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FEATURES

# Retrofit Stormwater Management

***Navigating multidisciplinary hurdles at the watershed scale***

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Heavy machinery strips the land of trees and topsoil and compacts the ground. Roads, parking lots, commercial buildings, and residential housing cover the landscape with impervious surfaces. Precipitation runs off the landscape. Erosive gullies form. Trash and chemical pollutants wash into storm drains. Streams are impaired, and only the most tolerant species persist.

In the present housing boom, this scene is becoming typical across the United States. Many communities are considering options to address stormwater runoff problems in already-developed areas, such as those pictured in Figure 1. However, such retrofit stormwater management is riddled with legal constraints (e.g., private property rights), economic challenges (e.g., stormwater fees not tightly linked to runoff), and social concerns (e.g., basement flooding). Although a multidisciplinary approach that directly incorporates the various legal, social, economic, and hydrologic aspects of stormwater management is therefore more appropriate, such an approach is more complicated and thus rarely undertaken.

Stormwater runoff from new or existing development can be addressed using either centralized management systems, such as large

**Figure 1. Residential setting in Shepherd Creek catchment**

conveyance pipes and water treatment plants, or decentralized systems, such as retention ponds, grassy swales, and porous pavement. Although the centralized approach can minimize large fluctuations in streamflows and flooding risk to urban areas, this approach does not address the ecological requirements of maintaining adequate base flows and natural fluctuations in storm flows that are necessary for healthy aquatic ecosystems. Decentralized systems distribute stormwater management practices throughout watersheds and can more effectively mimic predevelopment hydrologic cycles throughout stream networks. While these systems require a great deal of coordination between landowners and government authorities, especially for long-term maintenance, decentralized systems have more flexibility than large centralized systems, allowing for adjustments and experimentation over time.

We present a multidisciplinary, adaptive management approach to urban stormwater management as applied to a pilot study watershed. This case study provides a framework for watershed-level retrofit stormwater management in other watersheds. With a team composed of lawyers, ecologists, hydrologists, and economists, we began by selecting a local watershed with clear evidence of impairment due to excess stormwater runoff. We then identified restoration goals for hydrology, water quality, and ecology, while checking a variety of potential economic incentive programs against legal constraints and integrating these with our knowledge of the watershed.



**Case Study: Shepherd Creek Watershed**

***Environmental Setting***

The Shepherd Creek watershed in Cincinnati, OH, is 1.8 square kilometers, approximately one-third of which lies within a city park with mature deciduous forest. The other two-thirds of the watershed represent a mix of 1960s through 1980s residential parcels in the headwaters and horse pastures at downstream locations. The watershed sits on calcareous shale and limestone formations with moderate slopes, and silt and silty clay loam soils dominate.

Figure 2 shows impervious areas and open spaces of the Shepherd Creek watershed and its five sub-watersheds. Sub-watershed imperviousness ranges from 12.5% at site 5 to 20.6% at site 2. At site 1, a majority of the impervious surfaces are parking lots and roads in the city park, while the other sites have relatively high proportions of imperviousness in rooftops and driveways. Table 1 lists the proportion of impervious surfaces as rooftops, driveways, sidewalks, parking lots, and roads in the sub-watersheds.

***Current Stream Condition***

Data collected in 2003–2004 demonstrate that the Shepherd Creek watershed and its tributaries are highly impaired and could benefit from mitigation. The cobble/gravel riffles are highly embedded, and a layer of silt covers a majority of the streambed in the tributary reaches. Where impervious surfaces are directly connected to streams via storm pipes, we observed scoured streambeds and bank erosion, typical consequences of “flashy” storm flow dynamics. Qualitative comparisons among changes in stream depth for two warm-season storms show that rates of rise at sites 3 and 4 are nearly three times greater than at site 1. In addition, time to peak flow follows a similar trend whereby sites 3 and 4 peak approximately 25 minutes before site 1. These results reflect the mitigating effects of buffers (i.e., forest and pond) that retain storm flows at site 1.

Water chemistry in the sub-watersheds is characterized by neutral to alkaline pH (average values range from 7.5 to 7.8), with high average alkalinity (223 to 287 mg $CaCO_3$sub>·$l^{-1}$) and specific conductivity (680 to 1,510 μs·$cm^{-1}$). Nitrogen and phosphorus concentrations are typical for urban and agricultural lands, with average baseflow values for dissolved inorganic nitrogen (DIN) and total phosphorus (TP) ranging from 0.18 to 0.77 $mg1^{-1}$ and 0.16 to 0.43 $mgl^{-1}$ respectively. Periphyton samples demonstrate high levels of chlorophyll *a* (4.0 to 10.5 mg·$m^2$), and a majority of the algal cells are cyanobacteria, reflecting poor water quality. Average fecal coliform bacteria and *E. coli* counts are one to two orders of magnitude higher than Ohio EPA’s ambient surface-water-quality criteria (e.g., mean limit 126 CFU 100 $ml^{-1}$ for *E. coli*). Macroinvertebrate assemblages also reflect poor stream conditions, with an average of 1.5 to 3.1 sensitive EPT taxa per site, and Hilsenhoff’s Family Biotic Index scores suggest fairly poor (5.76–6.50) or poor (6.51–7.25) water quality.

**Various Perspectives for Stormwater Management**

***Hydrology, Ecology, and Water-Quality Issues***

From a stream ecosystem perspective, the role of stormwater management is to significantly improve in-stream hydrology, water quality, and ecology. Based on current scientific literature, aquatic communities react to impervious surfaces nonlinearly; stream conditions decline faster above a threshold of about 10% to 15% imperviousness in a watershed. Thus, the goal from a stream ecosystem perspective would be to reduce the influence of impervious surfaces to well below this threshold, assuming that stream communities will improve with impervious surface mitigation.

Successful stream restoration therefore depends on mitigation or amelioration of land-use disturbances, such as increased imperviousness, at the *watershed* scale (versus stream segment or bank restoration). This suggests the need for a management approach that addresses both water quantity (e.g., mitigate flashy flows, reduce runoff volume, restore base flows) and water quality (e.g., reduce nonpoint-source pollutants). Source controls (versus end-of-the-pipe treatment) of stormwater runoff are ideal because they can infiltrate precipitation, thus recharging groundwater and increasing subsurface flows, creating a more natural flow regime in streams, and allowing for natural processes in soils to remove pollutants.

***Legal Issues***

While stormwater quality is regulated in the United States by the Clean Water Act (33 U.S.C. §1342(a)), stormwater quantity is not, and few communities have instituted taxes or land-use strategies to prevent watershed deterioration due to changes in hydrology. Without a legal limit on quantity to force compliance, the kinds of economic incentives that can be used to address stormwater quantity are limited. Further, if stormwater abatement tools involve private property, legal concerns associated with property rights must be addressed. The Fifth and Fourteenth Amendments to the US Constitution prohibit the government from taking private property for public use without just compensation and due process of law, respectively.

Our approach for urban stormwater management must be legally sound and operationally feasible for local governments. If the method is voluntary and the property owner will be appropriately compensated for use and maintenance of the land through a fixed–time period lease agreement, then any legal problems associated with unconstitutional use of private property by the government should be minimized.

***Socioeconomic Issues***

Optimally, expenditure on environmental quality should be financially efficient so as to minimize costs while maximizing ecological benefit. Regulations that require the polluter or generator of environmental damage to pay for and mitigate this damage can be economically efficient when the polluters seek cost-saving methods of reducing their own pollution. For example, a watershed-scale market-based incentive system has been shown to lower the cost of decentralized stormwater detention when used to supplement or replace a centralized management system. These markets create a demand among landowners for “allowed runoff,” using either price or quantity instruments as incentives.

Large-scale environmental manipulation is impossible in urban areas without considering socioeconomic issues. Ignoring these fundamental issues may lead to suboptimal participation and failure to achieve goals. Residents in the Shepherd Creek watershed are from various socioeconomic backgrounds and will have different perceptions about stormwater management practices. Further, they may be wary of certain stormwater management tools due to unfamiliarity, maintenance requirements, appearance, and/or potential side effects (e.g., basement flooding due to local infiltration, mosquitoes from standing water). Selecting options that have the highest chance of public acceptability and providing adequate public education would likely minimize the effect of these concerns.

**Multidisciplinary Stormwater Management Strategy**
***Incentive Approach***
Previous research by Parikh and co-authors considered four potential incentive approaches for controlling stormwater runoff: stormwater user fees, stormwater runoff charges, allowance markets, and voluntary offset programs. Each method was evaluated based on legal, economic, and hydrologic concerns and ranked for appropriateness within each discipline. For example, although a stormwater user fee program currently exists (and is therefore legally appropriate), such fees are not directly tied to storm runoff, thus providing little economic incentive for landowners to mitigate hydrologic problems. On the other hand, allowance markets (i.e., cap-and-trade) can guarantee ecological benefit and economic efficiency; however, the lack of a strict legal authority in the case of stormwater quantity undermines this option.

Although not ideal for any one discipline, the voluntary offset program was selected as the most appropriate mechanism from the combined viewpoints of all disciplines. Like trading, a voluntary offset program is a market mechanism based on incentives, such that homeowners will be compensated based on runoff abatement. However, voluntary participation necessarily reduces the incentive effect and the amount of runoff likely to be mitigated. Importantly, because participation is strictly voluntary, any legal concerns should be eliminated.

***BMPs: Rain Barrels and Rain Gardens***
We selected a decentralized stormwater management strategy for the Shepherd Creek watershed using best management practices (BMPs) in the form of rain barrels and rain gardens. These source-reduction strategies (versus downstream mitigation of flows in centralized approaches) should simultaneously provide better improvements to stream hydrology, water quality, and ecology. Further, because they are small in scale, decentralized BMPs allow for flexibility in implementation and distribution throughout a watershed. If these BMPs do not result in improvements to stream ecosystems, opportunities would remain within the watershed to try additional stormwater mitigation approaches (i.e., allowing for adaptive management). Finally, based on an economic model of the Shepherd Creek watershed, Thurston and co-authors found support for the hypothesis that incremental investments would cost less than large engineering infrastructure for the small scale of this project, making decentralized BMPs a viable approach.

Downspout rain barrels and landscaped rain gardens will be offered to reduce stormwater runoff from rooftops, driveways, and lawns. Rain barrels, or cisterns, serve to temporarily detain rooftop runoff, providing maximum benefits where gutter downspouts are currently connected to stormwater runoff pipes. Rain gardens, on the other hand, are small-scale bioretention areas that are designed to infiltrate surface runoff from upslope locations. The relatively high proportion of impervious area in rooftops and driveways, which account for a combined 50% to 72% of impervious area in treatment sub-watersheds, was an important factor in determining the scale of management and type of BMP. Further, there is an adequate amount of open space to allow for parcel-level rain gardens, and rain barrels could be easily attached to most gutter downspouts.

***Economic Auction***

We selected an economic auction, a type of voluntary offset mechanism, to distribute BMPs. A voluntary auction approach will encourage property owners to control the runoff contributed to a watershed in a decentralized manner, without necessitating a legal mandate. Similar to a tradable credit market, property owners who agree to accept a BMP on their property to lower their contribution of stormwater to the watershed receive a credit in the form of free BMPs plus some payoff. Yet, unlike a tradable credit system, property owners who choose not to accept a BMP are not penalized.

The auction procedure will include four steps as listed in Table 2. First, we will deliver brochures to all homeowners eligible for BMPs that will briefly explain stormwater runoff issues, the BMPs being offered, and the auction process. Homeowners will be allowed to submit bids for receiving rain barrels (a maximum of four) and/or a rain garden (a maximum of one). Homeowners whose bids are accepted will receive free BMPs plus monetary compensation equivalent to the bid price. It will be run as a sealed-bid, discriminative price auction (versus uniform price), where residents may receive different levels of subsidy for installing BMPs on their property, thus resulting in the maximum number of BMPs installed for the least cost to the watershed manager (i.e., lowest payout). Bids will reflect homeowners' willingness to accept BMPs based on (1) opportunity cost of land taken out of other uses, (2) non-market values residents place on positive changes in stream ecosystem health, (3) long-term maintenance costs, and (4) competitive pressures due to bidding against other homeowners.

Bids will be ranked by the auction manager according to a weighting factor that accounts for cost (i.e., lowest bid price) and potential environmental benefits (i.e., to obtain the highest "bang for the buck"). For example, environmental weighting factors for rain gardens specific for each parcel will include owner-specified location, soils, percent impervious area, percent impervious surfaces connected to storm sewers, and distance from stream channel. After ranking bids, subsidies equivalent to the bid amounts will be awarded from lowest to highest until reaching the maximum amount of money allocated for the auction.

**Monitoring Strategy and Expected Results**

The project uses a before-after-control-treatment design, where the treatment is the installation of parcel-level BMPs. We have established six monitoring sites in the watershed, four of which are in the areas that will receive BMPs (sites 2 through 5). This statistical design allows us to assess differences within sites before and after treatment, and account for natural variation associated with climatic differences using control sites. Streams have been monitored for hydrology, water quality, and ecology for two to three years prior to BMP implementation, and will be monitored for three years following implementation. Hydrology is monitored continuously at five-minute intervals using depth and velocity sensors and constructed flow controls. Water-quality monitoring includes nutrients, suspended sediment, metals, and bacteria and is sampled monthly during base flows (grab samples) and periodically during storm flows (automated hourly or parameter-based samples). Ecological monitoring includes benthic macroinvertebrates, periphyton, and habitat visual assessments sampled every six weeks from April through October each year.

After installation, a subset of BMPs will also be monitored at the parcel level to determine whether the BMPs are functioning properly and how much water is being collected or infiltrated. Homeowners will be responsible for draining rain barrels; the water may be used to water gardens and lawns, wash vehicles, or drain passively to lawns, preferably after a storm event. How the homeowners choose to maintain their rain barrel(s) will help determine potential environmental benefits. For the purposes of testing stream responses to properly maintained rain gardens, these areas will be maintained for a period of three years by professionals. Ten rain gardens will be instrumented at the time of installation to measure on-lot precipitation, water depth, and water leaving via the underdrain.

According to our projections shown in Figure 3, there is potential to reduce the influence of total impervious area in the test watersheds below the ecological threshold of 10% to 15% impervious area, the level at which impairment has been observed in other temperate watersheds. Figure 3 is based on the assumption that rain barrels and rain gardens can effectively eliminate runoff effects from both rooftops and driveways. With 100% homeowner acceptance rates, these BMPs have the combined potential to reduce effective impervious area in sites 2 through 5 from above the threshold to well below the threshold. If 50% of the homeowners have BMPs installed, it is still likely that some sub-watersheds will exhibit improvements in stream condition. It will be two to three years before we know whether decentralized stormwater management is cost-effective based on BMP acceptance rates, and whether we observe improvements in stream hydrology, water quality, and ecology.

**Conclusions**

We described a course of action for retrofit management of stormwater quantity, with the overarching goal of improving ecosystem conditions in receiving streams. Table 3 lists the recommended steps to a watershed scale retrofit using a multidisciplinary approach. These steps were used for the Shepherd Creek watershed, where decentralized stormwater management in the form of parcel-level rain barrels and rain gardens was determined to be the best option. Legal constraints were avoided by using a voluntary approach to BMP implementation, and costs are expected to be minimized using an auction. A monitoring plan (step 5) is necessary to evaluate whether this approach is cost-effective and to what extent improvements in stream ecosystem health are realized.

We have learned that the integration of disciplines forces compromise so that optimal solutions for each discipline are replaced by the most feasible solution for all disciplines. For example, there may be no legal authority to support application of certain sound economic theories, and certain hydrologic or ecologic goals may be economically untenable. Ultimately, the multidisciplinary adaptive management approach has produced a policy prescription for urban stormwater management that is, if not ideal in one discipline, sound in all disciplines.

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