of a GI approach to address CSOs result in regulatory issues that differ from those associated with more conventional or traditional engineering solutions to address CSOs?

Historically, there was a struggle to get regulatory agencies to keep up with practitioners. In Chicago, we do not have a consent decree as a regulatory driver. In our experience, most GI policy barriers were internal rather than external. For example, we found code conflicts, policy conflicts, or traditions as major GI obstacles. Chicago addressed many of these internal obstacles through an intensive code audit that resulted in the award winning *Adding Green to Urban Design* plan, which presents a rationale, a vision, and a detailed implementation strategy for economically sound and environmentally sustainable urban design. The plan is intended to provide direction to the Chicago City Council to regulate urban design and to the Chicago Plan Commission to review individual development projects. It is also expected to guide the Chicago City Council and City departments to make decisions about public investment and improve Chicago's built environment.

Question 5: Can you identify a few key challenges that you have encountered in implementing GI?

Key challenges in the City of Chicago were to address our internal policies that were GI obstacles. We lacked an overall strategic framework to coalesce multiple agency efforts. Also, climate change ultimately became our umbrella issue under which to organize our efforts. More recently, the City evolved its framework into the *Sustainable Chicago 2015* plan. We also found that there is a huge need to manage expectations. Different stakeholders have very different notions of what GI is and what it is capable of achieving. For example, most engineers like to have a problem to solve, and their expectations of GI were measured against traditional costs and benefits, where many homeowners expected to see a difference with a single rain barrel. It seems to me that the industry of GI has matured a lot in the past few years, with more moderate expectations for green and gray solutions.

Question 6: Beyond the goal of using GI to address pollutant loadings in receiving waters, in your experience, what other community/social or economic benefits resulted from using GI?

In the City of Chicago, we used education successfully to increase awareness. This education led to conversations about behavior change, rate raises, infrastructure value, and shared responsibility for stormwater management. Engaging people and communities was important to them and for us.

Question 8: What programs or assistance are available to advance the use of GI, and what criteria are used to determine what type of solution is most appropriate?

I think we need to be explicit about what GI means to the different professionals involved in its implementation. In Chicago, “new development” is actually redevelopment since there is very little greenfield construction. Private sector implementation is driven by regulation. Municipal employees who manage our growth (redevelopment) are generally zoning-, planning-, and buildings-oriented staff who pass ordinances with City Council approval. This is in stark contrast to the right-of-way (ROW) management, where transportation agencies follow their own standards. GI in the ROW has a completely separate group of people and processes. The private sector can be regulated, but ROW change is through leadership and responsibility.

Question 9: Can you share a “success story”? If so, who was involved (e.g., organizations, volunteers, or researchers)?

One of the successes of the City of Chicago was passing the Chicago stormwater ordinance, which provides a framework and broad exposure to the principles of stormwater best management practices. It is a framework design based on performance metrics, which can be adjusted over time as needed. Our second success was the development of a world-class sewer model that built on tremendous city-wide GIS data sets, allowing us a very granular detail at a city-wide scale. The power of this model is the integration of the best science available to inform policy planning and design.

On the other side of the coin, we learned a lesson the hard way. Although we tried to be comprehensive in our approach with a holistic look at the process, we did not account for the different material types that would be proposed with additional GI. As a result, some early projects were burdened with higher costs due to delays in projects that sought exemptions or the selection of higher-cost products. Essentially, we did not keep our sewer material codes up to date with the market. This highlights the need to embrace a very broad/holistic perspective when stimulating new approaches.

Question 10: Based on your experience with GI, what research or other work (e.g., coordination or programs) is still needed for its effective watershed management application?

I think we need to understand the “secondary” GI values, such as community benefits and water resource benefits after the water exits our GI network. We also need to develop more diverse investment opportunities that create incentives for stakeholders to support GI solutions, such as behavior changes and/or maintenance.

Suggested resources

Please read the companion "Ask the Expert" on Aaron Koch

Adding Green to Urban Design
http://www.cityofchicago.org/content/dam/city/depts/zlup/Sustainable_Development/Publications/Green_Urban_Design/GUD_booklet.pdf

Chicago Center for Green Technology http://www.chicagogreentech.org/

City of Chicago Department of Water Management
http://www.cityofchicago.org/city/en/depts/water.html

City of Chicago Stormwater Management Ordinance Manual
http://www.cityofchicago.org/content/dam/city/depts/water/general/Engineering/SewerConstStormReq/2012StormManual.pdf

Greenleaf Advisors LLC http://greenleafadvisors.net/

Sustainable Chicago 2015
http://www.cityofchicago.org/city/en/progs/env/sustainable_chicago2015.html

Brandon C. Vatter, PE

Senior Project Manager, Hatch Mott MacDonald

Brandon Vatter is a senior project manager and watershed/wet weather technology expert for Hatch Mott MacDonald in the Cincinnati, Ohio, office. A registered professional engineer with more than 16 years of experience, Brandon has been involved in all aspects of collection system and wet weather modeling, planning, and design. He has directed the planning and design of multiple green and gray infrastructure projects within the combined and separate sewer systems to reduce overflow volume and stormwater runoff by addressing stormwater at its source. Brandon's work focuses on affordable water quality—integrated watershed management to obtain the optimum public investment to improve water quality. Brandon is currently helping several utilities implement integrated watershed planning based on the US Environmental Protection Agency's (USEPA's) Integrated Planning Framework. Brandon's work also includes regulatory risk advisement to more cost-effectively and efficiently implement pollution abatement programs to minimize impacts to sewer rates and improve efficiency and lower costs within a utility. Previously, Brandon was the director of planning and design for Sanitation District No. 1 (SD1) of Northern Kentucky. He was one of the main architects of SD1's innovative watershed plans, which combine gray, green, and watershed-based controls to comply with the Clean Water Act and balance affordability with measurable water quality improvement. This watershed-based approach was designed to save the ratepayers of SD1 nearly $2 billion compared to a traditional combined sewer overflow (CSO) and sanitary sewer overflow (SSO) approach. Brandon has a BS in civil engineering from the University of Cincinnati.

Question 1: Please tell us a bit about the watersheds where you have worked (geographical location).

In the last few years, I have worked primarily in northern Kentucky and Cincinnati, Ohio. These watersheds drain to the Ohio River and ultimately to the Gulf of Mexico. The urban and suburban watersheds where I work have impervious cover that ranges from approximately 70% to 100%. Most waterways in these areas are listed on USEPA's Clean Water Act Section 303(d) list as a result of this dense urban development; the existing CSOs, SSOs, stormwater runoff, industrial discharges, and dry weather pollution (i.e., illicit discharges) are causing water quality impairments.

Question 2: How does your organization define green infrastructure?

Green infrastructure (GI) uses innovative engineered systems to mimic the natural hydrologic cycle and treat stormwater where it falls to renew the resource rather than create a nuisance. GI can provide triple-bottom-line benefits to include water quality improvements as well as economic and social benefits. However, GI is simply one tool in the water quality management toolbox used to develop integrated watershed plans to address urban, rural, and agricultural pollution in our watersheds.

Question 3: What is your experience with GI, and what reasons or decision-making processes were behind the adoption of this approach to address CSOs, whether throughout the region/area or for a specific project?

From my experience, I learned from utilities that had already addressed wet weather consent decrees that building larger tanks and conveying and treating more flow at the wastewater treatment plant required significant capital investment, but typically did little to improve instream water quality because other pollution sources were left uncontrolled. Therefore, a watershed-based approach to address the multiple pollutant sources is needed. If your approach starts at the stream and works back to the pollution sources causing the streams not to meet water quality standards—including stormwater discharges, dry weather sources, overflows, and even habitat issues—then a holistic and more affordable pollution abatement program can be developed. An integrated watershed-based approach using a balance of green, gray, and watershed-based controls to abate the various pollution sources in context with one another can be more cost-effective and provide significantly more instream water quality improvement and public health protection than a traditional convey-and-treat CSO/SSO approach. The bottom line is: stormwater causes sewer overflows. We don't have CSOs or stormwater discharges when it is not raining. Dealing with the root cause of the problem, stormwater, is a key to success.

Question 4: Does the adoption of a GI approach to address CSOs result in regulatory issues that differ from those associated with more conventional or traditional engineering solutions to address CSOs?

Traditional approaches focus on the quantity of flow controlled. Instead, we should focus our efforts on instream water quality improvement through an integrated watershed management approach. This focus gets us right to the heart of Clean Water Act regulatory compliance—our waterways meeting water quality standards. For each GI project, the goal should be to measurably improve instream water quality. Stormwater volume managed or CSO reduction is a design criterion, but the goal of either a GI approach or a traditional solution should be measurable improvement to instream water quality. When we begin to think of GI projects and traditional solutions in terms of instream water quality improvements, then we can begin to develop an *affordable* and integrated combination of green, gray, and watershed-based controls to maximize water quality and public health improvements at the lowest cost.

Question 5: Can you identify a few key challenges that you have encountered in implementing GI?

GI is an institutional change from the "normal" convey-and-treat approach of a sewer utility, and not everyone is comfortable implementing and maintaining GI yet. In addition, demonstration projects to date do not definitively show that GI can achieve similar "consistent" benefits. Stormwater sources originate in urban settings, where space and logistics often make it a challenge to install infrastructure to manage the necessary stormwater runoff volume. The third issue is that GI typically involves more public exposure and involvement, which requires more intensive community outreach to those who live and work in the area where we want to implement GI. A utility's commitment to public outreach is necessary to achieve a partnership with the public that, in many cases, is essential for proper operation and maintenance of the GI.

A fourth challenge for implementing GI is that GI requires a paradigm shift in utility thinking on maintenance and often requires learning new maintenance techniques. Some utilities are uncomfortable maintaining GI; we know how to maintain sewers, but not GI. However, if you talk to a sewer dig-up crew they would likely rather pull weeds and install plants versus stand in sewage and fix a broken sewer pipe. A fifth challenge for GI is understanding that it is a tool in the toolbox to manage water pollution, but it is effective only if designed with clear performance goals. Identifying measurable and achievable water quantity and water quality performance goals at the onset of a project and knowing how they will be measured post-construction is a key challenge to address. Documented performance and familiarity with the long-term operation and maintenance of GI will establish the utility’s confidence to meet all of these challenges.

Question 6: Beyond the goal of using GI to address pollutant loadings in receiving waters, in your experience, what other community/social or economic benefits resulted from using GI?

Beyond cost savings compared to traditional gray infrastructure, GI can also provide job creation, neighborhood beautification and recreation, carbon footprint reduction, economic redevelopment, energy savings, offsets to climate change, air quality improvements, property value increases, habitat restoration, and urban heat island reduction. GI can also help reduce overland flooding, basement sewer backups, and impacts from more frequent storm events. GI offers a triple bottom line with benefits that can exceed those of traditional gray infrastructure projects.

Question 8: What programs or assistance are available to advance the use of GI, and what criteria are used to determine what type of solution is most appropriate? Which assistance needs are being met, and which are not? Is the information getting to the practitioners?

The Water Environment Federation (WEF) is developing a GI implementation publication that will be available in 2014 and will provide a comprehensive reference to implement GI. WEF has solicited input for the publication from more than a dozen national experts. The publication will provide a basis for the selection of GI solutions, such as performance goals; existing site features and constraints (utilities, grading, and drainage areas); watershed target pollutants to remove; and the level of community involvement and acceptance. Based on my experience, folks who are implementing GI approaches should talk with other utilities with GI implementation experience for their feedback and lessons learned. Many times, utility folks have learned by doing which design details work and which design details do not work. For example, a common question asked is what to do if waterlines or sewer laterals are in the way of the excavation needed for the GI feature. The answer to this question can be best obtained by talking to others in the field who have encountered this issue and constructed these installations.

Before GI implementation, make sure to develop specific measurable performance goals that go beyond just capturing the first inch of runoff. For example, at the project level, we want to see that the GI system functions as designed, achieves the estimated stormwater reduction and pollutant load reduction, achieves the CSO volume reduction that we estimated during design, and has operation and maintenance costs that match what were expected. At a watershed scale, we check that GI is functioning with the other pollutant source controls to achieve the instream water quality improvements that we projected. We also want to confirm that the GI achieves the social and economic benefits that we estimated through the triple-bottom-line analysis.

Once these measurable goals are established, one should develop a cost-effective yet appropriate post-construction monitoring program to verify that the performance goals are met. Just because GI is installed does not necessarily mean that a CSO volume reduction or water quality improvement will be achieved. These two key points tend to get lost, and without them you may not reach your overall regulatory goals.

Question 9: Can you share a “success story”? If so, who was involved (e.g., organizations, volunteers, or researchers)?

In Philadelphia, our firm has experienced the community embracing GI projects across the city while working with the Water Department. This program has included community involvement in design, landscaping, and maintenance activities. Also, property owners have added to the program by installing rain barrels and stormwater planters. Through this process, the residents embraced GI and the community benefits that result.

At SD1, one of my keys to success was personalizing the problem—getting the ratepayers to understand that we as a society created this water pollution problem and it will take involvement from all of us in order to fix the problem. This is not a utility problem, but a community problem. I like to say, “Had we known back then what we know now, we would have done things differently so we would not be facing this water pollution problem today.” This type of approach garnered community support for the watershed-based approach as well as for the implementation of individual, private-property GI projects. I recall that before one public meeting started, one of the more vocal property owners whispered in my colleague’s ear that “we were in for a lot of public resistance tonight.” We completed our “personalizing the problem” presentation and then answered several questions about the presentation from the audience. After that point, the “public resistance” we were promised changed to one of collaboration and working together. Comments went from “not on my property” to “how can I save my landscaping when my downspout is disconnected?”

Question 10: Based on your experience with GI, what research or other work (e.g., coordination or programs) is still needed for its effective watershed management application?

GI water quantity and water quality performance effectiveness data are available, but the datasets in many cases are limited, so more work to confirm GI’s effectiveness needs to be done. GI can be an effective tool to improve water quality; however, GI does not typically address all of the pollutant sources in a watershed. In order to develop effective watershed management, we need to understand the full range of pollutant sources so as to optimize affordable green, gray, and watershed-based controls to maximize water quality and public health improvements. Various universities, including the University of New Hampshire and Villanova University, have active GI research and development programs. The Water

Environment Research Foundation (WERF)/USEPA/American Society of Civil Engineers (ASCE) international best management practice (BMP) database is an updated resource for available GI performance data. However, you will notice upon review that the amount of GI performance data for various BMPs is still limited in the database. Before using GI in a watershed, we recommend that the planned BMP types be pilot tested to confirm both water quantity and water quality performance goals based on local conditions. If GI is to be used to address CSOs or to reduce pollutant loading by managing stormwater runoff, pilot testing that confirms GI effectiveness is critical to a successful program. Implementing GI on a wide scale without proper pilot testing can result in a pollutant control program that does not meet its goals and costs a community more money in the long run. Once pilot testing confirms GI effectiveness, simply installing GI with the intent that it will perform as desired is not sufficient. An ongoing GI post-construction monitoring program to confirm consistent and reliable performance is needed. This GI monitoring program should be incorporated into the overall watershed water quality compliance monitoring program.

Suggested resources

WERF/USEPA/ASCE International Stormwater BMP Database www.bmpdatabase.org

University of New Hampshire Stormwater Center http://www.unh.edu/unhsc/

USEPA Economic Incentives for Stormwater Control
http://cfpub.epa.gov/si/si_public_record_report.cfm?dirEntryId=235389

Villanova University Urban Stormwater Partnership http://www3.villanova.edu/vusp/

Franco Montalto, PhD, PE

Assistant Professor, Civil, Architectural, and Environmental Engineering Department, Drexel University

Franco Montalto is a licensed civil/environmental engineer and hydrologist with 20 years of experience working in urban and urbanizing ecosystems as a practitioner, designer, and researcher. This experience includes planning, design, implementation, and analysis of natural area restoration and green infrastructure (GI) projects, featuring natural treatment systems for wastewater and stormwater management as well as water harvesting and reuse systems. In addition to serving as the president and principal engineer of eDesign Dynamics LLC (EDD), Franco directs the Sustainable Water Resource Engineering Laboratory at Drexel University, where he was appointed as an assistant professor in the Department of Civil, Architectural, and Environmental Engineering in 2007. He is a member of the advisory board of the New York City (NYC) Natural Areas Conservancy, among other organizations, and serves as co-chair of the American Society of Civil Engineers' Technical Committee on Low-Impact Development Computational Methods. Prior to founding EDD and joining academia, Franco served as the wetlands engineer at the New Jersey Meadowlands Commission, where he was responsible for large urban wetland restoration projects, such as the engineering design of the 139-acre Mill Creek Marsh in Secaucus, New Jersey. Franco has also worked in Europe, Africa, the Caribbean, and Latin America. In addition, he was formerly a fellow at the Earth Institute at Columbia University, a Fulbright Scholar, and an adjunct professor at Cooper Union for the Advancement of Science and Art.

Question 1: Please tell us a bit about the watersheds where you have worked (geographical location).

My interest is in heavily urbanized watersheds. I work principally in the regions in which I live or have lived in NYC, Northern New Jersey, and Philadelphia, though I have also worked internationally in places like Italy, Ethiopia, Denmark, and Haiti. Work in urban and urbanizing watersheds is extremely important because the world's population continues to urbanize and the shortcomings of traditional end-of-pipe water management strategies are now widely recognized. Innovations in urban watershed management are urgently needed.

Question 2: How do you define GI?

I define GI broadly as decentralized engineering, enhancement, or protection of multifunctional landscape features. Although the principal driver for, and characteristics of, each GI project will differ based on local conditions, all GI projects provide multiple benefits.

I wear three hats that include practitioner, researcher, and community stakeholder. As a practitioner at EDD, I am typically tasked with developing GI designs that reduce the rate and volume of runoff generated on urban catchments. However, these same designs can also provide new urban microhabitats; become a source of nonpotable water; remove pollutants; or aesthetically enhance a streetscape, alley, courtyard, playground, or park. As a researcher, I quantify how much water directed to specific GI facilities evaporates, replenishes the soil moisture, or infiltrates. These hydrologic processes underlie many important ecosystem services. Urban evapotranspiration, for example, wicks heat away from the city, mitigating the urban heat island effect. By replenishing soil moisture, GI practices can enhance the ability of urban vegetation to sustain prolonged droughts, though they can also create waterlogged conditions that are detrimental to certain types of vegetation. Infiltration can recharge local aquifers but, if promoted in the wrong places, can also create basement flooding problems or otherwise interfere with the functioning of underground infrastructure, such as buried utilities or subway tunnels.

Question 3: What is your experience with GI, and what reasons or decision-making processes were behind the adoption of this approach to address combined sewer overflows, whether throughout the region/area or for a specific project?

I have been a consultant and scientific advisor to the NYC Department of Parks and Recreation, the NYC Department of Environmental Protection (DEP), and the NYC Mayor's Office of Long-Term Planning and Sustainability, among other organizations. All of these government divisions were interested in GI, both as a cost-effective combined sewer overflow (CSO) control strategy and to promote various urban sustainability goals. One of the most interesting periods of my career was between 2005 and 2007, when decision makers in New York began to seriously consider GI at a large scale. The case for GI was made, initially during the advisory board meetings that led to PlaNYC, the City's blueprint for sustainability and climate change adaptation. Stakeholder input was a key part of this process. The case for GI was built further during intense debates that occurred during the Citizen's Advisory Committee meetings held during the development of the City's long-term control plans for CSOs and during public hearings organized by City Councilman James Gennaro, chair of the council's Environmental Committee. Around this same time, GI was also discussed extensively in public comments associated with a variety of large redevelopment projects then underway across the city, such as the World Trade Center site, Hudson Yards in Manhattan, and Atlantic Yards in Brooklyn.

Q4: What were the reasons behind your research focus in this area? Why is GI a good solution for CSOs?

I first became interested in GI as a CSO abatement strategy while teaching a class in 2004. I gave students in my class at Cooper Union a typical knee-of-the-curve chart that displayed how much CSOs into Brooklyn's Gowanus Canal could be reduced using detention tanks of different sizes. I asked them to develop a similar set of curves associated with decentralized stormwater control measures. After 16 weeks of analysis, the students produced results showing GI systems to be cost-competitive with the centralized approach. After further scrutinizing the findings myself, we published it in the *Journal of Landscape and Urban Planning*. The publication was immediately posted on the website of the Mayor's Office in NYC and on US Environmental Protection Agency websites. I became interested in how individual types of GI work, how their performance compares to one another, and how their benefits scale as more and more decentralized practices become installed in urban watersheds. Nine years later, my Drexel research team is studying more than 15 GI practices in NYC, New Jersey, and Philadelphia. Currently, we are also conducting paired urban catchment studies that monitor flow at the manholes, catch basins, and at the "downstream" city block for catchments that will be greened (test sites) and those that will not be greened (control sites). Using GI to reduce CSOs is wise because of all of the other ancillary benefits that GI provides, and this enhances the argument for its cost-effectiveness.

Question 5: Does the adoption of a GI approach to address CSOs result in regulatory issues that differ from those associated with more conventional or traditional engineering solutions to address CSOs?

Now that cities like NYC have committed to GI, regulators are expecting it to reliably reduce CSOs. Because GI is implemented gradually over time, I believe that cities committed to the GI approach will more easily meet regulators' expectations than those that have elected to take a grey infrastructure approach. Since GI is implemented gradually over time, the design of specific practices can be improved as more is learned about what does and does not work. The ability for urban watershed managers to gradually refine GI system designs as successive waves of GI are built and tested is a great advantage over centralized grey approaches that are designed, built, and then subsequently not easily modified.

Question 6: Can you identify a few key challenges that you have encountered in implementing GI?

Early on, GI implementation was hindered by a lack of governmental leadership. However, the current NYC DEP Commissioner, Carter Strickland, joined the agency already with a deep interest in GI. Thanks to his leadership, the City has formally committed to GI, and implementation challenges today are largely associated with physical constraints posed by the urban environment. The siting of GI systems is constrained by mandatory setbacks from foundations, property lines, and underground utilities, as well as by the presence of high bedrock and shallow groundwater. Other considerations include on-street parking, driveways, contaminated soils, and the root systems of mature existing street trees, all of which are common in the postindustrial landscape of NYC. After all these factors are considered, the area that is actually available for GI on a typical NYC block may be very limited, and this is a key challenge. For GI to get approved and built in these kinds of environments, creative and innovative design strategies are needed. For example, on some of our most challenging projects, my firm has designed shallow, lined constructed wetlands on brownfields adjacent to building foundations. We have even used solar and human-powered pumps, float valves, and other advanced control systems to enhance and dynamically manage retention capacity. Currently, we are working on the design of a lined curbside bioswale for detention of the water quality volume in areas with high bedrock.

Another key challenge to GI implementation is the push toward standardization, which can hinder design innovation. Local officials need to standardize GI design practices to streamline the siting, design, and approval of GI systems. But if the codes become overly prescriptive, it will become very difficult to achieve the level of GI penetration needed to significantly reduce CSOs. The local officials that permit GI practices need to find ways to simplify the design and permitting process while simultaneously allowing for the development of site-specific design innovations.

Question 7: Beyond the goal of using GI to address pollutant loadings in receiving waters, in your experience, what other community/social or economic benefits resulted from using GI?

The more we can engage urban stakeholders in GI siting and design decisions, the more successful urban GI programs will be, and the more benefits this unprecedented investment in urban neighborhoods will engender. Without public support, it will be difficult and costly to maintain a decentralized network of GI facilities. On the other hand, if local residents are engaged throughout the greening process underway in their communities, they are more likely to become GI stewards. There are many ways to do this. GI systems can be incorporated into urban agriculture facilities, for example, and can become visually engaging amenities to otherwise sterile or barren urban landscapes. These projects can also motivate urban residents to attend public meetings and to participate in local government. Community-based organizations can be employed in the ongoing operation, maintenance, and monitoring of GI systems. All of this is only possible if government agencies commit to involving the public in GI decisions.

Question 8: What programs or assistance are available to advance the use of GI, and what criteria are used to determine what type of solution is most appropriate? Which assistance needs are being met, and which are not? Is the information getting to the practitioners?

In NYC, there have been multiple grant programs that have created opportunities for many designers, property owners, and other watershed stakeholders to participate in the design, construction, maintenance, and monitoring of specific GI projects. These programs have been effective at engaging and educating individuals and firms about GI. Practitioners in NYC now also have available to them the recently issued GI Design Standards released by NYC DEP's Office of Green Infrastructure. I believe we still need to improve the baseline assessment protocol used to determine which types of GI facilities are most appropriate for specific sites. This will happen naturally as we learn more from implementation and monitoring studies.

Question 9: Can you share a "success story"? If so, who was involved (e.g., organizations, volunteers, or researchers)?

A very rewarding project for me has been helping the NYC Department of Parks and Recreation (Parks) to monitor and to build stormwater capture capabilities into their Greenstreets Program. In the past four years, we installed sensors in five different Greenstreets built in traffic islands and bumpouts. We have also established an ecological reference site, an old growth forest in Alley Pond Park in Queens. The monitored Greenstreets are hydraulically connected to impervious catchment areas in different ratios, have different inlet designs, and different stormwater storage capacities. The instrumentation, funded by the National Science Foundation, New York State Department of Environmental Conservation, and New York State Department of State, now provides real-time, continuous monitoring of climatic, hydrologic, and groundwater conditions at all the sites, which we use to help Parks improve their GI design strategies. The collaborative research effort involves both undergraduate and graduate students from Drexel, as well as a variety of engineers, landscape architects, and designers from Parks. Starting this year, the monitoring will also involve a troop of Citizen Scientists who live near the sites.

Question 10: Based on your experience with GI, what research or other work (e.g., coordination or programs) is still needed for its effective watershed management application?

We need site-specific studies that document how the GI facilities' performance changes over time and also how the GI practices perform when subjected to extreme climatic events, such as Hurricane Irene in 2011 and Superstorm Sandy in 2012. We need to better understand the fate of infiltrated water in heavily urbanized watersheds. We need to be able to predict the GI facility density required for measurable CSO reductions. Finally, I believe we need to find efficient, constructive ways to engage urban residents in GI practice decisions in their neighborhoods.

Suggested Resources

eDesign Dynamics www.edesigndynamics.com

Sustainable Water Resource Engineering Laboratory at Drexel University website—see the Greenstreets video http://www.cae.drexel.edu/swre/home.html

Standards for Green Infrastructure (right-of-way bioswale standards for NYC) http://www.nyc.gov/html/dep/pdf/green_infrastructure/bioswales-standard-designs.pdf

John W. Schombert

Executive Director, 3 Rivers Wet Weather, Inc.

As executive director of 3 Rivers Wet Weather, Inc. (3RWW), John Schombert played an instrumental role in the founding of this nonprofit organization in 1998. Prior to 3RWW, John worked for nearly three decades in the Allegheny County, Pennsylvania, Health Department's water pollution, public drinking water, and waste management programs. Most recently, he served as chief of public drinking water and waste management. In October 2002, John was appointed to the Pennsylvania State Board for the Certification of Sewage Treatment Plant and Waterworks Operators, and in 2011, he was appointed to the Pennsylvania Water Resource Advisory Board. John also serves on several boards, including those of the Local Government Academy and the Nine Mile Run Watershed Association. A registered environmental health specialist and a graduate of Thiel College with a BS in physics, John is an expert on wet weather issues.

Question 1: Please tell us a bit about the watershed where you work (geographical location).

I work for a nonprofit environmental organization that was incorporated by the Allegheny Health Department in 1998 to address the region's water quality issues impacted by wet weather overflows. 3RWW supports 83 Allegheny County, Pennsylvania, municipalities, including the City of Pittsburgh, in a 305-square-mile area serviced by the Allegheny County Sanitary Authority (ALCOSAN).

Question 2: How does your organization define green infrastructure?

In its simplest form, green infrastructure (GI) is the use of natural processes for managing stormwater. In our region, there are a number of separate GI projects that will be used as research and demonstration projects, including monitoring installations to define which GI approaches are most cost-effective and appropriate for our area and the impact on overflows and the scope of gray infrastructure. We have steep topography, low soil permeability, urban/suburban areas, high water tables, aged systems, and systems with streams connected to them. During dry weather, only about 40% of the flow treated is sewage, and about 60% is inflow and infiltration from a number of direct stream connections and groundwater. It is a challenge to define source reduction and to decide which GI approach will be most effective. We have identified seven specific best management practices (BMPs) that are readily applicable in our region.

Question 3: What is your organization's experience with GI, and what reasons or decision-making processes were behind the adoption of this approach to address combined sewer overflows, whether throughout the region/area or for a specific project?

Our area has become very interested in GI, especially in the last few months with the release of the ALCOSAN draft wet weather plan for public comment. ALCOSAN, the regional treatment authority, is under a federal consent decree to reduce overflows from a system that is a tributary to a plant that treats 225 million gallons a day. During wet weather events, the storm and sewer flow can exceed 1 billion gallons. ALCOSAN's draft wet weather plan addresses the capacity of the sewage treatment plant and the connected river infrastructure for this regional sewer authority. The plan is controversial because of the estimated high cost and the difficulty in coordinating the ALCOSAN plan with the 83 municipal wet weather plans, which include GI. To facilitate the integration of municipal GI into the overall regional wet weather plan, 3RWW is providing assistance to municipalities to identify opportunities to site GI for their wet weather plans. We are piloting a GI placement program to explore the opportunities in combined sewersheds. To support this effort, we developed RainWays, an online interactive tool to support GI planning and implementation. This tool identifies BMPs, costs, contributing drainage areas, and stormwater capture; it connects the site-level information to more than 400 ALCOSAN connection points. RainWays provides the aggregate impact of GI practices on each of the ALCOSAN overflows at the municipal points of connection. RainWays provides an important planning-level tool tailored to support the area's wet weather plan.

Question 4: Does the adoption of a GI approach to address combined sewer overflows result in regulatory issues that differ from those associated with more conventional or traditional engineering solutions to address combined sewer overflows?

The challenge we are currently facing includes the ALCOSAN wet weather plan that focuses on tunnel and infrastructure expansion, which is not affordable for the region. ALCOSAN has submitted an alternate "recommended" plan that does not meet the full compliance requirements in the consent decree but is consistent with the US Environmental Protection Agency (USEPA) affordability criteria. The affordability criteria indicate that anything higher than 2% of the median household income for wastewater services is a high burden for the community. As a potential solution, 3RWW would like to include municipal GI as part of the source control program in the regional wet weather plan. Including GI in the plan would require using a phased approach, as other regions of the United States have done to evaluate and implement only the most effective wet weather control methods. When ALCOSAN submitted its wet weather plan on January 29, 2013, they requested that regulatory agencies extend the planning period by an additional 18 months to evaluate source reduction and GI approaches.

Question 5: Can you identify a few key challenges that you have encountered in implementing GI?

We need to overcome the urban myth that stormwater cannot be infiltrated in our region. In our experience, the GI sites can use engineered soils, underdrains, and/or overflows in the GI design to properly manage peak flows in the region. Existing land use and stormwater codes and ordinances in our 83 municipalities can be a barrier to GI. 3RWW and the University of Pittsburgh Environmental Law Clinic worked to identify existing obstacles and potential solutions in our land use and stormwater codes and ordinances. These findings were published in early 2013.

Question 6: Beyond the goal of using GI to address pollutant loadings in receiving waters, in your experience, what other community/social or economic benefits resulted from using GI?

We do not have enough experience with GI here to measure any social or community benefits yet. However, as demonstrated in other case studies, GI has the ability to attract the public to the process, including the triple-bottom-line (economic, environmental, and social) benefits.

Question 8: What programs or assistance are available to advance the use of GI, and what criteria are used to determine what type of solution is most appropriate?

There are several national and local GI models available that we use in addition to our own GI modeling tools to plan and implement GI. However, GI design and source reduction will be modeled using the Allegheny County "typical year rainfall" data (statistically similar to 2003 rainfall) to accurately design for GI performance. We focused on three watersheds in the community to characterize stormwater runoff with the Storm Water Management Model, then used USEPA's SUSTAIN model to identify site areas, and finally used our tool, RainWays, to plan specific site-level GI options. The three watersheds were selected based on their unique circumstances and challenges as multimunicipal and mixed combined/sanitary connections to the ALCOSAN system. Evaluating the GI options for these watersheds will provide important planning information for ALCOSAN and serve as a model for other watersheds.

Which assistance needs are being met and which are not? Is the information getting to the practitioners?

3RWW worked over the last 15 years with stakeholders representing our 83 municipalities. We used a consensus-based process to facilitate the development of the municipal wet weather plans. Our work focuses on the critical multimunicipal combined sewersheds where GI can be most effective. Public engagement is important to success.

Question 9: Can you share a "success story"? If so, who was involved (e.g., organizations, volunteers, or researchers)?

We expect to hear success stories as GI practices are implemented on a broader scale. However, I would like to share a success story that took place before the development of our GI program. About six years ago, 3RWW partnered with the Nine Mile Run Watershed Association on public engagement and education for a large urban stream habitat restoration project. This effort resulted in more than 1,000 rain barrel installations and a business plan for StormWorks, an initiative that supports commercial and residential education and GI implementation. While it's difficult to quantify the actual flow reduction with only 1,000 rain barrels, we do know, based on pre- and post-project surveys, that the rain barrel program significantly increased the residents' level of awareness and individual responsibility in protecting the watershed.

Question 10: Based on your experience with GI, what research or other work (e.g., coordination or programs) is still needed for its effective watershed management application?

We need incentives to implement the GI measures that we know work well in our region, such as green roofs, to make them initially cost-effective. We also need to measure the direct GI benefits for stormwater management. To do this, we need localized monitoring that includes performance measures at the site level to make GI management decisions.

We also need a change in governance to be sustainable. Currently, the ownership of the more than 4,000 miles of sewer collection system is distributed among 83 municipal entities. 3RWW is working with the region's leaders to change public policy for regional management of stormwater and sewer infrastructure. These regional changes are needed to integrate GI approaches into the management options for pollution reduction.

Suggested Resources

3 Rivers Wet Weather http://www.3riverswetweather.org/

RainWays http://www.3riverswetweather.org/green-infrastructure

USEPA's SUSTAIN Model http://www.epa.gov/nrmrl/wswrd/wq/models/sustain/