A multidisciplinary approach to stormwater management at the watershed scale

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ABSTRACT
Stormwater runoff from extensive impervious surfaces in urban and suburban areas has led to human safety risks and stream ecosystem impairment, triggering an interest in watershed-scale retrofit stormwater management. Such stormwater management is of multidisciplinary relevance, posing legal, social, economic, hydrologic, and ecological challenges and constraints. A multidisciplinary approach to stormwater management is being tested in the Shepherd Creek watershed, a 20 km^2 residential and forested watershed in Cincinnati, OH (USA). An assessment of the total impervious area (TIA) revealed that a majority (50–72%) of TIA in sub-watersheds is in rooftops and driveways, so we decided to use parcel-level best management practices (BMPs) in the form of rain barrels and rain gardens to mitigate stormwater runoff. To abide by laws concerning stormwater, a voluntary economic auction approach will be used to distribute BMPs and evaluate landowners' willingness-to-accept BMPs on their property in exchange for financial compensation. The hydrologic and ecologic responses to retrofit stormwater BMPs will be tested using a before-after-control-impact design, where the "impact" is the installation of BMPs. This research suggests a policy prescription for retrofit management of stormwater quantity that is, if not ideal in one discipline, at least sound in all disciplines.

KEYWORDS
BMPs; impervious surfaces; multidisciplinary; stormwater runoff; watershed management

INTRODUCTION
With urban sprawl, a greater number and proportion of watersheds are affected by concrete, buildings, and other impervious surfaces which impede the rapid infiltration of precipitation. These changes to the natural patterns of runoff have resulted in increased risk to human health and safety, and hydrological, geomorphic, and ecological impairment of receiving stream ecosystems (Klein, 1979; Paul and Meyer, 2001; Allan, 2004). Total impervious area (TIA) of watersheds often affects stream communities nonlinearly; stream conditions decline faster above a threshold of ~10–15% TIA in a watershed (Schueler, 1994; Booth and Jackson, 1997; Walsh, 2004). Successful stream restoration depends upon mitigation or amelioration of land use disturbances (such as increased TIA) at the watershed scale (Allan, 2004; Walsh, 2004).

Addressing stormwater runoff problems with centralized management systems (e.g., large conveyance pipes, water treatment plants, etc.) is less desirable for a variety of reasons when compared to decentralized systems (e.g., retention ponds, grassy swales, porous pavement, etc.; Sieker, 1998; Field and Sullivan, 2003). While the centralized approach can minimize large fluctuations in stream flows and flooding risk to urban areas, this approach does not address the ecological requirements of maintaining adequate baseflows and natural fluctuations in stormflows necessary for healthy aquatic ecosystems. Decentralized systems are distributed across the landscape and can more closely restore natural hydrologic cycles throughout stream networks. While these systems require a great deal of coordination between landowners and government authorities, especially for long-term maintenance (Coffman and Clar, 1003), decentralized systems have more flexibility than large centralized systems, allowing for adjustments and experimentation over time (Roe and Van Eeten, 2001).

By nature, stormwater management is an issue of multidisciplinary relevance. A combination of legal constraints, socioeconomic influences over impervious surface (e.g., zoning), and watershed-scale disturbance to the hydrologic and ecological conditions downstream of urban areas combine to require input from several disciplines for effective management. Although a multidisciplinary approach to stormwater management is therefore more appropriate, such an approach is more complicated and therefore rarely undertaken.

This paper presents a multidisciplinary adaptive management approach to urban stormwater management, as applied to a pilot study watershed, and provides a framework for watershed-level retrofit stormwater management to other watersheds. With a team comprised 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 hydrologic and ecological restoration goals, while checking a variety of potential economic incentive programs against legal constraints.

METHODS

Shepherd Creek watershed pilot study

Site description. The Shepherd Creek watershed in Cincinnati, Ohio (USA) is approximately 20 km^2, half of which lies within a city park with mature deciduous forest (Figure 1). The other half of the watershed represents a mix of 1960-1980s residential parcels in the head-waters, and horse and cattle pastures downstream. The watershed sits on calcareous shale and limestone formations with moderate slopes, and silt and silty clay loam soils dominate.

The project uses a before-after-control-impact design, where the "impact" is the installation of parcel-level best management practices (BMPs) (Underwood, 1992). We have established 6 hydrologic and ecological monitoring sites in the watershed, 4 of which are receiving streams for BMPs (sites 2–5, Figure 1). Sub-watersheds are predominantly forested (44–68%); however, a substantial portion includes pastures (18–33%) and TIA (13–23%; Table 1).

Impervious surface cover. In addition to classifying TIA from satellite imagery, we also hand-delineated TIA from digital orthophotos and categorized areas by impervious type (rooftop, driveway, sidewalk, parking lot, road; Table 2). TIA ranged from 12.5% at site 5 (confluence) to 20.6% at site 2 (a headwater residential area). At the reference site (site 1), a majority of the impervious was parking lots and roads in the city park, while the other sites had relatively high proportions of TIA in rooftops and driveways (Table 2).

Baseline stream data. Data collected from sites 1–5 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 (e.g., sites 2–4), we observed scoured stream beds and bank erosion, typical consequences of "flashy" stormflow dynamics (Booth and Jackson, 1997). Qualitative comparisons among stream depth time series for two warm season storm events with similar

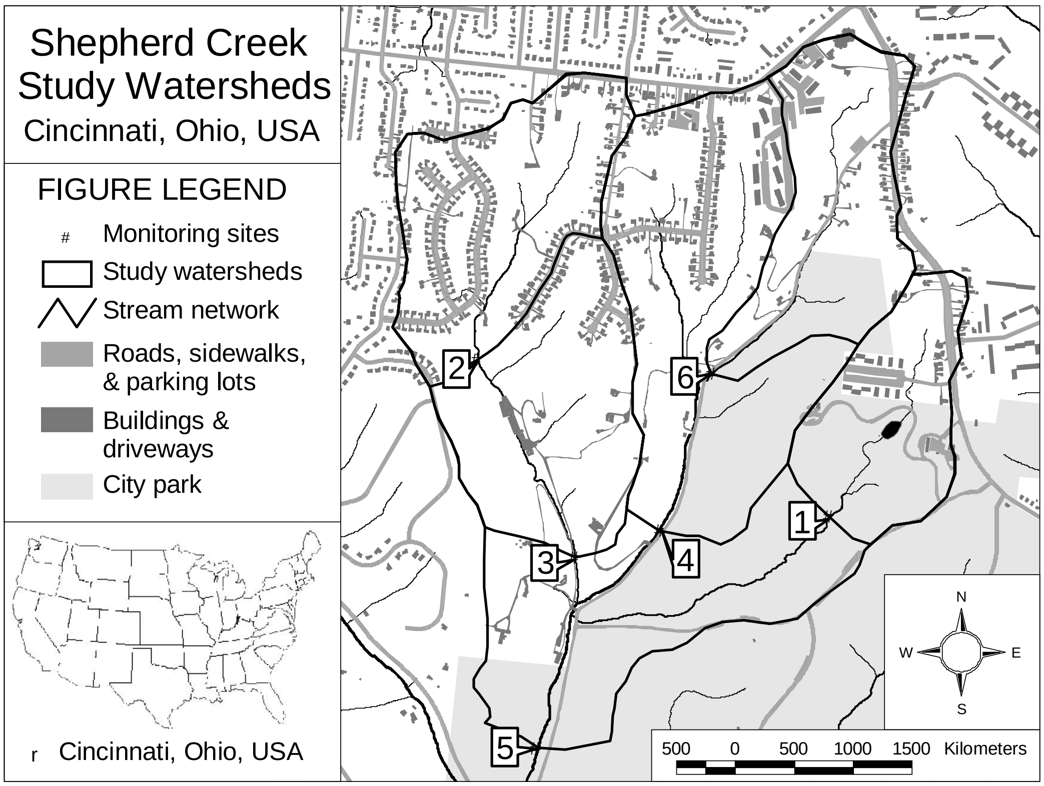

Figure 1. Map of 6 hydrologic and ecological study watersheds throughout the Shepherd Creek watershed, Cincinnati, OH, USA. Sites 1 and 6 are control watersheds that will not receive BMPs.

Table 1. Basin area and % land cover within each sub-catchment. Land cover was classified from 2001 satellite imagery (4 m resolution).

			% Land cover				
No.	Site name	Sub-catchment area (km^2)	Open water	Row crops	Meadow/ grass	Forest/ trees	Imperv-ious
1	Reference (control)	2.2	0.1	0.1	20.6	64.2	15.1
2	Powerline	3.2	0.5	0.1	32.9	43.8	22.7
3	Driveway	6.3	0.3	0.4	35.1	46.3	17.9
4	Road	7.6	0.1	0.1	18.1	68.0	13.6
5	Confluence	19.9	0.1	0.2	23.6	62.6	13.4
6	Urban (control)	2.8	0.1	0.3	19.8	66.4	13.4

Table 2. TIA as rooftops, driveways, sidewalks, parking lots, and roads.

Site	Impervious (% of basin area)						Impervious (% of total impervious)				
No.	Roof	Drive	Sidewalk	Parking	Road	Total	Roof	Drive	Sidewalk	Parking	Road
1	2.3	1.3	0.5	5.2	4.7	14.0	16.7	9.5	3.5	37.3	34.8
2	7.9	6.2	1.3	0.0	5.2	20.6	39.9	30.1	6.5	0.0	26.1
3	5.5	5.7	0.9	0.0	3.4	15.5	36.7	36.7	5.7	0.0	22.7
4	4.0	2.6	0.5	2.7	3.3	13.3	30.1	19.9	4.1	20.7	25.2
5	3.8	3.3	0.5	1.6	3.4	12.5	30.2	26.2	4.3	12.7	27.0
6	2.7	2.7	0.5	2.9	4.3	13.1	20.4	20.5	3.7	22.2	32.5

durations show that rates of rise at sites 3 and 4 are nearly 3 times greater than site 1. Time to peak flow follow a similar trend whereby sites 3 and 4 peak ~25 min before site 1, reflecting the mitigating effects of buffers (i.e., forest and pond) at site 1.

The water chemistry is generally alkaline (pH 6.9 to 8.3) with high average specific conductivity (580 to 953 $\mu s \cdot cm^{-1}$) at the sites. Nitrogen and phosphorus concentrations are typical for urban and agricultural lands (Table 3; Johnson *et al*., 1997; Hatt *et al*., 2004). Periphyton samples demonstrate high levels of chlorophyll *a*, and a majority of the algal cells are blue-green algae, reflecting poor water quality (Stevenson and Smol, 2003). Average fecal coliform bacteria and *E. coli* counts are 1–2 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*; USEPA, 2002). Macroinvertebrate assemblages also reflect poor stream conditions, with an average of 1.5 to 3.1 sensitive EPT taxa per site, and Hilsenhoff's (1988) Family Biotic Index scores suggesting fairly poor (5.76–6.50) or poor (6.51–7.25) water quality (Table 3).

Stormwater management: disciplinary issues and multidisciplinary solution

Hydrologic and ecological issues. From a hydrologic and ecological standpoint, the goal of this effort is to significantly improve in-stream conditions in sites receiving BMPs. Because TIA is linked to ecological impairment (e.g., site 2, with the highest TIA, has the highest average NO_2+NO_3-nitrogen concentration and chlorophyll *a* biomass, and lowest macro-

Table 3. Average (± *standard deviation*) stream characteristics for 10 sample dates from May–November 2003 and 2004. Nitrite + nitrate nitrogen (NO_2+NO_3) and total dissolved phosphorus (TDP) data are from 2004 (not sampled in 2003). CFU = colony forming units. EPT = richness of orders Ephemeroptera, Plecoptera, and Trichoptera. FBI = Family Biotic Index (Hilsenhoff, 1988). No data are available for site 6 (sampling began in 2005).

Site	NO_2+NO_3	TDP	Chlorophyll	% Blue-	Bacteria (CFU 100 ml^{-1})		Invertebrates	
no.	($mg \cdot l^{-1}$)	($mg \cdot l^{-1}$)	*a* ($mg \cdot m^{-2}$)	green algae	Fecal coliform	*E. coli*	EPT	FBI
1	0.76/*0.44*	0.10/*0.08*	4.5/*3.3*	95.0/*3.8*	7326/*7346*	1312/*1166*	1.8/*0.9*	6.8/*0.7*
2	1.16/*0.25*	0.10/*0.06*	10.5/*9.5*	86.7/*10.4*	11349/*14638*	3162/*3576*	1.5/*1.1*	5.9/*0.5*
3	0.74/*0.36*	0.33/*0.24*	4.0/*4.0*	91.7/*12.6*	24220/*27425*	4292/*5751*	1.6/*1.0*	6.8/*0.7*
4	0.62/*0.46*	0.16/*0.05*	8.2/*3.3*	89.8/*17.6*	8046[a]/*11252*	5754[a]/*8956*	1.8/*1.2*	7.1/*0.6*
5	0.48/*0.21*	0.17/*0.07*	7.2/*5.6*	88.9/*10.9*	13549/*14099*	2332/*2730*	3.1/*1.9*	6.6/*1.1*

[a]Excludes high outliers in June 2004 for fecal coliforms (3,650,000) and E. coli (2,100,000).

invertebrate EPT richness), we expect that reduction of runoff from TIA will improve stream conditions. Based on published disturbance thresholds, observable improvement may require reduction of runoff from impervious surfaces such that TIA is < 10–15%.

Legal issues. The approach developed for urban stormwater management ultimately must be legally sound and operationally feasible for local governments to apply elsewhere. 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.

Economic issues. Optimally, expenditure on environmental quality should be efficient, minimizing costs for the maximum 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 (Thurston *et al*., 2003). These markets create a demand among land-owners for “allowed runoff,” using either price or quantity instruments as incentives.

Multidisciplinary solution. Previous research evaluated four potential incentive programs for controlling stormwater runoff for appropriateness within each discipline (Parikh *et al.*, 2005). Whereas allowance markets (i.e., cap-and-trade) can guarantee ecological benefit and economic efficiency, the lack of a strict legal authority in the case of stormwater quantity undermines this option. Conversely, certain legally acceptable price instruments (e.g., storm-water user fees) could result in low landowner investment and inadequate stormwater mitigation. Although not ideal for any one discipline, the voluntary offset program was selected as the most appropriate mechanism for all disciplines (Parikh *et al*., 2005). Like trading, a voluntary offset program is a market mechanism based on incentives; however, there is no legal mandate to force participation.

RESULTS AND DISCUSSION

Stormwater management strategy and mitigation potential

We selected a decentralized stormwater management strategy for the Shepherd Creek watershed. Small-scale techniques allow watersheds to be adaptively managed based on experimental results if they do not initially meet ecological goals (Roe and Van Eeten 2001). In addition, these source reduction strategies (vs. downstream mitigation of flows in centralized approaches) should provide better in-stream hydrological and ecological benefits (Walsh, 2004). Further, Thurston *et al.* (2003) found that incremental investments would cost less than large engineering infrastructure for the small scale of this project.

The relatively high proportion of TIA in rooftops and driveways (combined 50.0–72.3% of TIA in sub-watersheds receiving mitigation) was an important factor in determining the scale of management and type of BMP. Downspout rain barrels and landscaped rain gardens will be offered to reduce stormwater runoff from rooftops and driveways, respectively. Rain barrels will be required pre-requisites for rain garden installation to ensure maximum economic efficiency (since they are cheaper to install) and hydrologic effectiveness (since rain gardens may be overwhelmed by runoff from rooftops). Depending on BMP acceptance rates, there is potential to reduce TIA below the ecological threshold of 10–15% TIA, at which impairment has been observed in other temperate watersheds (Schueler, 1994; Booth and Jackson, 1997; Walsh, 2004). Assuming BMPs can effectively eliminate runoff effects from impervious areas, these BMPs have the combined potential to reduce TIA from 12.5–20.6% (sites 2–5) to 4.3–6.5% if 100% of landowners accept BMPs (Figure 2). If only rain barrels are used, and there is a 100% acceptance rate among homeowners, TIA will be effectively reduced to 8.0–12.7% in the watersheds receiving mitigation (Figure 2). It will be 1–2 years before we know whether decentralized stormwater management is cost-effective based on BMP acceptance rates, and whether we observe hydrologic and ecologic improvements.

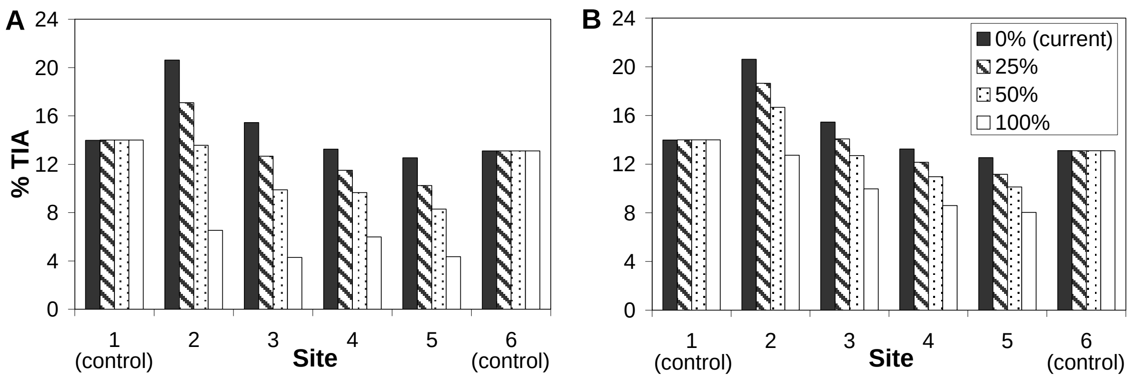

Figure 2. Percent TIA given 0, 25, 50, and 100% landowner acceptance rates of A) rain gardens and rain barrels, and B) rain barrels only. Projections assume BMPs will effectively eliminate TIA in rooftops and driveways for rain barrels and rain gardens, respectively.

Distributing BMPs via an economic auction

We selected an economic auction approach to distribute BMPs using a voluntary offset program. The auction takes advantage of the differentiation of the cost of abating stormwater runoff in each parcel based on land use and soil type. An 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 would receive a credit in the form of a free BMP plus some payoff. Unlike a tradable credit system, property owners who do not accept a BMP are not penalized. The “sealed bid” auction will allow landowners to submit bids for receiving rain barrels and rain gardens of various sizes. It will be run as a discriminative price auction (vs. 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 manager (i.e., lowest payout). Bids will reflect landowner’s willingness-to-accept BMPs based on 1) construction and maintenance costs, 2) opportunity cost of land taken out of other uses, and 3) non-market values residents place on positive changes in stream ecosystem health.

The legality of installing BMPs on homeowner property

Because the BMPs are on private property, we addressed several legal concerns associated with property rights. The Fifth and Fourteenth Amendments to the U.S. Constitution prohibit the government from taking private property for public use without just compensation and due process of law, respectively. However, because participation in the auction is entirely voluntary, and the property owner will be appropriately compensated for use and maintenance of the land through a fixed-time period lease agreement, our approach should avoid any legal problems associated with unconstitutional use of private property by the government.

Additional disciplinary issues and resolutions

Socioeconomics. Large-scale environmental manipulation is impossible in urban areas without considering socioeconomic issues, although such issues may lead to suboptimal participation and failure to achieve goals. Residents in the Shepherd Creek watershed are from various socioeconomic backgrounds and will likely demand different levels of payment to receive BMPs. After the auction is completed, we will evaluate the role of socioeconomics in BMP acceptance rates, and the extent to which auction results can be applied to other areas.

Educating landowners. Although landowners may place lower bids if well-educated about stormwater runoff risks and BMP mitigation techniques, wide-spread education also incurs costs for overall stormwater management. Due to the small sample size (i.e., approximately 400 property owners) and our additional interests in socioeconomic differences, we are unable to test separate groups with various levels of education. Instead, we will deliver brochures to all landowners eligible for BMPs that will briefly explain stormwater issues and the auction, thus insuring a minimum level of understanding at a minor cost.

CONCLUSIONS

We described a course of action for retrofit management of stormwater quantity that can be replicated using the following steps:

1) **Determine scope of hydrologic and ecologic impairment, and potential for improvement.** The sources of runoff must be quantified first; in some cases, the primary source of excess runoff may not be easily reduced with a decentralized management approach. Stream conditions should be quantified both before and after improvements are made; if hydrologic and ecological conditions do not meet targets, either the improvements were not adequate to overcome environmental thresholds, or the main source of deterioration was not mitigated.
2) **Assess legal issues.** If there is no legal authority to set limits or regulate stormwater quantity, determine the degree to which other policies or programs can be implemented and create “limits” through voluntary actions. If watersheds straddle jurisdictional boundaries and more than one agency is responsible for stormwater management, additional complications may arise.
3) **Assess cost of alternative management strategies.** Funding for improving stormwater management may come from several agencies, but is likely to be in short supply. Depending upon many factors, further improvements to a centralized system may be more financially feasible than creating a decentralized system. In all cases, the time frame of the cost and benefit considerations should be made explicit, as should expectations of future land use change that would require additional changes to stormwater management structures.
4) **Select a stormwater management strategy and develop an implementation plan.** Begin by assessing the efficiency of the existing stormwater system. The new strategy should be compatible with all disciplines and have potential to mitigate stormwater problems.

We have demonstrated that the combination 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, this research has produced a policy prescription for urban stormwater management that is, if not ideal in one discipline, at least sound in all disciplines.

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