Research in Urban Stormwater BMPs

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Abstract

The use of best management practices (BMPs) in an urban watershed can provide adequate degrees of treatment at a relatively low cost. BMPs can range from being management operations (such as street sweeping or reducing the amount of pesticides used on urban lawns) to structural treatment options (the four most common alternatives being detention/retention ponds, swales, filter/buffer strips and constructed wetlands). This paper focuses on structural BMPs and overviews the state of the knowledge, the unknowns, and research programs being undertaken by the U.S. Environmental Protection Agency and other key organizations to address the unknowns.

Keywords: Best management practice; BMP; model; design; aquatic stressors; cost; imperviousness; hydrology.

Introduction

For the past three decades, municipalities in the United States have successfully addressed pollution in the watershed by collecting and treating their wastewater. Currently, all municipalities provide secondary level treatment, and in some cases tertiary treatment, and industries provide best available/best practicable treatment. This has had great benefits. More rivers are meeting water quality standards, and the public health is being protected from waterborne disease. The challenge now facing us is to address pollution associated with stormwater runoff, or wet weather flow, since this is now the last major threat to water quality. An associated challenge is in sustainable communities, that urban areas can continue to flourish while maintaining the basic necessities to support themselves.

It is less costly to prevent the generation of runoff than to treat it. Today, many municipalities are looking at low cost best management practices (BMPs)that prevent runoff. The lowest cost BMPs, termed non-structural BMPs, include practices such as limiting pesticide use in agricultural areas or retaining rainwater on residential lots (currently termed "low impact development"). There are a set of higher cost BMPs, which involve building a structure of some

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kind to store stormwater until it can be bled into existing wastewater treatment facilities, that are also used. These can be more costly, especially in areas where land costs are high. The four most commonly used structural BMPs are detention/retention ponds, swales, filter/buffer strips and constructed wetlands; these are the focus of this paper and of the research currently underway at the Urban Watershed Management Branch of the US EPA Office of Research and Development.

In urban/suburban areas that are sewered, storage of WWFs is often used. Several cities use the option of storing flows in the large sewers throughout the metropolis. Modern approaches use computer technologies to track the storm, identify areas of high intensity, and adjust sluice gates/etc to store flows where the greatest capacity exists. These real-time control (RTC) methods have the advantage of using existing storage capacity rather than having to build separate facilities, and therefore are lower in overall cost.

For the past ten years, the Environmental Protection Agency (EPA) has been encouraging that water pollution controls be approached on a watershed basis. This is sometimes difficult due to municipal interests, but a watershed approach allows tradeoffs between point source treatment, pollution prevention, and optimal balances between the two. BMPs fit well within the watershed approach.

Current Concerns with BMP Performance

The overriding concern with structural BMPs is that you cannot link their installation to water quality improvements. In fact, receiving water quality often seems unchanged before and after the construction of the BMP. Two other major concerns are that we cannot tell what levels of pollutant removal can be associated with a particular BMP and that identical designs produce differing performance levels at different locations. Finally, there are few methodologies/models to tell water quality managers where to place the BMP in the watershed to get optimal water quality results.

Concerns about BMP performance leads us to a research program that addresses how the BMPs work, what they cost, how effective they are, and where to best place them in the watershed.

The five aquatic stressors of concern in the United States are nutrients, suspended solids and sediments (SSASs), pathogens, flow, and toxic chemicals. These same stressors have worldwide significance.

Current Concerns with BMP Design Guidance

There are several publications available that address BMP design. These publications are generally not well done and do not use basic hydrologic, hydraulic, and pollutant removal engineering approaches resulting in BMP facilities that are either not well designed or not well maintained. In addition, many practicing engineers for small municipalities do not incorporate water quality aspects of urban runoff, or small storm hydrology and its control into their stormwater control planning and design. As a result, many existing facilities do not perform properly and actually produce nuisance mudholes and standing water. BMP designs should address: (1) hydrologic criteria, such as continuous wet- and dry- weather infow, average storm characteristics, etc.; (2) hydraulic characteristics, such as flow velocities inside the pond or water retention times/ overflow rates in the pond, and (3) water treatment criteria, such as suspended solids (SS) removal, particle settling velocities, and nutrient absorption. Because of the increase of BMP usage and the current inadequate design guidance, there is a need for more complete guidance based on solid engineering principles.

Problem Statement

As a national assessment of urban runoff quality in the United States, EPA's Nationwide Urban Runoff Program (NURP) study[1] clearly showed that urban storm-water runoff was not clean or pure. Subsequent studies showed similar results.[11] The U.S. Geological Survey (USGS) further studied storm-water runoff,[111] again concluding that storm water carried a significant contaminant load. In short, urban storm-water runoff contains environmental contaminants at higher concentrations than found in the runoff from undeveloped areas.

Stream flow hydrology is significantly different in urban areas than in natural undeveloped areas. The major problem is imperviousness. Man-made impervious areas decrease rainwater infiltration and have a twofold effect on stream flow. First, because impervious areas quickly and efficiently transport rainwater away from an area, the stream flow hydrograph is sharpened and narrowed. Second, the decreased infiltration reduces available groundwater resulting in decreased base flow. Combined, these effects produce highly variable stream flow conditions, changes in stream power, and upsets to the established sediment equilibrium (forcing geomorphic alterations leading to stream incising and braiding). Unchecked urbanization increases runoff, decreases stream base flow, and destabilizes the streambed and bank. Booth and Reinelt,[1] studied forested watersheds of the Pacific Northwest and observed that when the 2-year post-development flow exceeded the 10-year pre-development flow in channels, the channels in the watersheds became unstable. This occured when the watershed imperviousness reached about 10%. Investigators from various humid U.S. regions support this observation, reporting both channel instability and an abrupt decline in indices of aquatic ecosystem integrity occurring at 10 to 20% watershed imperviousness.[11123] Other researchers,[4] directly measuring ecosystem indices, suggest the threshold values may be lower, perhaps as low as 5% imperviousness. Ongoing EPA-funded research suggests using a simple imperviousness threshold is an oversimplification. The connection between imperviousness and the distribution of rainfall within a watershed significantly affects the aggregated runoff.[5] Similarly, the local terrestrial characteristics (steepness, soil structure) and stream characteristics (slope, bed and bank geology, and vegetation) greatly influence the probable changes in fluvial geomorphology and resulting habitat alteration.[67]

Recognizing that increased runoff volume and increased contaminant concentration combine to generate an increased runoff load, it is not surprising the EPA's most recent release of the compiled States' biennial reports on water quality to Congress[8] showed the States collectively believe about 40% of assessed U.S. streams, lakes, and estuaries do not support the criteria for locally designated uses such as fishing and swimming. The commonly reported stressors include bacteria, nutrients, toxics (largely metals and pesticides), and silt. High stressor concentrations in storm-water runoff from agricultural and urban areas are a leading cause in the failures to meet designated use criteria. EPA analyzed the environmental effects of storm water[9] and urban hydrology,[10] concluding that the runoff from human-modified land areas can harm surface water resources, change flow patterns and hydrology, destroy habitat, and elevate pollutant concentrations.

Research Questions

The overall goal of EPA research is to develop techniques and approaches that allow community-based environmental planners to select cost-effective, watershed-wide solutions to restore and protect the receiving water quality from storm-water runoff contaminants on a watershed scale within a predictable time.

The basic research questions associated with BMP design and effectiveness are presented below.

Table: EPA-ORD Research Questions for Urban Stormwater BMPs

BMP Design/Costs	What is the best approach to selecting or eliminating from consideration the various BMP options?
	What are appropriate design requirements (e.g., removal of pollutants, quantity control, control of maximum discharge rates) of BMPs that will lead to achievement of management goals (e.g., protection of water quality, preservation of aquatic ecosystems)? What are the appropriate requirements of some stormwater control regulations (which determines BMP selection and sizing on the local level)?
	What design methods will result in BMPs that meet design requirements? How will design basis (hydraulic, hydrologic, particulate/dissolved fraction characteristics, water quality, stressors [or pollutant] reductions, etc.) influence BMP design and performance?
	How does cost influence design of BMPs? How does design influence construction and maintenance costs?
BMP Performance/ Effectiveness/ Placement in the Watershed	Does this BMP meet design performance requirements? What are the appropriate sampling methods (e.g., annual average vs. event-based measurement, concentration-based or influent loading-based removal for constituents, large vs. small storm quantity control, particulate/dissolved fraction characteristics, water quality, stressors [or pollutant] reductions,) for measuring BMP performance?

	Do BMPs continue to meet design performance requirements over time? Does maintenance impact BMP performance over time? What is the useful life of various BMPs?
	What are the ancillary benefits of various BMPs (e.g., aesthetic value, recreational space, multi-uses, wildlife habitat, irregation)?
	How do the performance of individual BMPs affect the watershed as a whole? Does BMP placement in the watershed matter?
	What are the costs of maintaining BMPs? How should BMP costs be evaluated?
BMP User-Assistance Tools	How can available models for design and analysis of BMPs (including computer simulations, design equations/models, and costing equations/models) be improved?
	Are new models needed for BMP design and analyses? What characteristics of a model are important for BMP design and analysis?
	Are current models adequate to apply for a system- or watershed-wide approach?
	How well do available models represent actual BMPs or watersheds with BMPs?

Source: November 2000. Internal Draft. Urban Stormwater Best Management Practices: a WWF Research Focus Area. by Richard Koustas, Environmental Engineer. USEPA, Edison, NJ.

Research Approach

Current watershed research in the branch is focusing on better definition of the BMP influent. Like any unit operation, the influent characteristic will strongly affect the performance. The collected data will simultaneously help to define the range that we must evaluate in the BMP model development. Despite national monitoring efforts, surprisingly few useful data are available to predict storm-water constituent concentrations. These monitoring efforts have produced a wealth of data identifying the constituents, but these data were largely collected for other purposes (e.g., defining if the water body meets the designated use) and generally do not fit our needs. EPA has begun research efforts to evaluate the expected storm-water concentrations using a nested hierarchical design to examine differences caused by land use and season. Follow-on work will establish if these results are regionally specific, and the extent to which they can be extrapolated to other regions and mixed land uses. Concurrent efforts are attempting to isolate the portion of the load that can be attributed to atmospheric deposition.

An early outcome of the ongoing problem-definition effort in describing the BMP influent is the clear evidence that existing permit compliance storm-water sampling techniques will be inadequate for research needs. Several issues, many mechanical, have developed during the EPA storm-water sampling. A simple example is the difficulty of measuring and sampling the low storm-water runoff flow rates, typical early and late in most storms and low-intensity rain events, in medium to large-diameter pipes.

The second stage of the research will occur at several physical scales. In some cases, the removal process is already reasonably well understood and requires only limited study (e.g., infiltration). In other cases, it is less clear that existing models can adequately describe the process in the needed techniques (e.g., temporal and spatial changes in infiltration rates with the accumulation of settled material in detention basins). Similarly, a physical process can apply to several different BMPs (e.g., chemical stressor partitioning between sediment and aqueous phases). Sometimes a series of experiments will be required. The coliform decay process is often described by a series of first-order relationships with time[11] based on light, temperature, dissolved oxygen, pH, and mechanical processes (sorption, filtration, and sedimentation). The EPA research will evaluate the first-order kinetic assumptions and estimate the kinetic constants generating a simplified combined decay model. Before beginning this work, we will measure the range of temperatures to be expected and the light levels, particularly the UV-B components from 280 to 320 nm as extinction coefficients with turbidity in local ponds. These data will help enable us to span the needed ranges in controlled-condition research.

Bench- or beaker-scale experiments should be sufficient to model many processes that occur in commonly used BMP. For example, this scale is adequate to augment the settling velocity data presented by Driscoll, et al.,[12] or to evaluate the equilibrium contaminant-sediment partitioning relationships. Other evaluations require larger-scale experiments. Relating the BMP residence time and dead zone formation,[13] a controlling feature in many processes (primarily in wetlands, detention, and retention ponds), to geometric shape and inlet position, to link hydraulic efficiency with clean sediment removal as suspended solids reductions using tracer techniques shows promise[14][15] but must be evaluated at physical scales greater than bench-top evaluations allow. This effort can build from the existing research.[16] Evaluating microbial processes in the rhizosphere similarly requires larger-scale experiments and longer experimental times. Generally, these require a test chamber that covers several square meters and will be completed in the on-site greenhouse. Finally, we require full-scale evaluations to properly consider previously controlled random events (e.g., wind) and evaluate the predictive ability of developed models. These evaluations will require measurements at constructed BMPs. Although we cannot identify a definitive list of the most commonly installed urban BMPs, patterns emerge when reviewing state regulations. The key selections appear to be retention and detention basins, constructed wetlands (including bioretention techniques such as rain gardens), infiltration techniques, and vegetated swales. WMRT storm-water research will begin with these BMPs, recognizing that we can often extrapolate the information to other BMPs. The increased hydraulic roughness measured in a swale will have obvious application to stream corridor buffer strips, for example. As additional information becomes available, the targeted BMPs may change.

Throughout the research, the pragmatic part of BMP construction must be a consideration, including retrofit concerns. Specifying grasses for swales, for example, must consider drought tolerance, mowing height and frequency, and the ability to slow overland flow. The water volume that must be controlled, the balance between extended holding to allow for settling and mosquito control, or BMP performance in low-volume rain events and flood events are other pragmatic concerns. New York specifies water quality management BMPs based on complete control of a ½-inch rain event,[17] the same volume Florida requires for drainage areas less than 100 acres.[18] Mosquito control, for example, suggests that the upper limit of extended detention must be less than the time required for mosquito development although longer detention would increase settling. Michigan recommends 48-hour holding and suggests less than 72-hours.[19] California recommends[20] 40-hour detention to capture fine clay particles while simultaneously cautioning against the associated short draw-down period linked with smaller storms having the same outlet configuration.

The broader question, restoration or protection of water quality, is much more complicated than the already substantial question of BMP performance. If we treated the total storm-water discharge to an impaired receiving water to pristine standards, it is unlikely that the receiving water would immediately recover. A time lag while residual contaminants leach from the sediment and habitat recovers, allowing benthic and higher order populations to return is part of the process. Community watershed planners need to have a realistic understanding of the time required for this recovery. Storm water will increasingly become part of the load considered in developing TMDLs. In-receiving water processes drive the recovery and attenuation process. To understand these issues, develop BMP effluent guidance, and define the needed predictive accuracy will require an ORD-wide effort.

References

1. U.S. EPA. (1983). Results of the Nationwide Urban Runoff Program, Volume 1 – Final Report.
2. Makepeace, D. K., D. W. Smith, and S. J. Stanley. (1995). Critical Reviews in Environmental Science and Technology. 25(2):93-139.
3. Marsalek, J. (1990). Evaluation of Pollutant Loads from Urban Nonpoint Sources, Water Science Technology. 22(10/11):23-30.
4. Driver, N. E., M. H. Mustard, R. B. Rhinesmith, and R. F. Middleburg. (1985). U.S. Geological Survey Urban Storm Water Data Base for 22 Metropolitan Areas Throughout the United States. Report 85-337. USGS: Lakewood, CO.
5. Mustard, M. H., N. E. Driver, J. Chyr, and B. G. Hansen. (1987). U.S. Geological Survey Urban Stormwater Data Base of Constituent Storm Loads: Characteristics of Rainfall, Runoff, and Antecedent Conditions;and Basin Characteristics. USGS Open File Report 987-4036. USGS: Denver, CO.
6. Driver, N. E. and G. D. Tasker. (1990). Techniques for Estimating Storm-Runoff Loads, Volumes, and Selected Constituent Concentrations in Urban Watersheds in the United States. USGS Water Supply Paper 2363. USGS: Denver, CO.
7. Booth, D. B., and L. E. Reinelt. (1993). "Consequences of urbanization on aquatic systems – measured effects, degradation thresholds, and corrective strategies." In Proceedings of Watershed '93. EPA 840-R-94-002. 545-550.
8. Morisawa, M., and E. LaFlure. (1979). "Hydraulic geometry, stream equilibrium and urbanization." In Adjustments of the Fluvial System. (Rhodes, D. D., and G. P. Williams, Eds.). Kendall-Hunt: Dubuque, IA. 333-350.
9. Booth, D. B. (1990). "Stream channel incision following drainage basin urbanization." Water Resources Bulletin. 26(3):407-417.
10. Booth, D. B. (1991). "Urbanization and the natural drainage system-Impacts, solutions and prognoses." Northwest Environmental Journal. 7(1):93-118.
11. Booth, D. B., and L. E. Reinelt. (1993). "Consequences of urbanization on aquatic systems – measured effects, degradation thresholds, and corrective strategies." In Proceedings of Watershed '93. EPA 840-R-94-002. 545-550.
12. Schueler, T. (1994). "The importance of imperviousness." Watershed Protection Techniques. 1(3):100-111.
13. May, C. W., E. B. Welch, R. R., Horner, J. R. Karr, and B. W. May. (1997). Quality Indices for Urbanization Effects in Puget Sound Lowland Streams. Technical Report 154. University of Washington, Water Resources Series.
14. Bledsoe, B. and C. C. Watson (in press) Effects of Urbanization on Channel Instability. Journal of the American Water Research Association.
15. Bledsoe, B. and C.C. Watson (2000). Logistic analysis of channel pattern thresholds:

meandering, braiding, and incising. Gormorphology 978

16. Bledose, B (2000) Stream Erosion Potential Associated with Differing Stormwater Management Strategies.
17. U.S. EPA. (2000). Water Quality Conditions in the United States: A Profile from the 1998 National Water Quality Inventory Report to Congress. Office of Water: Washington, D.C. http://www.epa.gov/305b/98report/98summary.html
18. U.S. EPA. (1992). Environmental Impacts of Storm Water Discharges: A National Profile. EPA 841-R-92-001. USEPA: Washington, DC.
19. U.S. EPA. (1997). Urbanization and Streams: Studies of Hydrologic Impacts: A National Profile. EPA 841-R-92-001. USEPA: Washington, DC.
20. Khatiwada, N. R., and C. Polprasert. (1999). Kinetics of Fecal Coliform Removal in Constructed Wetlands. IAWQ, Elsevier Science Ltd.
21. Driscoll, E. D., D. Di Toro, D. Gaboury, and P. Shelley. (1986). Methodology for Analysis of Detention Basins for the Control of Urban Runoff Quality. EPA 440/5-87-01. U.S. EPA: Washington, DC.
22. Werner, T. M. and R. H. Kadlec. (2000). "Stochastic simulation of partially-mixed, event-driven treatment wetlands." In Ecological Engineering. (14) 253-267.
23. Walker, D.J. (1998). "Modeling residence time in stormwater ponds." In Ecological Engineering. (10) 247-262.
24. Rash, J. K., and S. K. Liehr. (1999). "Flow pattern analysis of constructed wetlands treating landfill leachate." Water Science Technology. (40) 3, 309-315.
25. Werner, T. M., and R. H. Kedlec. (2000). "Stochastic simulations of partially-mixed, event-driven treatment wetlands." In Ecological Engineering. (14) 253-267.
26. NYSDEC. General Permit for Construction Activities– Stormwater Management Guideline for New Development (TOGS 5.1.10), Appendix D.
27. Florida DEP. (1995). Regulation of Stormwater Discharge. 62-65.
28. Michigan Department of Environmental Quality. (1999). Stormwater Management Guidebook.
29. California. (1993). Municipal Handbook.

Watershed Management Strategy in Taiwan

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Introduction

With the rapid urbanization and intensive industrialization in the past decades, the environmental quality in Taiwan has been greatly degraded in many aspects, such as water quality. Given the fact that river quality is a key element for national health as well as a pivotal indicator of living quality, it is an extremely important subject to strengthen the watershed management strategy as to resolve pollution problems and maintain sustainable aquatic environment.

Pollution Conditions

According to the monitoring data, it is indicated that the river quality reached the worst condition in 1996, during which period the percentage of severely polluted river sections was once as high as 14.9% as opposed to 12% for the time being. Although the severely polluted river section has been lessened in the past years, the improvement appears to be slow, especially for those urban rivers with dense population. The downstream areas of nearly 10 rivers in the southwest regions in Taiwan have been classified as "severely-polluted", which has imposed great threats on the living quality and drinking water safety for the local residents.

As for the water quality of reservoirs, monitoring data of 20 major reservoirs indicated that 15 reservoirs were eutrophicated in 1997, as opposed to 7 in 2000. The quality of many reservoirs has been improved in the past years, whereas some still remain polluted.

In brief, it is obvious that the water quality of aquatic systems in Taiwan has been improved as long-term pollution control projects being implemented in the past years. However, in order to meet the increasing demands on water quality from the general public, the Environmental Protection Administration in Taiwan (TEPA) is determined to carry out various projects to maintain the natural balance of the ecosystem and the sustainable development of the environment.

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