Catchment-scale stormwater management via economic incentives – an overview and lessons-learned

Gestion des eaux pluviales échelle du bassin versant par des incitations économiques - une vue d'ensemble et des leçons apprises

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RÉSUMÉ

En français

ABSTRACT

Long-term field studies of the effectiveness and sustainability of decentralized stormwater management are rare. From 2005-2011, we tested an incentive-based approach to citizen participation in stormwater management in the Shepherd Creek catchment, located in Cincinnati, OH, USA. Hydrologic, biological, and water quality data were characterized in a baseline monitoring effort 2005-2007. Reverse auctions held successively in 2007 and 2008 engaged citizens to voluntarily bid on stormwater control measures (SCMs); and successful bids led to implementation of SCMs, which led to an enhancement of catchment detention capacity. We tested for attributes of sustainability (co-consideration of social, economic, and environmental (hydrologic, soils, aquatic biology) aspects), and summarize lessons-learned. Our results and outcomes provide a basis for planning future field studies that more fully determine the effectiveness of stormwater management in terms of sustainability.

KEYWORDS

Cultural capital, economic incentive, green infrastructure, sewer overflow, social capital, stormwater control measures, urban stormwater management

1 INTRODUCTION

Impervious surface is a consequence of urban development and also the primary factor that distinguishes pre-development from urban water cycles (Lee and Heaney, 2003; Davis, 2008). As a result of a shift to runoff becoming the predominant factor in the urban water cycle, the sheer volume and dynamic quality of runoff flows present a set of environmental stressors. The role of urban runoff is particularly pronounced in storm-sewer systems, as it contributes to sewer overflows in both septic-separated and combined systems (Montalto et al., 2007); and has led to the demise of aquatic ecosystems that receive storm runoff from stormwater-separate wastewater systems (Booth and Jackson, 1997). Since unmanaged urban runoff flows present an overall insult to the environment, the management of urban runoff flows has received a great deal of attention in recent times. Enforcement of environmental regulations is the most common driver for management, though both the Clean

Water Act (United States, 1972), and the Water Directive Framework developed by the European Union address to different extents and specificity the significant role played by runoff volume in urban water resources management. This has led to restrictions on stormwater runoff by indirect means, such as permits that require a decrease in the frequency and volume of runoff from combined sewers. In this way municipal sewer-system operators find that reducing stormwater inputs into the combined system may be a lower-cost approach than building temporary storage facilities to store combined sewer overflow volume.

The issue at hand is the effectiveness of SCMs in carrying out their objective task of absorbing or detaining stormwater runoff. Beyond the environmental aspects of SCM effectiveness, these management practices may also contribute toward economic stability and social equity. The ecosystem services provided by SCMs such as green infrastructure (i.e., plant-soil systems designed to manage the water cycle, or engineered approaches for rainfall capture) may add value to vacant land through performing functions ordinarily carried out by wastewater infrastructure, and create neighborhood-level amenities by increasing the proportion of green space in areas historically lacking in natural or potentially recreational spaces. The matters of environmental quality, social equity, and economic stabilization may jointly define the main attributes of sustainable systems. Therefore, a holistic approach to evaluating the effectiveness of SCMs would include monitoring for each of these attributes of sustainability.

The concepts of source control, economic incentives for citizen participation, and testing for effectiveness of these management objectives were brought together in the Shepherd Creek pilot study (Thurston et al., 2008). This research set out to determine if paying opportunity costs arising from the use of private property to retrofit stormwater management controls would result in: 1) a sufficient number of rain barrels and rain gardens placed to affect increased detention; and 2) whether the extent of the implementation would lead to a reduction in runoff volume at the sub-catchment level. This reverse-auction approach, where landowners place bids on how much they desire to be paid to receive SCMs, is an attractive option, as it presents citizens with a potentially lower level of risk with regard to legal and social entanglements. A voluntary offset is translated into environmental management by incentivizing voluntary citizen participation in the management of an environmental stressor. The management actions taken by citizens (on their private property) potentially leads to incremental offsets against the stressor, with a subsequent improvement in environmental quality. We studied parcel-level management of stormwater volume (Mayer et al., 2012; Parikh et al., 2005) via voluntary incentives to foster citizen participation in stormwater management in the Shepherd Creek catchment. This long-term study created opportunities to account for environmental (Shuster and Rhea, 2012), economic (Thurston et al. 2010), and social-cultural (Green et al. 2012) performance of SCMs, though left some questions unanswered. It is the objective of this paper to highlight the importance of monitoring for attributes of sustainability (as environmental, social-economic factors), some lessons-learned, and suggest a minimum dataset for future studies.

2 METHODS AND BASIS FOR LESSONS LEARNED

Shepherd Creek is a tributary to West Fork Mill Creek, located in Cincinnati, OH (USA) (Figure 1). The catchment is approximately 1.8 km^2 with a mosaic of land uses. The suburban development that produces the majority of stormwater runoff is impervious area that is typical of 1960s – 1980s American single-family residential construction and transportation infrastructure. The area is drained by centralized, stormwater-separated sewerage, and the outfalls from this system pour directly into the headwater and tributary stream network that comprises the Shepherd Creek catchment. Runoff is also observed to flow to tributaries via infiltration-, saturation-excess, or direct-runoff mechanisms from areas used for forest, equestrian activities (especially a bare-soil horse exercise area), and low-density residential dwellings, lawns, and driveways. The subdivisions were developed on level loess deposits (predominantly silt loam and silty clay loam soils) in hilltop areas that overlay calcareous shale and limestone formations on moderate slopes. Our treatment areas included forested parcels, along with a bare-soil equestrian yard and numerous residential parcels, dominated by pervious lawns. A city park occupies the eastern side of the catchment and was used as a natural reference area (Sub5 & 5a), with a complementary and more urbanized reference sub-catchment in the northeast side of the catchment (Sub4; Figure 1).

A reverse-auction approach was used to encourage implementation of stormwater management practices on private property by providing rain gardens and rain barrels for free or for an owner-defined bid amount. Each of 350 eligible parcels could potentially receive a single rain garden (16 m^2 in area), or up to four rain barrels (approx. 280 l capacity each). Two rounds of reverse auctions in 2007 and

2008 placed 81 rain gardens and 165 rain barrels onto 75 private properties. This confirmed that the reverse-auction approach was viable to encourage implementation of stormwater management practices on private property. The high proportion of $0 bids for rain gardens and rain barrels suggests that there is a sizable majority of property owners who are willing to participate in a decentralized program for stormwater management. Discharge was measured for each sub-catchment, and overall catchment rainfall, within the period 2005-2011 (see: Shuster and Rhea, 2012). The overall impact of the SCM installations was a small, but statistically significant decrease in stormwater quantity at the subcatchment scale (Shuster and Rhea, 2012). The impact of the treatments was also manifested in synthetic unit hydrograph parameters that indicated treatments had decoupled rainfall from discharge, a consequence attributed to SCMs increasing detention at the sub-catchment scale.

Thurston et al. (2010) found that the mean cost per liter of runoff detention in both years of our study was $0.36 for gardens and $0.59 for barrels. Since ~ 55% of bids required no payment (i.e., $0 bids), this suggests that an educational campaign may result in substantial runoff mitigation without economic incentives. Of course this arrangement would require that utilities pay for the installation of stormwater management practices. However, we found that an auction promoted more participation than education alone and at a cheaper per-unit control cost than a flat stormwater control payment plan. Overall, this study demonstrates that relatively minimal financial incentives can result in homeowners' willingness-to-accept stormwater management practices on their property, thus opening an important avenue for retrofitting catchments with land that is largely in private ownership.

We assessed the role of social capital in as a potential contagion effect by comparing the spatial distributions of neighbors with and without SCMs over the two bid cycles (Green et al., 2012). The presence of non-randomness in the spatial distributions of bid responses among parcels was determined by applying boot-strapping (with replacement) techniques to develop a distribution of distance metrics, or parcels linked by each of several pairwise distances between properties. We compared the mean pairwise distance between the parcels with successful bids to the mean pairwise distance between an equal number of properties that were randomly selected from the full set of parcels that were eligible to participate in the auction. We then employed bootstrapping techniques to generate 10,000 sets of randomly-selected groups of properties, computed the mean pairwise distance for each of these sets, and then ranked the mean pairwise distance for those parcels that had successfully bid. A comparison of these values generated a probability-of-occurrence (*P*) value, which was used to discern the significance of spatial structure among neighbors between the two bid cycles.

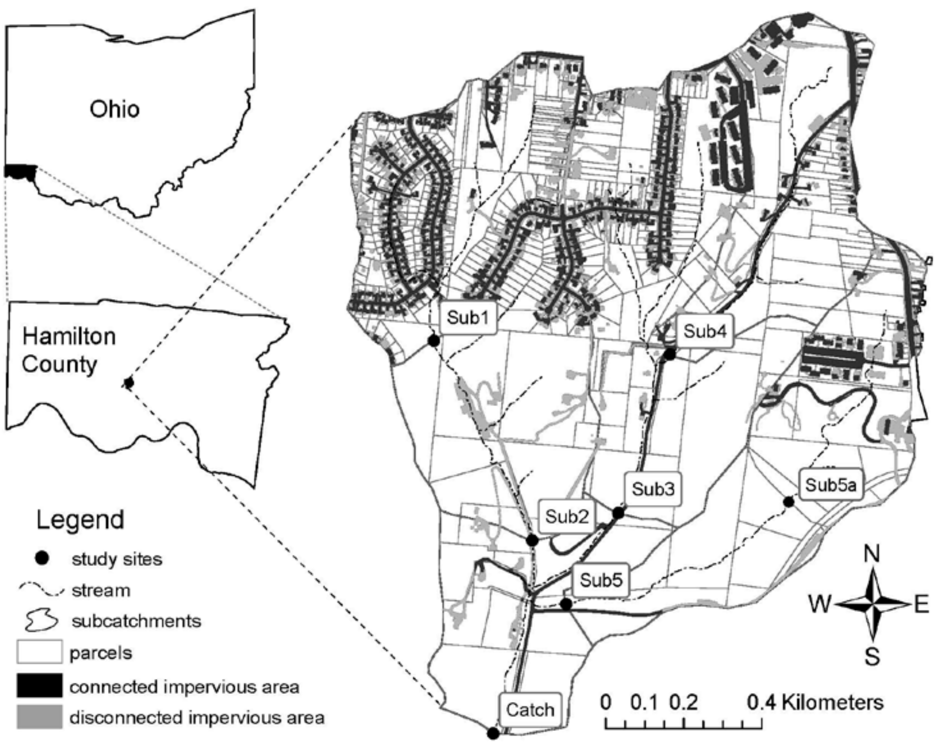

Figure 1. Shepherd Creek drains a suburban, mixed-land use,1.8 km^2 catchment area that has 13% total impervious area, which generates stormwater runoff volume that presents as a stressor to the network of stream ecosystems. The Before-After, Control-Impact (see text) experimental design, called for two controls (Sub1 & 6); and four treatments (Sub2, 3, 4 & 5). From: Mayer et al. 2012.

3 RESULTS AS LESSONS LEARNED AND DISCUSSION

3.1 Experimental Design

Lesson 1: Use an experimental design with multiple control catchments to focus the monitoring effort, account for nuisance effects, and provide a basis for robust statistical analysis.

The impacts of retrofits at larger field-scales have been analyzed with straightforward statistical techniques (Potter, 1991; King et al., 2008). From an experimental design and analysis perspective, designs such as before-after, control-impact (BACI, see Green, 1993; Downs et al., 2002) have been used to make inferences on both the spatial and temporal dimensions of field studies that involve some sort of management intervention. The BACI model was expanded with terms that account for “nuisance” effects including: seasonality; varying antecedent soil moisture conditions; trends in precipitation-runoff apportionment; and discrete shifts in rainfall-runoff responses. We also decomposed empirical unit hydrographs (estimated using cross-correlograms between lagged precipitation and stream discharge) into their limb centroid heights and lag time of both the rising and falling limbs, and the height and lag time of the hydrograph peak and subjected these parameters to analysis of variance (ANOVA; see Shuster and Rhea 2012).

The extent of SCM implementation was relatively modest and we anticipated that any treatment effects would be subtle. However, several factors in experimental design and analysis were important in ensuring the thorough evaluation of the effectiveness of our treatments. We found that having multiple control (i.e., reference) catchments was essential to maintain contrast with treatment catchments.

Given the long-term nature of the urban catchment study, all of the monitored sub-catchments were subject to disturbances (e.g., sewer system and road maintenance, brush removal from riparian zones). If there had been only one control, any of the unanticipated disturbances would have decreased the ability of our statistical model to discern the impacts of our treatments. With two control catchments, there was additional flexibility for both controls, or one control or the other to provide a basis for optimal contrast with treatment effects. Multiple treatment and control catchments also allow for greater accounting of spatial variability among catchments, and thereby offer an increased level of discernment of treatment effects.

Another issue in this analysis is that the nature of the meaning of “treatment” in this experimental design was by nature diffuse. The actual landscape position of the rain garden was negotiated with the landowner, and so the runoff-generating area was different for each installation. Due to differences in antecedent conditions (especially soil moisture status), the available detention capacity was also different for each rain garden. This meant that the effectiveness of the rain gardens was different for each installation. In order to more accurately determine the role of rain gardens in creating detention capacity, individual rainfall-runoff models would have been needed for each parcel. The effectiveness of rain barrels was more predictable. Roof runoff is directed into the rain barrel, which reaches its capacity and either overflows to the turf yard area, or overflow is directed into the storm sewer inlet. After the first season, many rain barrel overflow outlets were not returned to their original position in the sewer inlet; thereby making it more likely that rain barrel overflow was allowed to overflow out to the turf area. Therefore, it was difficult to separate out the contribution of any given SCM. In terms of our experimental design, the treatment was defined by the aggregate impact of 81 rain gardens and 165 rain barrels.

3.2 Hydrometry

Lesson 2: In order to maximize likelihood of registering a treatment effect, conduct long-term, hydrometric studies at as many levels in the drainage hierarchy as possible.

We retrofit catchment areas with SCMs with the goal of disconnecting impervious area from the storm sewer system. Doing this at the parcel level helped to manage stormwater runoff volume at volumes and flows that were tractable in the context of rain gardens and rain barrels. By the same token, quantifying discharge at each outfall position required a great deal of investment in specialized monitoring equipment (see Shuster and Rhea, in press, 2012). The United States Geological Survey was engaged to install rainfall and runoff monitoring equipment and lent a consistency in data quality over this 6-year effort.

This experiment presented several challenges to the task of understanding the influence of SCMs on runoff volume. Firstly, we understood that the temporal resolution of rainfall and discharge data should be relatively high, so as to capture rapidly changing conditions during stormflow. Our rainfall dataset was continuous and based on a tipping-bucket rain gage located at the Sub 3 pour-point, which was complemented by 6 years of interpolated radar rainfall data (also 5 minute resolution; Vieux Incorporated; Norman OK USA), with a single rainfall pixel approximately covering each of the sub-catchments. The hydrometric part of the monitoring program should also be long-term, with at least 2 years baseline (pre-treatment) data, at least two years after SCM interventions are installed. The long-term approach also ensures that a large number of storm and baseflow periods can be documented, lending some understanding of the impact of antecedent conditions on runoff production, both without and with SCMs. In order to determine the relationship between rainfall and runoff, and landscape response to rainfall forcing across highly heterogeneous land uses in urbanized (particularly suburban) catchments, hydrometry should be carried out at the stormwater outfall, the sub-catchment, and catchment scales.

3.3 Aquatic Biota

Lesson 3: Include multiple biotic response variables, measured seasonally for several years to account for intra- and inter-annual variability.

Periphyton and macroinvertebrates were sampled five times per year during the warm-season (April through October) for 4-years prior and 2.5-years following installation of stormwater management measures. We observed high seasonal variation in biotic assemblages, suggesting that canopy cover (low in April and October) and summer low flows are important variables determining biotic condition in these small, headwater streams. Such seasonal variation is not surprising (Clarke et al., 2010), and suggests that sampling multiple times per year, or a consistent time of year with similar abiotic conditions, is important for assessing impacts of stormwater management. Furthermore, given the interannual variability in flow conditions and its influence on macroinvertebrates (Bradley and Ormerod, 2001; Jackson and Fureder, 2006), our post-treatment sampling was likely insufficient to detect biotic responses, if they did occur. Sampling for at least five years post-treatment should account for interannual variation and provide sufficient time for organisms to respond given their life span and dispersal potential.

Previous studies have demonstrated the value of sampling multiple biotic endpoints to detect responses to disturbance (Dale and Beyeler, 2001). Given their shorter life cycles, it was not surprising that the periphyton assemblage was more sensitive to the treatments than macroinvertebrates. Moreover, by examining multiple periphyton response variables (e.g., composition, diversity, biotic integrity), we were able to pinpoint the likely mechanism of response to a shift in canopy cover rather than stormwater management. Although the masking of the treatment response was an unintended aspect of the study design, the collection and analysis of multiple variables allowed us to effectively interpret the findings. For macroinvertebrates, few responses to treatments were detected, and those that were limited to a only a few variables. Using multiple variables with specific expected responses to disturbance, such as species traits (Vieira et al. 2006), is likely to increase the potential to detect and interpret stream biotic responses.

Issues of taxonomic accuracy and consistency can arise in multi-year studies with different taxonomists (Cao and Hawkins, 2011). We observed this problem with the periphyton, where differences in the identification methods across contractors resulted in extreme differences in periphyton assemblages (Roy, unpublished data), ultimately necessitating the use of the same contractor for the entire 7-year study. For macroinvertebrates, we had three different contractors and numerous sorters and taxonomists throughout the study. Despite the similar requirements for identifying macroinvertebrates to the lowest possible taxonomic level, there were differences in level of identification and naming conventions across contractors that had to be reconciled. If consistent taxonomists cannot be used, it is essential to address issues of data comparability (Cao and Hawkins 2011) to ensure that differences in taxonomy do not mask biotic responses to treatments.

3.4 Soil Survey

Lesson 4: Take time to characterize the hydrologic role of surface and subsoils, especially where infiltration and redistribution are used as mechanisms for stormwater control.

For the most part, available soils information is not specific enough to make decisions or properly simulate rainfall-runoff behavior at the parcel scale. For their significant position in the hydrologic cycle, soils are given relatively little consideration given their importance in cycling water and their impact on drainage. In this project, we carried out a highly-detailed, sub-Order 1 soil survey to understand layering of urban soils in the Shepherd Creek catchment. Subsoils permeability is a major predictor of drainage in infiltration-based stormwater management practices such as rain gardens. We therefore based our rain garden design on subsoil hydraulic conductivity as the limiting factor, expressed within a continuous simulation model specialized for rain gardens (RECARGA ; http://dnr.wi.gov/topic/stormwater/standards/recarga.html). We identified three distinct soil types in the Shepherd Creek catchment, and for each of these soils we made measurements of subsoil hydraulic conductivity as a proxy for drainage rate and potential of the soil to exfiltrate and redistribute soil moisture. We used soil texture, subsoil hydraulic conductivity, and presence/absence of redoximorphic features (as a cue that soils tended toward protracted periods of saturation) to properly design the rain garden (see: Shuster et al 2008).

3.5 Economic Considerations

Lesson 5: *It is likely that cost considerations are paramount, and so some basis for understanding tradeoffs and economic performance should be developed.*

As communities start to investigate the use of incentive mechanisms to encourage stormwater runoff control, comparison of the effectiveness of more traditional stormwater programs to wholly voluntary programs such as the one outlined in this paper, allows managers to weigh the pros and cons of various approaches to management of excess stormwater runoff and choose the approach most appropriate for a given area and its constituency. In areas where it is legal and politically feasible it may be preferred to require stormwater management practices be installed through command-and-control, or by using an economic incentive program that requires participation, such as a cap-and-trade policy. We have shown elsewhere that non-voluntary, but economically incented, policies can be used to control stormwater runoff at a lower per-unit cost than strictly voluntary programs. However, in many cases where development has already occurred, voluntary retrofit opportunities are among very few options currently available to local governance or wastewater management authorities.

We have shown that a reverse-auction is an effective mechanism to encourage the adaption of retrofit stormwater runoff detention capacity. In particular, we find that a reverse auction mechanism is a more cost effective way of identifying and securing the adoption of storm water management practices on those residential parcels thought to potentially provide the greatest level of ecological benefit per program dollar spent. Further research is needed to explicitly address and account for the role of education in the recruitment of homeowners for stormwater control.

3.6 Social and Cultural Considerations

Lesson 6: *If possible, use survey and quantitative techniques to better understand patterns in and barriers to acceptance and ongoing use of SCMs.*

As a federal research organization, we were unable to interview residents to gather information about landowner decisions. We therefore used indirect methods to evaluate what we qualitatively understood as a role played by social capital in building stormwater detention capacity through SCM deployment on private property. Over the course of 2007 and 2008 SCM implementations, we saw that once homeowners understood that this was an authentic offer, we noticed that neighbor-to-neighbor interactions were probably leading to in-fill adoption of SCMs. This speculative assumption was quantitatively evaluated by analyzing the proximity of parcels adopting (i.e., bidding successfully on) SCMs from 2007 to 2008. A more formal assumption is that homeowners that had been skeptical of the program, discarded the initial mailing as junk mail, and may have engaged with the program in its second year after seeing neighbors participate successfully. In addition, we assumed that any neighbor influence would be greatest for adjacent properties, and accordingly this influence would decrease with increasing distance. Thus, the presence of social capital should be evidenced by an increased correlation between the number of successful bids when comparing nearby properties against widely separated properties.

Our analysis found an increased frequency of successful bids among nearest-neighbors with a concomitant and decreased incidence of successful bids registered among properties that were more widely separated; and all of this relative to a random distribution of inter-parcel (with SCMs) distances. More specifically, homeowners that were proximate to a successful bidder within a five property distance were more likely to be successful bidders themselves. This was in fact the mechanism that led to the development of clusters of homeowners that adopted SCMs (Figure 2). Follow-up research may include verification of our assumption concerning social network and adjacency of properties. For example, a survey of participants' motivations and levels of communication amongst other participants would shed light on the role of social capital in this context.

Figure 2. Map of suburban development in the Shepherd Creek catchment shows eligible parcels and the development over the two-year SCM installation period of clustering among successful bidders that became participants in stormwater volume management.

As evidenced in the Shepherd Creek experiment, social capital may be just as, if not more, vital to widespread acceptance of SWMPs as physical, human (education), or financial capital. Thus, managers should be aware of the benefits and pitfalls of social capital when investing in physical capital. Investing in strategies that grant responsibility and power to individuals may increase the economic benefits of financial investments in small to medium sized physical projects by inducing collective action and strengthening social cohesion. Thus, increased investments in social and human capital must coincide with increased investment in physical and natural capitals in order for the projects to realize maximum benefit.

4 CONCLUSIONS

The Shepherd Creek experiment was broad in scope, and reflecting on our experience has given us the opportunity to share several lessons learned. The use of multiple controls and similar catchment sizes among treatment and control sub-catchments resulted in a robust statistical design. Fine-resolution soil characterization formed the basis of designs that produced effective rain gardens, and aided in the prediction of redistribution potential for infiltrated stormwater volume. This experiment also presented a unique forum to couple stormwater volume management to scaling its impact on improving aquatic ecosystem condition. Economic alternatives to the reverse auction for encouraging adoption of SCM practices warrant further study. For example, a paired catchment approach with a treatment that explicitly uses education without the auction, and one that uses the auction with minimal education could be tested. Also a split sample wherein one group receives education and installation, or subsidized installation, and a group that receives education without installation, would enhance our understanding of public acceptance. A post-implementation survey of homeowner participants would shed light on peoples' motivations for participation. Such a survey would ask questions about awareness of stormwater runoff pollution problems, susceptibility of people to the influences of educational material and neighbors' actions, and inform future programs to be more effective at recruiting participants. Local stormwater authorities could start with an education and survey campaign to understand the familiarity that property owners have about stormwater issues and their willingness to devote space on their property to SCMs. A pilot project in one or more small catchments would help determine how best these rain gardens and rain barrels can be distributed for the most improvement at the least cost. Larger distribution systems would likely require a dedicated source of funding and may be more difficult to administer, unless the area was divided into smaller catchments that could be addressed in phases. And lastly, our findings show that social and cultural capital investments should be commensurate with investments in natural and financial capital for the long term success of green infrastructure projects. The subtle improvements realized through a modest implementation of SCMs should help to garner public support for taking next steps toward larger-scale disconnection of impervious surfaces from sewer systems. For example, the mitigation and monitoring of runoff from transportation surfaces – a predominant form of impervious are in subdivisions – remains a challenge that may be made tractable and through application of these lessons.

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