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Front-loading urban stormwater management for success – a perspective incorporating current studies on the implementation of retrofit low-impact development

William D. Shuster, Matthew A. Morrison, and Rachel Webb

Abstract

Recent work into the implementation of low-impact development (LID) suggests that a decentralized, source-control approach has the potential to significantly reduce urban stormwater runoff quantity. The practice of retrofit stormwater management is currently dominated by demonstration projects, and some additional momentum is required to spur upscaling of LID practices so that the scale of this management approach can better match the scale of disturbance, and furthermore broaden adoption of these practices. This momentum may be provided in part by targeted research into effectiveness of stormwater best management practices insofar as research accounts for cost and effectiveness (e.g., water quality benefits, and actual stormwater capture) under a variety of climate conditions. We posit that the factors of increasing public participation in stormwater management; engaging local agencies and non-governmental organizations (NGOs); application of proven source control methods to mitigate runoff formation; and science-based, comprehensive monitoring strategies are all important to the sustainable implementation of retrofit low-impact development. From the perspective of federal researchers and local NGOs, this paper presents features, objectives, and costs of recent efforts to properly scale demonstration projects and broader LID initiatives. In order to realize the full benefits of decentralized LID stormwater management practices in urban and suburban areas, we conclude that a nexus must exist of a motivated and engaged citizenry, solid support from municipal and regional agencies, sound source control management practices, and follow-up monitoring to judge effectiveness.

Keywords

Stormwater; low-impact development (LID); sustainability; monitoring; source control; participatory environmental management.

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INTRODUCTION

Stormwater runoff is a major environmental stressor in many landscapes across the United States, but particularly in urban landscapes where land use change involves the removal of vegetation and replacement with impervious surfaces such as roadways, sidewalks, driveways and housing. When rain falls on urbanized areas, little of the precipitation is detained, retained, or infiltrated, as impervious areas replace infiltrative surfaces (e.g., vegetation and soils; Imhoff et al. 2004; Pauleit et al. 2005). The majority of rainfall is converted directly to runoff, and this runoff will tend to accumulate to greater volumes at lower amounts of rainfall compared to pastoral or forested settings where there are many opportunities for rain to be intercepted by foliage or to move into soil via infiltration processes. Centralized stormwater management arose in response to urban flooding and wastewater management problems. Cities and suburban areas (or municipalities), traditionally route stormwater runoff to underground pipes and convey it to centralized treatment facilities or to the nearest flowing stream or river, depending on both volume and general approach to system design. In densely developed urban areas, large volumes of stormwater are concentrated by public infrastructure, such as curbs, that convey runoff volume to street-side drains leading directly to underground pipe networks. Residential properties are connected to stormwater infrastructure by gutters, downspouts, underground pipes, and direct runoff to street-side drains. Combined sewer designs mix stormwater with raw sewage, while separate storm sewer designs carry only stormwater flows. Separate stormwater designs can alleviate the problem of frequent sewage overflows to surface water, but they still produce adverse effects in urban ecosystems because large volumes of runoff are still routed separately and directly to streams and rivers. Separate sewer systems are subject to infiltration and inflow into either type of sewer line, which leads to sanitary sewer overflows. The centralized approach has led to environmental degradation at local and regional watershed scales. The deleterious impacts of urban storm flows on aquatic and terrestrial ecosystems (e.g., soil erosion, scouring and widening of stream beds, mobilization of nonpoint-source pollutants) have been long recognized. The limitations of centralized management become a rationale for retrofitting existing infrastructure and decentralization of stormwater management (Hammer 1972; Klein 1979), though only recently have these changes been implemented in innovative ways (Booth and Jackson 1997; Villareal and Bengtsson 2004).

Decentralized approaches to stormwater management involve both structural (e.g., detention basins, rain gardens) and non-structural (e.g., education, reduced irrigation) source controls of runoff volume, and typically fall under the umbrella of low-impact development (LID; Ahern 2007; Dietz 2007). The objectives of LID borrow from the tenets of restoration ecology, wherein one primary goal is to match the scale of the management action to the scale of the disturbance (Engstrom et al. 1999; Borgström et al. 2006). Another primary goal is to match or mimic hydrologic processes present in the pre-development condition. For these reasons, LID is a set of techniques that typically operates at small spatial scales (landscapes, residential homes, neighborhoods) and articulates a decentralized approach to linking site design and storm water management objectives across larger spatial scales (municipalities, cities, regions). This naturally calls on the notion of source control, where stormwater volume is dealt with at or nearby the point where runoff is generated, by detaining, storing, and redistributing it at the site as it would in more natural settings. Retrofit management is simply the practice of placing LID practices within existing urbanized areas.

To accomplish LID objectives, development is designed around natural hydrological features and runoff patterns. Where runoff is generated from impervious or semi-pervious surfaces, the resulting stormwater is managed through small-scale structures dispersed throughout a site to uniformly detain stormwater volume. These small-scale, integrated management practices may include singly or in combinations: rain gardens, bioretention, rain barrels or cisterns; vegetated swales; tree box filters; curbless roads with swales; and pervious pavement, among other practices to create permeable patches in the landscape or collect water for later use. Some immediate benefits of these techniques include: increased recharge of soil and ground water resources, reduction of the quantity of water leaving a site, and provision of water resources for on-site irrigation. In addition, modeling work by Semadeni-Davies et al. (2008) has shown that LID and sustainable urban drainage systems (SUDS) may sustain some ecosystem-level services. One of which would be resilience (as this concept pertains to the preservation and recovery of sensitive terrestrial and aquatic species) wherein some extent of additional capacity is built-in to an ecosystem such that press or pulse disturbances can be effectively weathered. For example, LID retrofits can add additional local storage capacity for stormwater volume, which may be a valuable ecosystem-level service in the face of uncertainties in rainfall distribution brought about by climate change.

Recent developments in the field of LID, such as Portland's Green Streets program (Portland Bureau of Environmental Services 2008) and Kansas City's 10,000 Rain Gardens project (10,000 Rain Gardens 2008), represent a call-to-action where citizen participation is critical for success. With participatory approaches to environmental management, we engage (or awaken) this social and cultural capital and substitute this for a part of the technological and infrastructure-heavy capital that we currently have practiced with centralized stormwater quantity management. An additional benefit of widespread public engagement is a shift in perception that embraces stormwater as a resource, rather than a potentially hazardous waste product to be shunted off to streams or wastewater treatment plants. However, some degree of oversight is required to ensure that appropriate LID practices are chosen, and that their design is reliable. Therefore, some degree of administration and technical guidance which we will term front-loading, are required from the inception of LID projects. We posit that a 100% front-loaded management system would be equivalent to command-and-control, a highly regulated approach that has dominated the stormwater management industry for many years. On the other end of the spectrum, a zero-percent effort into front-loading a management system would be equivalent to a purely uncoordinated voluntary action program. Yet, by screening and evaluating management practices, providing incentives and extension resources to deploy the environmental management practices as retrofits to urbanized watersheds, there is a moderate amount of front-loading to the environmental management system that offers options for substitutability among different types of capital (e.g., social and cultural versus more intensive technological and natural resource capitals) to achieve or strengthen attributes of sustainability in a stormwater management framework.

We posit that decentralized stormwater management can be realized through guided public participation and local partnerships that foster the acceptance and implementation of LID as source control and maintenance and monitoring, is necessary for sustaining and documenting effectiveness of appropriate "green" retrofit stormwater management techniques that are adopted in urban areas. The objectives of this paper are threefold: 1) to detail the circumstances necessary for effective adoption of LID through public participation and local partnerships; 2) to provide substantive examples of LID adoption using two case studies from Ohio, USA; and 3) to emphasize the importance of monitoring to quantify the benefits of LID, and the potential use of this data to spur wider adoption of LID practices. In addition, the paper will detail and thereby disseminate the costs associated with monitoring practices for the two LID case studies.

SOURCE CONTROL AND THE NEED FOR LID AS A REDRESS FOR THE EFFECTS OF CENTRALIZED STORMWATER MANAGEMENT

The goal of LID with respect to hydrology is to mimic predevelopment conditions; this goal may be achieved through a combination of detention and retention of stormwater runoff at or near the source. Increased retention or detention capacity can be provided by connecting impervious surfaces (and their runoff volume) to detention (or retention) via infiltration and redistribution in soils. Each type of LID practice has a certain fundamental mechanism of operation (infiltration, evapotranspiration, or other losses), which prescribes its application, potential effectiveness, and susceptibility to failure. It is critical, therefore, that LID practices are matched and scaled carefully within a proposed management application. Temporary detention is the primary job of rain barrels and cisterns (Figure 1), whereas rain gardens (Figure 2) and bioretention areas rely on infiltration to move water into a high permeability rooting zone to store and redistribute water into shallow groundwater and provide additional losses through transpiration. Grassed swales can extend the hydraulic length of a drainage area, provide hydraulic resistance in the form of turf or other vegetative cover so as to slow down flows, provide infiltration opportunities, and contribute to delaying any contribution to peak flow at the drainage outlet (Figure 3). In areas where a wide variety of runoff sources are present in a dense urban area, treatment trains (where a number of LID practices are strung together in series or parallel) have been shown to be effective in taming large quantities of urban runoff from high-density urban areas (Villareal and Bengtsson 2004). Wet detention ponds, dry detention basins and wetlands all contribute to delays in peak flow, but are typically too large to be used for retrofit management or in dense urban areas where available space is scarce and likely expensive.

Figure 1. At this residence, rain barrels were installed under several downspouts. A rain garden was installed in the backyard, providing for a more complete on-site detention of stormwater volume.

Existing pervious surfaces in urban areas such as parks, lawns, and gardens provide some capacity for infiltration of stormwater runoff quantity, but this is conditional and relies upon type and condition of vegetative cover, soils, and the type and extent of impervious surface in the drainage area. There are several reasons why pervious cover may be overemphasized for its role in the mitigation of stormwater runoff. First, the type and condition of land cover (e.g., turf at

50% coverage) and antecedent moisture conditions dictate the unique and dynamic hydrology of pervious surfaces. This affects the capacity of pervious surfaces to capture runoff volume, and their tendency to produce runoff itself. This can occur via well-known hortonian (infiltration-excess) or saturation-excess mechanisms of runoff production. Second, impervious surfaces can be disconnected, wherein runoff from these surfaces flows onto adjacent pervious areas. Patterning of impervious areas in urban areas tend to leave pervious areas as sometimes isolated patches that retain a high degree of hydraulic connectivity to impervious areas. This typically leaves the pervious area (if it was relied upon for infiltration of stormwater runoff) undersized and unable to offer sufficient capacity for the amount of runoff generated from surrounding impervious areas. A simulation of LID effectiveness at the residential level undertaken by Xiao et al. (2007) showed that infiltration and surface runoff processes are sensitive to soil physical properties and the depth of soil to bedrock or other restrictive layers. Therefore, implementation of effective LID in great part relies upon specific knowledge of soil hydrology and soil physical properties, and it follows that assessment of these properties will largely dictate the type of LID practice used in a given situation and its capacity for retaining and infiltrating stormwater runoff.

Figure 2. A nascent rain garden implemented in a neighborhood that drains to the Shepherd Creek. This one-year old planting survived drought conditions in 2007 and plant cover is starting to fill in. Due to lack of grade and proximity to a sidewalk area, this rain garden was installed without an underdrain. Gardens without underdrains were dug deeper (~0.6 m) to provide slightly more infiltration capacity than rain gardens with underdrains (which were about 0.5 m deep). Note that the homeowners have used an ordinary garden hose to route rain barrel overflow to the rain garden.

It is not expected that LID practices will replace centralized stormwater infrastructure or negate the need for flood control drainage. LID practices can, however, distribute stormwater more efficiently across sites, reduce runoff and may allow for downsizing or elimination of some traditional stormwater ponds, curbs, and gutters. Possible outcomes of this process could include the reduction of infrastructure, operation, and maintenance costs for developers and communities. This relief would be particularly important for cases where existing civic stormwater infrastructure may have become overloaded due to unchecked development and poor planning practice. The adoption of practices that contribute to small-scale source control of runoff is supported by simulations, which indicate that micro-topographic influences on flow concentration can contribute to local flooding in urban areas, and that localized flooding may be mitigated by management of flows at the level of local micro-topography (i.e., across landscapes and within individual parcels; Aronica and Lanza 2005). LID practices are also increasingly recognized as viable options for stormwater permitting and in the reduction of overflows from combined sewer systems (US Environmental Protection Agency 2008).

Figure 3. A bioswale was installed at this location in Orange Village (a suburb of Cleveland OH, USA) to expand infiltration opportunities for excess stormwater runoff generated by roads, nearby residential development, and legacy drainage issues. A catch basin was installed in the center of the bioswale run wherein monitoring gear is installed among the attractive horticultural plantings.

INDUCEMENT OF PUBLIC PARTICIPATION TO FOSTER LID IMPLEMENTATION: TWO CASE STUDIES

Implementation of LID presently occurs at a nexus where motivated stakeholders, expertise in LID, favorable policy and regulatory circumstances, and funding intersect (see Thornton and Laurin 2005; Martinez et al. 2006). Comprehensive stormwater management may be made more sustainable through active citizen participation by accurately identifying, drawing responses from (with economic assessment tools such as auctions, surveys, and requests for proposals) and working with affected stakeholders to implement parcel or local-level LID. An effective approach to sustaining stakeholder buy-in to LID would be to make LID more or less a part of everyday business.

We currently study public participation in LID implementation across two distinct demonstration (or pilot scale) projects. The Shepherd Creek project is located in Cincinnati OH; urban development is concentrated in the headwaters of this 1.8 km^2 watershed, which drains to the Mill Creek and ultimately the Ohio River (see Roy et al. 2006 for additional site details). The larger objective of this unique project is to test a legal, socially-acceptable method of voluntary offsets for management of stormwater quantity through the installation of parcel-scale stormwater best management practices (Parikh et al. 2005). The incentive program used in the Shepherd

Creek study is a reverse auction that accepts voluntary bids from landowners for a single rain garden, and up to four rain barrels. Up to four 284 L (75 gallon) rain barrels (Figure 1) were offered in the auction. Auction participants also had the opportunity to bid on a single rain garden (Figure 2) sized to 16 m^2 for this residential application. The rain garden design was based on average residential impervious area, local hydrology, topography and soils and offered in variants with or without an underdrain. Bids were collected, ranked in ascending order, and then weighted on the basis of objective criteria that would affect effectiveness (e.g., area of directly-connected impervious area, soil runoff potential, proximity to a stream reach). The rain gardens and barrels were subsequently installed at no charge for the landowners for whom bids were found acceptable (summer 2007) and will be maintained for three. The bid amount is paid out to the landowner, which is their "willingness to accept" compensation for the burden of having an LID practice placed on their property and maintained by an outside entity for three years. The bid reflects landowner values regarding decentralized stormwater management. A lower bid would indicate that the landowner saw value in LID practices equivalent or greater than that associated with land use or costs. This bid amount may also be used to estimate the opportunity costs of dedicating privately-owned land to stormwater management objectives.

To test the efficacy of a reverse auction approach in placing rain barrels and rain gardens onto private property and reduce stormwater quantity, an actual auction was held in April 2007 (Thurston et al. 2008). Out of a possible 350 parcels (and accounting for un-occupied houses), we obtained an auction response rate of approximately 25%. We received 57 bids for rain gardens and 63 bids for rain barrels (accounting for a total of 121 barrels). About 60% of the bids were for \$0, and the maximum bid received was for \$500. The large proportion of \$0 bids indicates that we provided an appropriate incentive to place stormwater management practices on individual parcels. Furthermore, this result may also indicate that rain barrels and gardens appeal to landowners and that homeowner perceptions of environmental and aesthetic benefits may be jointly important. The non-zero bids may indicate a perceived burden (i.e., opportunity costs) such as losses of owner opportunity to utilize their landscape space. As a result of the reverse auction, 100 barrels and 50 rain gardens were installed across the watershed at 68 residences, with most participants accepting a rain garden and at least one rain barrel. The overall distribution of LID practices on parcels was generally uniform throughout the developed headwater areas (Figure 4). Based on the number and distribution of rain barrels and rain gardens implemented in 2007, Shuster et al. (2008) concluded that while only a small amount of impervious area was disconnected from stormwater drains and piping (ranging 0.2 – 0.4% across subwatersheds), there was a larger increase in potential storage capacity (via detention in rain barrels and infiltration into rain gardens). For a small (0.6 cm) rain fall event, this increase in potential capacity ranged from 16 to 28% over pre-implementation conditions for the five subwatersheds in the Shepherd Creek drainage. However, residents would have to route rooftop runoff and rain barrel overflow to rain gardens to utilize all of this potential capacity. We have noted that some (i.e., four) enterprising residents have done exactly this with imaginative use of garden hoses and placement of rain gardens proximate to downspouts. Furthermore, we found that residents who successfully bid on barrels and/or gardens were satisfied that the installations resulted in aesthetically pleasing retrofit LID with maintenance handled by contractors for a three-year period. Yet, many residents who had not participated in the 2007 auction expressed a desire (Ward Wilson, pers. communication) to participate, if there would be another auction in 2008. In addition to this largely anecdotal interest from landowners, there were additional practical reasons for attempting to implement more LID in the watershed. Based on projections made by Roy et al. (2005), a 25% reduction in total impervious area (TIA) as driveways and rooftops within each subwatershed of the Shepherd Creek drainage would bring the extent of TIA just below a 10-12% average empirical threshold, which marks the onset of ecosystem impairment from impervious areas. Therefore, a second auction was held in April 2008 to determine if additional benefits accrued from a second offer of the same suite of LID practices; results from this auction will be presented in future papers but initial values suggest a 50% increase from the number of presently installed rain gardens and barrels.

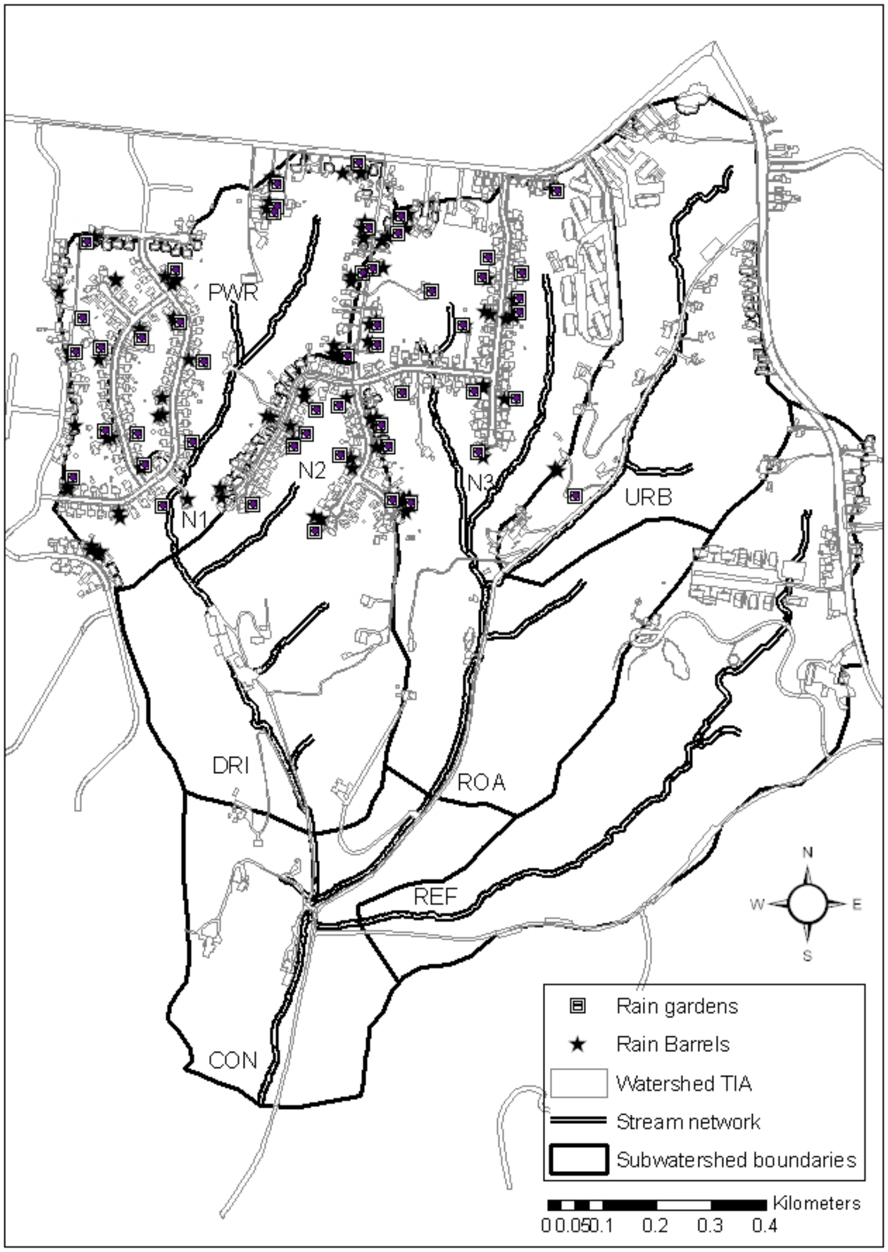

Figure 4. Watershed map for the Shepherd Creek and its tributaries illustrates the location of stormwater management practices that were deployed in 2007 on the basis of an economic incentive system administered to local landowners as a voluntary, reverse- auction. Labeled sites (N1, PWR, etc.) indicate locations of hydrologic monitoring stations which measure stream or outfall discharge.

The second project was established under the U.S. EPA's National Community Decentralized Demonstration Project grant program (a program now discontinued). The Chagrin River Watershed Partners, Inc. (CRWP) received Federal funds for a grant to Demonstrate Innovative Approaches to Distributed Storm Water Management in Northeast Ohio (Chagrin River Watershed Partners 2008). The Chagrin River watershed encompasses approximately 700 km^2 in northeastern OH, and is divided into 36 member communities representing about 95% of the population and land area in the watershed. The primary goals that CRWP integrates within a watershed management context are: the development and implementation of model codes (stormwater, riparian zone setbacks, etc.); stakeholder education and outreach; comprehensive planning; and conservation development. The LID Demonstration project offers technical support and public education for LID through demonstration sites, which will be monitored to provide long-term data to advance LID implementation in Northeast Ohio. The CRWP incentivized participation in the LID Demonstration project by posting a request for proposals to all of their member communities and offering partial funding for selected projects. A total of five proposals were returned, and each scored on the basis of perceived demonstration value, clarity of management objectives through LID, and potential effectiveness. Four projects were selected from the request for proposals. The proposals were finalized over the summer of 2007, and three of the four projects were installed during the winter and spring of 2008. The value of these demonstrations for public education will be evaluated through a number of venues including client satisfaction surveys and inclusion of these sites on tours of innovative stormwater management approaches.

The four demonstration projects that were chosen provided a broader range of LID practices and applications compared to the parcel-level efforts of the Shepherd Creek project. The first project proposed to mitigate increased runoff quantity resulting from an office building renovation and addition of a parking area at a local architecture firm (Cawrse, located in the suburb of South Russell Village). The Cawrse project will involve LID retrofits arranged as a treatment train. First, a rain garden will receive runoff from the roof of a newly constructed building; a pervious pavement system will then facilitate drainage and routing from the driveway and parking area; and two bioswales will receive discharge from the rain garden, pervious paver underdrains, and any remaining overland runoff from the driveway and parking area. The second project site, Pepper Pike, is a bioretention installation along a major thoroughfare (Pepper Pike) that runs adjacent to a high school facility. The project receives runoff from the roadway and overland flow from the large extents of impervious areas associated with the school facility. Third, a series of bioswales were installed on both sides of a residential street in Orange Village that was prone to flooding. The swales provide increased storage capacity for stormwater volume, and have helped to mitigate local flooding and provide some degree of water quality treatment by filtration of runoff through the bioswale soils. The fourth project was the installation of three rain gardens at a Munson Twp. outdoor recreational area, where two gardens receive runoff from the roof of picnic pavilions (6 and 96 m^2), and a third (45 m^2) installation catches drainage from a small parking area.

In each of these two case studies, some measure of front-loading was used to initiate the projects. In the Shepherd Creek case, we used an auction mechanism to inform homeowners and solicit their participation, and as a mechanism to implement carefully-designed LID practices according to local and regional landscape characteristics. In contrast to the Shepherd Creek project, the CRWP used a request for proposals to encourage participation followed by a review committee that included local stakeholders, and made sure that the final designs for each LID project passed independent engineering certification prior to implementation. In both cases, participants were willing to accept conditions on their participation in the LID projects and enter into an agreement with the entity that initiated the projects. The clear goal for front-loading in each case was to improve the potential outcomes, both in terms of the environmental management goals and the goal of increasing future public participation.

THE ROLE OF MONITORING IN THE PROMOTION OF LID TECHNIQUES

Monitoring programs can impart a science-based assessment of environmental management practices and document their effectiveness for promotion to the public and local stormwater managers. In addition, monitoring can alert managers to conditions under which failure may result, and provide evidence for adaptation of the practices and needed maintenance following implementation. Due to a lack of structured monitoring of many management actions, many LID approaches are assumed to impart long lists of anticipated benefits. As Caughlan and Oakley (2001) point out, the largest proportion of funding for monitoring of LID implementation projects usually goes towards data collection. This emphasis on gathering data can occur at the expense of scientific oversight and input in the early stages of project planning (e.g., framing hypotheses), training, data management and quality assurance, and proper reporting.

Monitoring is a critical tool for providing feedback to stakeholders and for directing their actions in an adaptive management framework informed by data, and should therefore be part of any stormwater management project. However, it is key to the success of LID that specific and carefully-collected monitoring data be generated and archived to fairly judge performance of LID as a comprehensive management approach. It is a false-economy to provide no scientific backing for benefits claimed at the inception of an LID management action.

Each monitoring effort for the two case studies detailed above was designed to evaluate the performance of the distributed practices, determine water quality and quantity control under varying climate conditions, and assess specific operation and maintenance needs. Each of these plans produce data to address whether the dominant process of an LID practice (infiltration, detention, etc.) is functional in a given setting, and whether there are conditions that limit or enhance LID effectiveness. Yet, the constraints of duration and costs (which will be treated below by project) associated with monitoring the project can have much to do with the success of the overall monitoring effort and applicability and utility of the data.

The issue of project time period is more general but is also less tractable than other aspects of monitoring plans. Most grants have a two or three-year time period, and so all project objectives must be met within a relatively short time frame. For this reason, many statistical experimental designs are disqualified or are used in a manner inconsistent with their intended purpose. There is typically not time to gather sufficient climate and hydrologic data to produce meaningful before and after comparisons. There is also no basis in most grant funded projects for replication in time (no two storms are exactly alike) or space. Replication of LID as treatments - as in a traditional agronomic plot experiment - relegates project results to a highly specialized and constrained context. For these reasons, it is likely much more important and productive to assess the conditions and the processes under which the LID practice actually works. Therefore, each Chagrin River Watershed project monitoring approach is unique for each demonstration, and tailored to understanding effectiveness across four different LID practices and settings. This attention to LID process integrity is also called for by the difficulty involved in finding control or reference areas with comparable physiographic characteristics. In keeping with the theme of this paper, we will emphasize the water quantity aspects of these management actions. The monitoring effort focuses on collecting time series data to assess water quantity (and quality), flow and frequency, and climate which will be collected on a more or less continuous basis.

The Shepherd Creek project is less constrained with respect to monitoring opportunities than the Chagrin River Watershed project sites. An important part of the Shepherd Creek research is that we currently gather baseline hydrologic and ecological data, and our monitoring effort will continue after the LID practices are installed. Using this data, we thereby form the basis for making inferences about factors contributing to effectiveness of both economic incentives and the resulting distribution of rain gardens and rain barrels in meeting environmental management objectives. The Shepherd Creek project takes advantage of the varied geography in this watershed, and utilizes a before-after, control-impact design (BACI), which has been used by ecosystem ecologists to infer change on the basis of an environmental management action. The monitoring data will be analyzed using a statistical approach known as a BACI analysis of variance (Green 1993), which is a repeated-measures statistical model optimized for experimental settings by accounting for low or no replication. To service the data requirements of the BACI experimental design, we have accumulated about two and a half years of pre-treatment hydrologic, water quality and ecological data, and will continue to monitor past the implementation of LID practices for another three years. In combination with specific economic data gathered from the project, we will study relationships between inferred environmental change due to management, and observation of any economic efficiency that may be gained. This is an end product of a carefully-conceived monitoring program, such that each parameter is consistently measured over the time period of the project, and utilizes appropriate statistical approaches so that inferences can be made about the potential for LID to effect change in runoff quantity at the watershed scale.

Since hydrology is considered a master variable that regulates water quality and biological conditions (Konrad and Booth 2005), we put particular emphasis on comprehensive hydrologic assessments for the Shepherd Creek project, both within the watershed and for the installed LID practices. An interagency agreement was struck with the United States Geological Survey (USGS) Ohio Water Science Center to design, implement, and collect hydrologic data from neighborhood, subwatershed, and watershed areas. We installed nine stream gauges, three of which were fixed onto neighborhood stormwater outlets and six of which were set into reaches at the outlet of subwatersheds, and crest stage gauges that were used to passively measure peak flows at the watershed outlet. This effort provides quality-assured discharge data at a time resolution of 2 min. for the neighborhood-level outfalls, 5 min. data for subwatershed-level streamflow, and a modeled mean-daily discharge for the watershed outlet, where accurate records of peak stage (from crest stage gauges) were used with a hydraulic model (HEC-RAS) to calculate discharge. The purpose of a crest-stage gage is to passively (i.e., not automated) record the maximum water level at the location of the gage by floating cork particles along a cedar stick that is housed in a metal pipe; the cork line left after storm flow recedes marks the maximum water level. The annual costs of a hydrologic monitoring program of this scope was in the neighborhood of (US)$140,000, not including equipment (loggers, sensors, etc.) and infrastructure (flow controls, fabrication of gauges) costs, which involved an initial investment of about (US)$100,000. The USEPA team also monitors water balance in five rain gardens with soil water content sensors set at 10cm depth increments to 50cm. Rain barrel water use patterns are monitored with vented water level loggers set at the bottom of barrels.

As for monitoring LID retrofits in the Chagrin River, a custom monitoring design was conceived for each of the funded project proposals. The monitoring objectives for the office expansion and parking lot addition at the Cawrse site entails the measurement of: flow and water quality from overland and underdrain flow from the pervious parking area; infiltration characteristics of the pervious pavement system; maximum water levels in the rain garden and bioswales; and rainfall and air temperature at the site. Precipitation will be measured on site by means of a heated tipping-bucket gauge. A crest-stage gauge will be used to measure the maximum water level in the rain garden. Two nests of three time-domain reflectometry (TDR) sensors will be permanently installed to measure soil water-content under the pervious paver parking area at various depths below the ground surface. This sensing arrangement will facilitate analysis of the drainage characteristics of the permeable base material above the underdrains. Discharge from the pervious paver underdrain system and parking lot overland runoff will be monitored by means of prefabricated H-flumes that will connect to an external stilling well that is equipped with pressure transducers and data loggers for measuring and recording water level. The discharge from the bioswale outlet will also be monitored by means of prefabricated H-flumes, conductivity/temperature sensors, and automated samples as detailed above for the pervious pavers system. A second crest-stage gauge will be installed in the bioswale near its outlet.

The Pepper Pike bioretention site entails a different set of monitoring objectives, wherein the occurrence and duration of overflows to the catch basin will be measured with a crest-stage gauge installed in the bioretention swale to assess maximum water levels in the swale during storm events. This installation along a major thoroughfare will be monitored for frequency and duration of overflow into a surface catch basin in the bioretention swale; the maximum water level in the swale during storm events; soil water samples from one location at two depths below the ground surface to assess changes in water quality as runoff infiltrates through the swale soils, and rainfall and air temperature.

The remaining LID demonstration projects use solely passive approaches to monitor for frequency of failure (e.g., overflow of swales). The monitoring objectives for the residential Orange Village site are to measure: frequency and duration of overflow in the catch basins of two bioswales; maximum water level in the bioswales and frequency of overflow stage; and rainfall and air temperature. Much like the Pepper Pike site, the occurrence and duration of overflows will be monitored with crest-stage gauges installed in each of the north and south bioswales to document maximum water levels during storm events. Both the Pepper Pike and Orange Village sites will be monitored for storm events where runoff may overflow from the bioretention swale areas into a catch basin, so as to document swale "failure" as direct flow into the storm sewer system. For the three rain gardens installed at a Munson Township outdoor recreational area, the monitoring objectives are straightforward and call for measurement of the maximum depth of water in each rain garden with crest-stage gauges, and total rainfall at the site with a simple collecting rain gauge.

The important matter of monitoring costs to CRWP – a non-profit organization – was solved by a creative approach to first determining then leveraging local stakeholder abilities. The CRWP has partnered with the Northeast Ohio Regional Sewer District (NEORSD), U.S. EPA’s National Risk Management Research Laboratory, and the United States Geological Survey for their monitoring campaign. An approximately (US)$10,000 grant from the Lake Erie Protection Fund - Small Grants Program provides supplemental funding for monitoring. The NEORSD is responsible for all analytical support for water quality samples collected at each demonstration site and will provide technical assistance and data analysis. The U.S. EPA has also secured the use of automatic samplers from the U.S. EPA Region 5 office in Cleveland, to be used on the Cawrse site. The USGS has been retained under a cooperative agreement for monitoring the four demonstration projects at a cost of approximately (US)$230,000 (CRWP + ~$70,000 in USGS cooperative funds), and is responsible for installing and maintaining monitoring equipment, and for water quantity and climate data collection and analysis. In cooperation with CRWP, the USGS will also inform quality control protocols. CRWP has developed, and will maintain a Quality Assurance Project Plan (QAPP) for each demonstration site for all project partners. As is customary in most EPA grant-funded projects, data collection cannot begin until CRWP has obtained approval of the QAPP from the U.S. EPA Office of Water. This resulted in a project support network that linked municipal-level governmental units, and whose efforts were coordinated by the CRWP. In this case, the CRWP provides the greater proportion of logistical support, where a major gap existed. Costs associated with personnel and labor tends to be the larger line item costs in a contract, and so the NGO may play a cost-effective role by filling in logistical gaps (e.g., measurements that require more frequent site visits which CRWP now takes care of). CRWP and NEORSD (which contributes $75,000 through these in-kind services) will be responsible for the collection, transportation, and processing of all water quality samples for each demonstration site. This model may provide direction to other non-profits that seek to properly implement LID and monitor its performance. It is emphasized here that any organization considering this type of effort must fully consider local and regional resources, which would likely differ from the illustrative example given here.

CONCLUSIONS

The ultimate goal of the decentralized approach that builds on the levels of government and associated supporting structures is source control of stormwater run-off via participatory stormwater management. Citizens and local organizations take an active role in reducing stormwater quantity and provide a demand for local municipal managers and developers to engage in this work. We need demonstration projects to cultivate interest at the local level driven by regulatory support to guide networks of local NGOs, county and state agencies, municipal sewer districts (MSDs), and finally, federal research support. Networks such as these can provide funding, cost-sharing, monitoring support, and technical analysis – all so that the work of LID gets done properly, and to promote scaling-up of local LID to watershed, city-wide, and regional scales of stormwater management. In addition, more cost-benefit research needs to be done with LID methods, so that the full costs of maintenance and obtaining consistent performance of LID practices over time can be understood. A start in this direction is found in the work of Saiz et al. (2006), and also the net present value calculations performed by Carter and Keeler (2007) for vegetated roof systems. If properly disseminated, these realistic treatments of LID performance versus cost may help to ease perceptions of high initial cost versus benefits derived. Implementing LID as a part of a comprehensive urban civic infrastructure replacement program may be another way of directing existing resources (i.e., public works departments) towards more sustainable management of urban stormwater runoff in a greener age.

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*William D. Shuster, United States Environmental Protection Agency, National Risk Management Research Laboratory, Sustainable Technology Division, ML498, Cincinnati OH 45268. Tel.: 01-513-569-7244; Fax: 01-513-487-2511 shuster.william@epa.gov

Matthew A. Morrison, United States Environmental Protection Agency, National Risk Management Research Laboratory, Land Remediation and Pollution Control Division, Cincinnati OH 45268 morrison.matthew@epa.gov

Rachel Webb, Chagrin River Watershed Partners, Inc. P.O. Box 229 Willoughby, OH 44096-0229 rmw@crwp.org

*Corresponding author