Implementation of retrofit best management practices in a suburban watershed (Cincinnati OH) via economic incentives

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ABSTRACT

There is great potential for managing stormwater runoff quantity; however, implementation in already-developed areas remains a challenge. We assess the viability of economic incentives to place best management practices (BMPs) on parcels in a 1.8 km^2 suburban watershed near Cincinnati, Ohio (USA). A reverse auction, used to relieve legal constraints on BMP implementation on private land such that residents voluntarily bid on BMPs (rain gardens and rain barrels), was held in 2007. Out of a possible 350 homeowners, we obtained a ~25% response rate, and ~60% of the bids were for $0. Bids were ranked based on the basis of cost and an environmental benefits index. We ultimately installed 50 rain gardens and 100 rain barrels, which were uniform in their distribution across the watershed. Although BMPs did not disconnect an appreciable amount of effective impervious area from stream channels (0.2 – 0.4%), a dramatic increase (16-28%) in stormwater runoff storage capacity was imparted to the various subwatersheds. Ongoing monitoring at neighborhood stormwater outfalls and subwatershed tributaries will ultimately determine whether this approach yields an effective stormwater management strategy.

Keywords: stormwater, economic incentives, rain garden, rain barrel, retrofit

INTRODUCTION AND BACKGROUND

There is great potential for reducing stormwater runoff quantity through decentralized stormwater best management practices (BMPs) and disconnection of directly-connected impervious areas. In areas that are already developed, however, decentralization involves private property and existing infrastructure; and is thus challenged with legal hurdles and possible liabilities (Parikh et al. 2005). Consequently, management techniques must be applied in a way that is both acceptable to landowners and effective in terms of accrued environmental benefits.

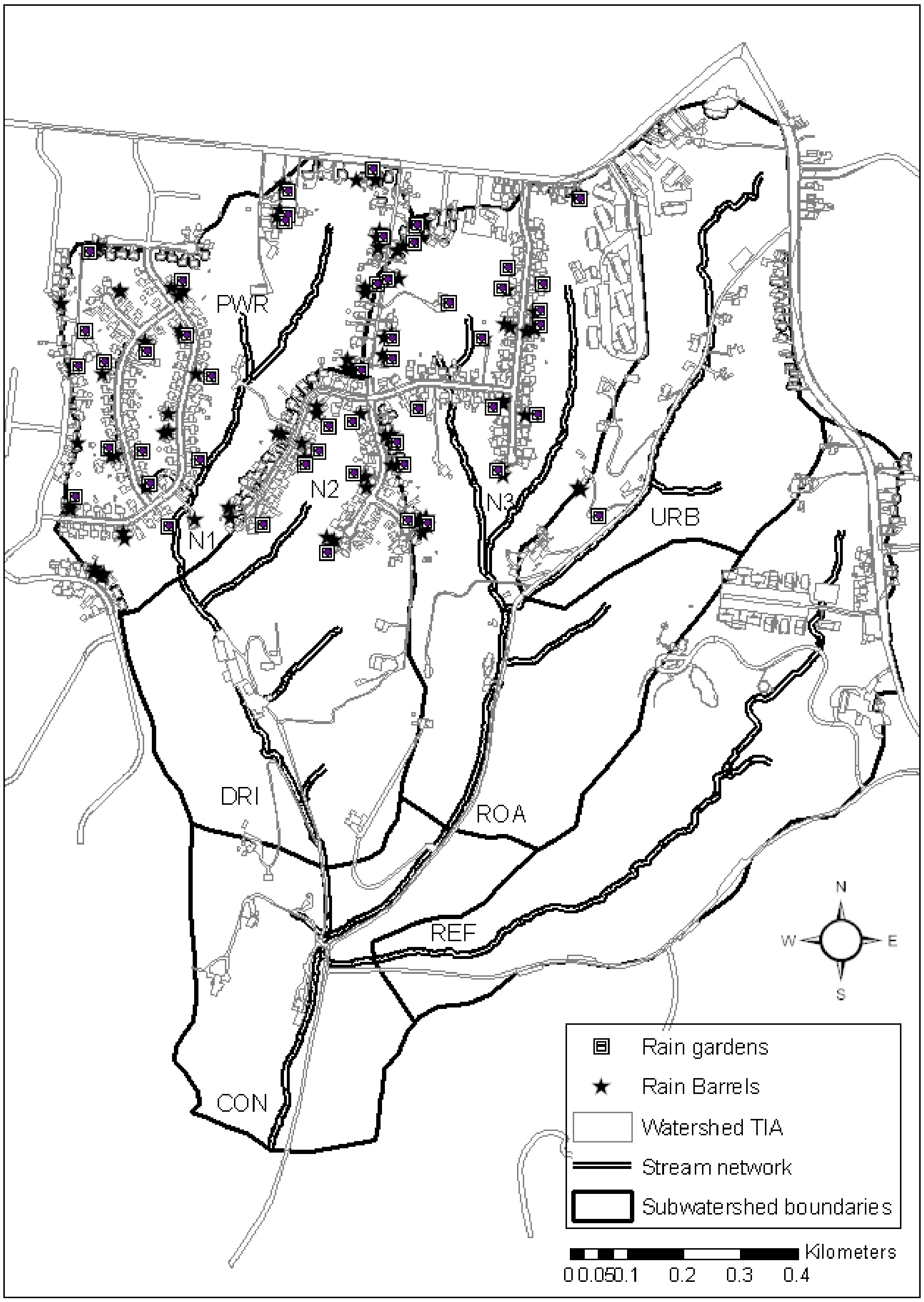
We assess the viability of economic incentives to place BMPs in a suburban watershed near Cincinnati, Ohio (USA), and evaluate the effectiveness of the resulting deployment in reducing the impacts of stormwater runoff. The selected retrofit BMPs are rain gardens and rain barrels, which are employed to disconnect impervious area that is directly connected to sewers and otherwise detain and store stormwater runoff. A reverse auction, wherein residents voluntarily bid on BMPs, was used because it encourages adoption of BMPs while respecting property rights issues. (Parikh et al. 2005). In the spring of 2007 a preview mailing, door-hanger reminder, auction package, and follow-up reminder were sent out consecutively, with about 1.5 weeks between each contact. These materials explained the basis for the study (i.e., stormwater runoff quantity reduction), presented a bid form, and described how successful bidders would receive a 16 m^2 rain garden and up to four rain barrels (at no cost) and receive a one-time payment of their bid amount. It was also explained that these BMPs would be maintained by an EPA contractor for a period of three years post-installation.

The bid reflects landowner values regarding decentralized stormwater management, opportunity costs of dedicating their land to stormwater management objectives, and other non-market values. Bids were collected, ranked in ascending order, and then weighted on the basis of objective criteria that would determine effectiveness (e.g., area of directly-connected impervious area, parcel soil hydrology, proximity to a stream reach, etc.). A key component of this research is to address whether the BMP implementation is effective in the reduction of storm water runoff quantity via increased storage in any of the treatment watersheds. We expected that BMP installations in 2007 would lead to some degree of increased volume capacity for stormwater runoff, though we require knowledge of just how much capacity has been added, which is necessary information for planning and modeling purposes. Therefore, the objectives of the present study were to 1) estimate the post-treatment capacity for watershed stormwater capture, 2) calculate the degree to which connected impervious area was disconnected on the basis of rain barrels installed, and 3) to provide an accounting for the contribution of rain gardens in this respect.

SITE DETAILS AND METHODS

The Shepherd Creek catchment (Figure 1) in Cincinnati, OH (USA) is an approximately 1.8 km^2 catchment that sits on loess-capped, calcareous shale and limestone formations with moderate slopes, which have weathered to predominantly silt loam and silty clay loam soils. Residential areas built in the 1960's and 1980's construction on the east and west ends of the catchment, respectively occupy the headwaters, and are responsible for the majority of stormwater runoff. This runoff is routed via tributaries through mixed-land use coverage composed of forested, equestrian, and widely dispersed residential dwellings. A city park occupies the eastern side of the watershed and functions as a natural reference subwatershed. We have employed a before-after, control-treatment experimental design to structure our experimental approach and make inferences about change in terms of hydrology, stream biology, and water quality. In seven treatments (with BMPs; PWR, DRI, ROA, CON, Figure 1) and two control (without BMPs; URB, REF, Figure 1) subwatersheds, we have monitored for discharge; conducted water quality samplings on a monthly schedule with opportunistic storm samplings; and stream macroinvertebrate and periphyton sampling every 6 weeks in the period April through October. In addition, three sites were established at neighborhood stormwater outfall locations (Figure 1; N1, N2, and N3) where storm discharge was monitored at 2-minute intervals. In order to document environmental change due to BMP placement, we gathered three years of watershed data before BMPs were installed, and will continue monitoring for at least three years after BMP installations are complete.

Figure 1. Watershed map for Shepherd Creek and its tributaries with the locations of stormwater best management practices marked.



The retrofit management practices offered in the auction were up to four 284 L (75 gallon) rain barrels and a single 16 m^2 rain garden. The screened inlets at the top of the rain barrels were set under roof downspouts that had been cut to length. The overflow pipe for each rain barrel was then placed in the downspout drain. Some homeowners have routed rain barrel overflow to their proximate rain garden or lawn. The majority of rain gardens were installed by first staking out the area to conform to individual parcel landscape features and owner preferences. The area was then turned over with a walk-behind mini-excavator to 0.5 m, and amended with sand and fine-milled peat moss to create a more favorable soil texture so as to promote infiltration. Next, a trench was opened for a tile drain underdrain. Due to the heavy silty clay soils in the area, the underdrain was used to facilitate faster drainage of the rooting zone in most of the rain gardens.

Where topography prevented placement of the drain outlet at a downslope location, raingardens were installed without underdrains and instead had a deeper rooting zone, with excavation to 0.66 m, with the intent that the additional depth would offer more infiltration capacity. We estimated stormwater detention capacity by combining soil moisture storage (assuming an antecedent 0.15 cm cm^{-1} capacity for storage), surface storage in 15 cm of depth formed by the surface bowl shape of the rain garden, and 5 cm of “freeboard” allowed by the berm surrounding the downslope part of the rain garden. This calculation yielded 3.85 and 4.27 m^3 for gardens with and without underdrains, respectively. Since the installed sizes of rain gardens differed from the design size, capacities were subsequently adjusted to reflect the actual garden surface area.

The extent to which impervious areas were disconnected from storm sewers (and thereby receiving streams) and estimated volume capacity for stormwater runoff were determined from detailed GIS data on impervious surfaces. Total impervious area (TIA) and directly connected impervious area (DCIA) were previously calculated for subcatchments (Roy and Shuster, unpublished data). We plotted the locations of all rain barrels and rain gardens installed (ArcGIS, ESRI International; Redlands WA) from geo-located installation records. To determine impervious area mitigated by rain barrels, we subtracted the roof area draining into downspouts with rain barrels from subcatchment TIA, and subtracted the area draining connected downspouts from DCIA.

We evaluated potential effectiveness of these retrofit BMPs to capture runoff volume using a small, relatively frequent rainfall event (0.6 cm, or ¼ in). This rainfall depth would be expected to accumulate in less than 15 minutes and to recur every 2 months (Huff and Angel 1992) in the southwest climate region of Ohio. To translate this rainfall to runoff, we assumed that all rainfall from TIA is converted to runoff (and hence assume that the balance is completely infiltrated), and for each subwatershed estimated the total runoff volume with this equation:

$$\text{Runoff volume } (m^3) = \text{TIA } (m^2) \times \text{Rainfall depth (m)} \qquad \text{(Equation 1)}$$

We then totaled the estimated volume capacity of each rain garden and rain barrel for each subwatershed and subtracted these quantities from the previously calculated total volume runoff from impervious areas in each subwatershed. This calculation yielded an approximation of how much runoff volume might be captured in BMPs.

RESULTS AND DISCUSSION

Out of a possible 350 parcels, and accounting for un-occupied houses, we obtained a 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 have 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 perceptions of environmental and aesthetic benefits may be jointly important. The non-zero bids may indicate losses of owner opportunity to utilize their landscape space, and these costs are quantified as opportunity costs; or the willingness-to-accept cost that can represent non-specific non-market values of landowners. One rain garden bid and three rain barrel bids were rejected on the basis of high cost and low environmental effectiveness, or locations outside of the catchment. Landowners were notified of their bid status, landowner agreements drafted and signed, and then BMPs were then installed in the summer of 2007. Due to drought conditions in this period, planting the rain gardens was delayed until early fall. We ultimately installed fewer BMPs than accepted. This was due to several instances where an environmentally-effective location for BMPs differed with owner opinions or needs, or the owner decided after bid acceptance that they did not want a BMP after all; and in each of these cases no BMPs were installed. The distribution of these stormwater controls was uniform across parcels located in the headwater area of the watershed (Figure 1). This uniformity may illustrate an absence of collusion among neighbors who bid in the auction, in that there are no “hotspots” of bidding activity.

There were 100 barrels installed in the watershed (Figure 1), with the greatest numbers installed in the DRI subwatershed, and the fewest installed in ROA (Figure 2). Note that there was one barrel installed in URB, thus inadvertently treating stormwater in this control site (Figure 1). Given estimates of percent rooftop draining into each barrel and total rooftop area, the roof area draining into the barrels is 4303 m^2 (CON, Table 1) This amount of rooftop disconnected from the stormwater system resulted in a mitigation of 0.2% to 0.7% of total impervious area (TIA) across treatment subwatersheds (Table 1).We found that even after rain barrels were installed, subwatershed TIA levels were still well above the threshold of 8-12% TIA at which we would expect change in ecological integrity (Booth and Jackson 1997).

Table 1. Rain barrel data by subcatchment.

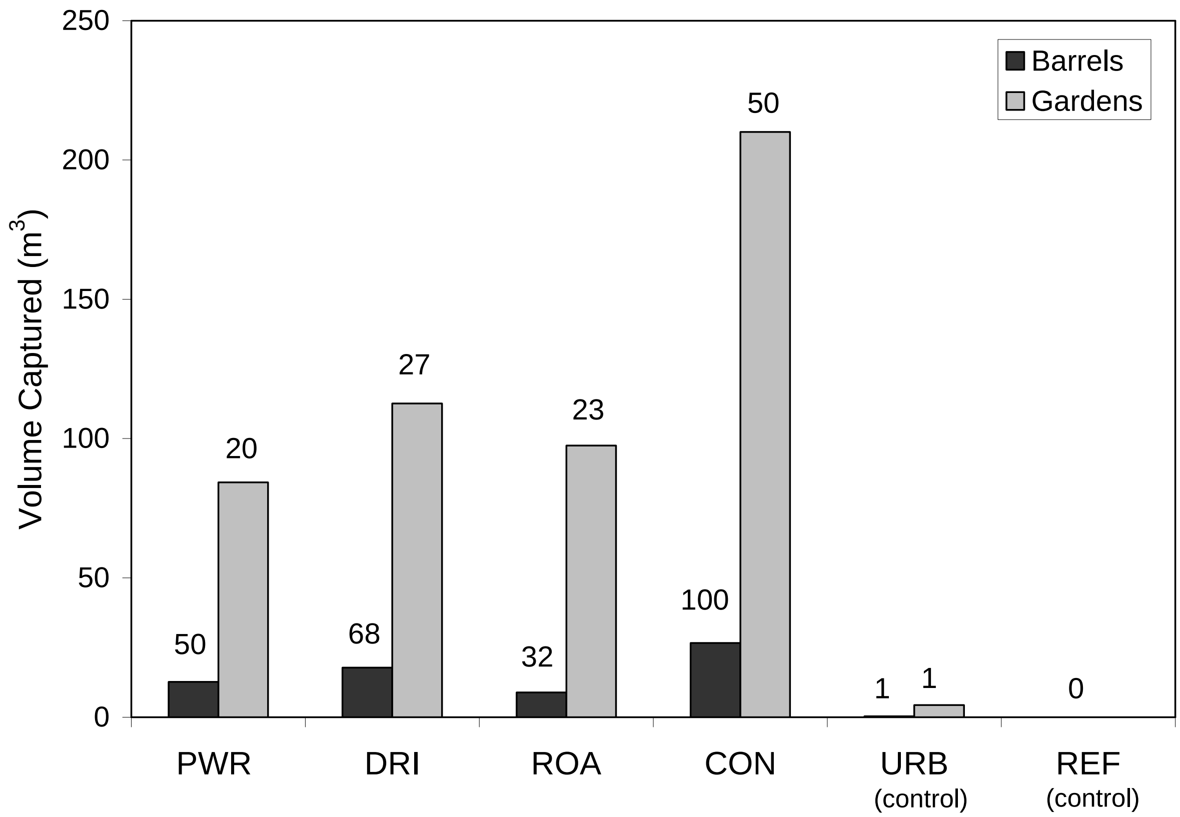
Rain barrel drainage status	PWR	DRI	ROA	CON	URB (control)	REF (control)
All Barrels						
# Barrels	50	68	32	100	1	0
Subwatershed area (ha)	28	58	69	183	25	35
Barrel volume (m^3)	12.7	17.8	8.9	26.6	0.3	0.0
Roof area drained (m^2)	2012	2874	1429	4303	48	0
Roof area drained (% TIA)	0.7	0.5	0.2	0.2	0.0	0.0
% TIA	19.2	15.8	12.9	12.9	11.2	12.1
Barrels on connected downspouts that drain into watershed						
# Barrels	32	40	29	69	1	0
Barrel volume (m^3)	8.1	10.4	8.0	18.4	0.3	0.0
Roof area drained (m^2)	1180	1539	1285	2824	48	0
Roof area drained (% DCIA)	0.4	0.3	0.2	0.2	0.0	0.0
% DCIA	11.2	8.7	7.2	7.2	5.4	7.3

We also considered the benefits of the rain barrel installation in terms of directly connected impervious area (DCIA). Due to supplier issues, some barrels were of smaller size than the specified volume, such that 77 barrels had 284 L (75 gal) capacity and the remaining 23 barrels captured a volume of 208 L (55 gal), yielding a total capacity of 2.6×10^4 L. Since there were 31 rain barrels installed on downspouts that had previously been disconnected, the remaining 69 barrels increased total volume capacity to 1.8×10^4 L (Table 1). Based on the roof areas that these barrels drain, treatment with BMPs decreased DCIA by 0.2% to 0.4% across all of the treatment subcatchments (Table 1). Because few studies have calculated DCIA, there is a wide range of estimates of DCIA thresholds of impairment (which according to Walsh et al. (2005) would be 6-14% for macroinvertebrates; 2-5% for algae, and 1-5% for water quality). These threshold values for DCIA are smaller than thresholds of TIA because TIA represents both disconnected and directly connected impervious area (Lee and Heaney 2003).

Because area-based calculations of TIA and DCIA do not take into account the volume of water the rain barrels store, we used volume calculations to compare mitigation potential for a certain size storm event. Since these retrofit stormwater management practices are meant to capture the more frequent storms with smaller total depth of rainfall, we examined effectiveness of the current deployment in capturing a 0.6 cm (1/4 in) storm event. We found that roof runoff draining into rain barrels ranged between 98 and 613 L for an average of 272 L. In practical terms, and when accounting for the variety of rain barrel sizes used in this study, 44% of the rain barrels would overflow. This barrel overflow volume may be routed either into downspout connections, rain gardens, or onto lawns, resulting in considerably different potential downstream effects. Although turf lawns constitute a pervious surface, infiltration characteristics vary greatly with turf condition and management practices, and antecedent moisture conditions.

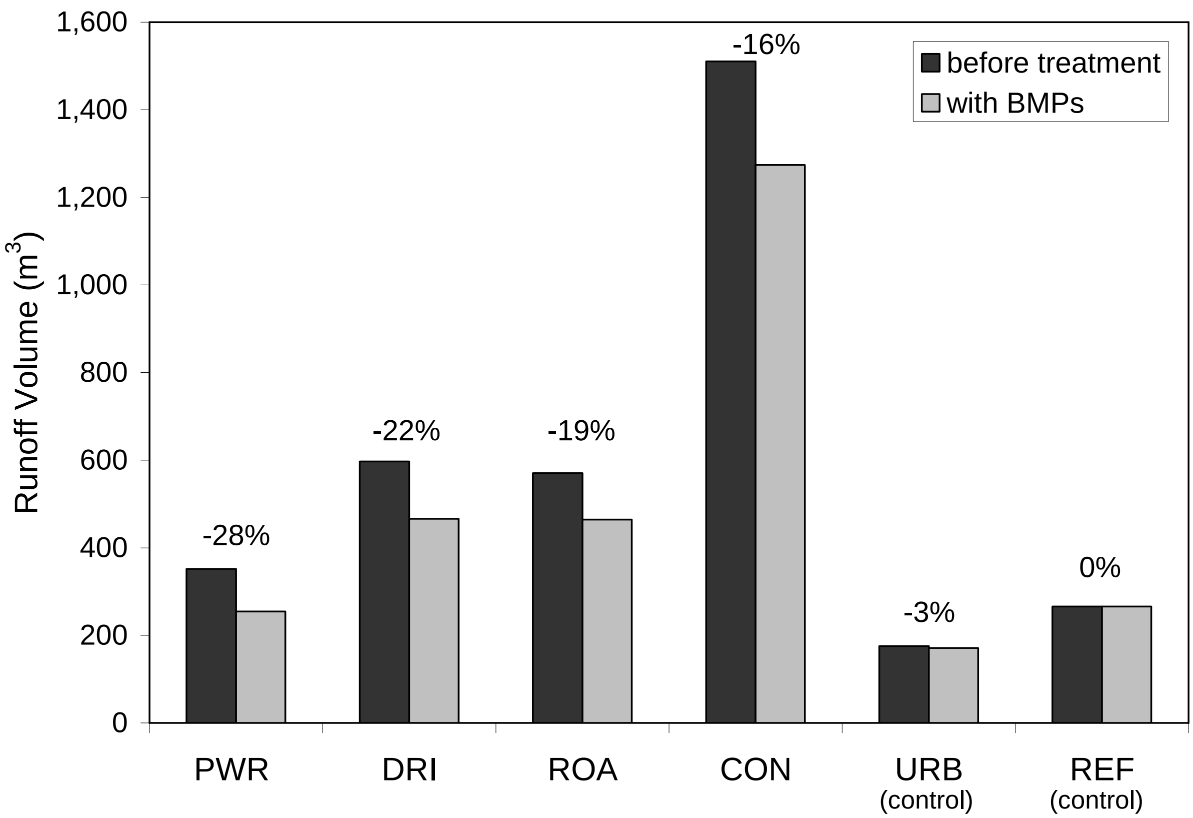
There were 50 rain gardens installed across the watershed (Figure 2), such that there were 34 with, and 16 gardens without an underdrain. Based on volume capacities of 3.85 and 4.27 m^3 for gardens with and without underdrains (adjusted for actual (installed) rain garden sizes), respectively, the total volume capacity contributed by gardens was 210 m^3. Rain gardens rely on infiltration and redistribution processes, such that their hydrologic status is dynamic, and antecedent conditions regulate their capacity for stormwater runoff. Therefore, we conservatively assumed that each rain garden unit had a certain amount of soil pore space available for storage, and treated these units as static with no consideration of redistribution processes. The static approach was taken due to the wide variety of rain garden placements, owner preferences in routing of rain barrel overflow to the rain garden; topography and how it may influence routing of sheet flow from lawn areas to the rain garden; and proximity to other impervious areas that may function as a source of additional runoff routed to the raingarden.

Figure 2. Volume captured in rain barrels and rain gardens, based on storage capacity (see text). The numbers of BMPs installed in each subwatershed are indicated above bars.



By combining the anticipated runoff capture volumes for rain gardens and rain barrels, we note that each subwatershed would see a decrease in the expected stormwater runoff quantity at the outfall (Figure 3), which ranged from 16 to 28%. Due to differences in assumed versus actual specific routing and impervious connectivity, we note that the role of each of the rain barrels or rain gardens is not specifically accounted for in this analysis. However, for preliminary modeling and planning purposes, these quantities estimate a metric of services that our environmental management approach may provide. A dynamic, spatially-explicit simulation environment that includes rain gardens interacting with their surrounding hydrologic landscape will be developed and studied, the details of which will be the subject of a future paper.

Figure 3. Estimated runoff volume for a 0.6 cm rain event is shown before and after installation of BMPs in each of four treatment subwatersheds. Values representing runoff volume before treatment are based upon total impervious area (TIA).



CONCLUSIONS

- Based on the 2007 reverse auction, 100 rain barrels and 50 rain gardens were installed, resulting in a watershed-wide increase in stormwater storage capacity of 26 and 210 m^3, respectively
- Although the more direct effects of DCIA on stream ecosystems were reduced by only 0.2 – 0.4%, we found that the additional detention of runoff volume from a small, frequent storm was estimated to range from 16 to 28% in treatment subwatersheds
- In addition, we will pursue a second reverse auction in the spring of 2008 and continue to monitor discharge, water quality parameters and biomonitoring at multiple scales to

better understand the implications of our management approach for decreasing stormwater runoff quantity in a suburban neighborhood

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