Determining Urban Storm Water BMP Effectiveness

By Eric W. Strecker,[1] Member, ASCE, Marcus M. Quigley,[2] Associate Member, ASCE, Ben R. Urbonas,[3] Jonathan E. Jones,[4] Members, ASCE, and Jane K. Clary[5]

Abstract: The goal of this U.S. EPA-funded cooperative research program with the ASCE is to develop a more useful set of data on the effectiveness of storm water best management practices (BMPs) used to reduce pollutant discharges from urban development. BMP monitoring data gathered at a particular site should not only be useful for that site, but also need to be useful for comparing the effectiveness of similar and different types of BMPs at other locations. Most BMP effectiveness studies in the past have provided data that is difficult, if not impossible, to use in comparing BMP design effectiveness and in the selection among individual BMP types to meet desired goals. This paper describes some of the comparability problems encountered between different BMP effectiveness studies. Also discussed are considerations that affect data transferability, such as methods used for determining efficiency and statistical significance. It outlines the efforts used to establish and analyze the currently available data and proposes protocols for future analyses, when more studies that have data are available. Finally, it recommends that effluent quality appears to be a much more robust measure of BMP efficiency than the currently used "percent removal" metrics.

INTRODUCTION

Many studies have been completed that have assessed the ability of storm water treatment best management practices (BMPs), e.g., wet ponds, grass swales, storm water wetlands, sand filters, dry detention, etc., to reduce pollutant concentrations and loadings in storm water system discharges. However, in attempting to review and summarize the information gathered from these individual BMP evaluations, it is apparent that inconsistent study methods, lack of associated design information, and reporting protocols make wide-scale assessments difficult, if not impossible. For example, individual studies often included the analysis of different constituents and utilized different methods for data collection and analysis, as well as reported varying degrees of information of BMP design and inflow characteristics. The differences in monitoring strategies and data evaluation alone contribute significantly to the range of BMP "effectiveness" that has been reported. These differences make combining these individual studies to assess what design factors may have contributed to the variation in effectiveness almost impossible (Strecker et al. 1992). Urbonas (1994, 1995) and Strecker (1994) summarized information that should be collected and reported regarding the physical, climatic, and geological parameters that likely affect the effectiveness and performance of a BMP, and considerations regarding sampling and analysis methods.

EFFICIENCY, EFFECTIVENESS, AND PERFORMANCE

In order to better clarify the terminology used to describe the level of treatment achieved and how well a device, system, or practice meets its goals, the following definitions of terms used in the literature are provided:

- Best management practice (BMP)—A device, practice, or method for removing, reducing, retarding, or preventing targeted storm water runoff quantity, constituents, pollutants, and contaminants from reaching receiving waters.
- BMP system—A BMP system includes the BMP and any related bypass or overflow. For example, the efficiency (see below) can be determined for an off-line retention (wet) pond either by itself (as a BMP) or for the BMP system (BMP including bypass flows).
- Performance—A measure of how well a BMP meets its goals for storm water that flows through, or is processed by it.
- Effectiveness—A measure of how well a BMP system meets its goals for all storm water flows reaching the BMP site, including flow bypasses.
- Efficiency—A measure of how well a BMP or BMP system removes pollutants.

Note that performance and effectiveness can be expressed in terms of pollutant removal or effluent quality and/or how well the increased flows due to urbanization are mitigated.

The ASCE project team has worked with the available data to determine efficiency of BMPs and BMP systems. In addition, effectiveness and performance have been evaluated, acknowledging the limitations of existing information about the goals of specific BMP monitoring projects. Quantification of efficiency only evaluates a portion of the overall performance or effectiveness of a BMP or BMP system. A list of typical goals and the current ability of the ASCE/EPA project to help evaluate them is summarized in Table 1.

PROBLEM: BMP MONITORING STUDY INCONSISTENCIES

Studies of BMP performance and effectiveness have utilized significantly different

- Sample collection techniques (e.g., from sample collection types—grab, composite, etc., flow measurement techniques, to how the sample was composited, etc.)
- Water quality constituents, analyses including chemical species, methods (detection limits), form (e.g., dissolved versus total versus total recoverable, etc.), and treatment potential
- Data reporting on tributary watershed and BMP design characteristics (e.g., tributary area or watershed attributes such as percent impervious, land use categories, rainfall statistics, etc.)

[1]Assoc., GeoSyntec Consultants, 3021 SW Dickinson St., Portland, OR 97219.

[2]Asst. Proj. Engr., GeoSyntec Consultants, 532 Great Rd., Acton, MA 01720.

[3]Chief, Master Planning and South Platte River Programs, Urban Drain. and Flood Control Dist., 2480 W. 26th Ave., Ste. 156-B, Denver, CO 80211.

[4]Executive Vice President, Wright Water Engrs., Inc., 2490 W. 26th Ave., Ste. 100A, Denver, CO 80211.

[5]Regulation Spec., Wright Water Engrs., Inc., 2490 W. 26th Ave., Ste. 100A, Denver, CO 80211.

Note. Discussion open until November 1, 2001. To extend the closing date one month, a written request must be filed with the ASCE Manager of Journals. The manuscript for this paper was submitted for review and possible publication on November 20, 2000; revised January 5, 2001. This paper is part of the *Journal of Water Resources Planning and Management*, Vol. 127, No. 3, May/June, 2001. ©ASCE, ISSN 0733-9496/01/0003-0144–0149/$8.00 + $.50 per page. Paper No. 22348.

TABLE 1. Goals of Storm Water BMPs and Ability of National Storm Water BMP Database to Provide Information Useful for Assessing Performance and Effectiveness

Category	Goals	Ability to evaluate performance and effectiveness
Hydraulics	Improve flow characteristics upstream and/or downstream of BMP	yes[c]
Hydrology	Flood mitigation, improve runoff characteristics (peak shaving)	yes[a]
Water quality (efficiency)	Reduce downstream pollutant loads and concentrations of pollutants	yes[a]
	Improve/minimize downstream temperature impact	yes[a]
	Removal of litter and debris	yes[b]
Toxicity	Reduce acute toxicity of runoff	yes[b]
	Reduce chronic toxicity of runoff	yes[b]
Regulatory	Compliance with National Pollution Discharge Elimination System permit	no
	Meet local, state, or federal water quality criteria	yes[a]
Implementation feasibility	For nonstructural BMPs, ability to function within management and oversight structure	no
Cost	Capital, operation, and maintenance costs	yes[b]
Aesthetic	Improve appearance of site	uo
Maintenance	Operate within maintenance, and repair schedule and requirements	yes[b]
	Ability of system to be retrofit, modified, or expanded	yes[a]
Longevity	Long-term functionality	yes[b]
Resources	Improve downstream aquatic environment/erosion control	yes[c]
	Improve wildlife habitat	no
	Multiple use functionality	no
Safety, risk, and liability	Function without significant risk or liability	no
	Ability to function with minimal environmental risk downstream	yes[c]
Public perception	Information is available to clarify public understanding of runoff quality, quantity, and impacts on receiving waters	yes[a]

[a]Can be evaluated using ASCE/EPA database as information source.
[b]Will be able to be evaluated using database as primary source of information after enough studies have been submitted.
[c]Can be evaluated using database primary source of information combined with secondary source of comparative data.

- Efficiency estimation techniques (there are at least four common techniques that have been utilized to assess efficiency that can cause significant differences in pollutant removal reporting, with the same set of data), and potential alternatives to reporting just concentration/loading reductions
- Statistical validation of results (typical lack of statistical tests to determine if the reported removal efficiency can in fact be shown to be statistically different than zero, e.g., reject the hypotheses that they are zero.)

Monitoring strategies that could be employed to monitor BMP effectiveness include

- New BMP installation with new development: Input/output (e.g., monitor new detention pond of newly developed watershed and evaluate inflow concentrations/loads versus outflows) or conduct a "control" watershed comparison.
- Retrofit of existing or new single BMP within existing watershed: Input/output and/or before/after (e.g., retrofit of an existing flood control basin for water quality)
- Watershed-wide new structural or non-structural BMP: "Control" watershed comparison (e.g., new BMP catch basins in developing area)
- Watershed-wide structural retrofit or application of non-structural BMP: Before/after and/or "control" watershed comparison (e.g., catch basin retrofit on watershed scale)

Input/output monitoring is the typical approach utilized. However, control watersheds and before/after approaches have also been employed. For these before-and-after studies, all of the other potential factors that could be contributing to differences in effectiveness must be identified and accounted for. On the other hand, it is beneficial to be able to show that a watershed-wide difference is or is not being detected with BMP implementation. These differences in monitoring approach certainly affect the ability to compare studies.

The ASCE project team has developed a set of protocols and a database on BMP effectiveness studies with the purpose of improving the consistency of BMP monitoring information. The project includes

- Developing protocols for BMP monitoring and reporting
- Developing a database on BMP effectiveness studies (details of development available at (http://www.bmpdatabase.org))
- Conducting an evaluation of existing information to assist the EPA in providing guidance to the regulated community

The long-term goals of the project are to expand and improve the BMP effectiveness information base to provide a source of useful effectiveness information and to ultimately help advance BMP design.

The database specifies a chosen set of reporting information, but does not guide one on how to develop such information. For example, it does not specify in detail what a flow-weighted composite sample is and how it should be collected. The next step beyond the EPA protocols and database effort will be a guidance document on monitoring data collection strategies and techniques to improve their consistency and ultimate transferability. The reader is referred to Urbonas (1994, 1995) and Strecker (1994) for a more in-depth discussion of recommended parameters for assessing BMP effectiveness including appropriate watershed and BMP design parameters, data-reporting protocols, quality assurance/quality control issues, and techniques for making comparisons to water utility criteria. The database product developed as part of the cooperative agreement provides a tool for implementing the recommended protocols. An overview of the data requirements for the database is given in Table 2.

The primary goals of the ASCE/EPA database development process were to facilitate efficient data entry, provide useful queries of stored data, and output information in a comprehensive and applicable manner through a user-friendly interface. The database was written in Microsoft Access incorporating Access' relational database engine and features, and the Visual Basic for Applications programming language for cus-

TABLE 2. Parameters to Report with Water Quality Data for Various BMPs

Parameter type	Parameter	Retention (wet) pond	Extended detention (dry) basin	Wetland pond basin	Grass swale/ wetland channel	Sand/ leaf compost filter	Oil and sand trap/hydro-dynamic device	Infiltration and percolation
Tributary watershed	Tributary watershed area, average slope, average runoff coefficient, length, soil types, vegetation types	•	•	•	•	•	•	•
	Total tributary watershed impervious percentage and percent hydraulically connected	•	•	•	•	•	•	•
	Details about gutter, sewer, swale, ditches, parking, and roads in watershed	•	•	•	•	•	•	•
	Land use types (residential, commercial, industrial, open) and acreage	•	•	•	•	•	•	•
General hydrology	Date and start/stop times for monitored storms	•	•	•	•	•	•	•
	Runoff volumes for monitored storms	•	•	•	•	•	•	•
	Peak 1-h intensity	•	•	•	•	•	•	•
	Design storm/flood recurrence intervals and magnitude	•	•	•	•	•	•	•
	Peak flow rate, depth, and Manning's roughness coefficient for 2-year storm				•			
	Depth to seasonal high ground-water/ impermeable layer		•		•			•
	Saturated hydraulic conductivity, infiltration rate, soil group				•			•
	Averge annual values for number of storms, precipitation, snowfall, minimum/maximum temperature	•	•	•	•	•	•	•
Water	Alkalinity, hardness, and pH for each monitored storm	•	•	•	•	•	•	•
	Water temperature	•	•	•	•	•	•	•
	Sediment settling velocity distribution, when available	•	•	•	•	•	•	•
	Facility on- or off-line?	•	•	•	•	•	•	•
	Bypassed flows during events	•	•	•	•	•	•	•
General facility	Type and frequency of maintenance	•	•	•	•	•	•	•
	Types and location of monitoring instruments	•	•	•	•	•	•	•
	Inlet and outlet dimensions, details, and number	•	•	•	•	•	•	•
	Media or granular material depth, type, storage volume, and porosity					•		•
Wet pool	Volume of permanent pool	•		•		•	•	
	Length of permanent pool	•		•		•	•	
	Permanent pool surface area	•		•		•	•	
	Littoral zone surface area	•						
	Solar radiation, days of sunshine, wind speed, and pan evaporation from weather station	•	•	•	•			•
Detention volume	Detention (or surcharge) and flood control volumes	•	•	•		•	•	•
	Detention basin's surface area and length	•	•	•		•	•	•
	Brimful and half-brimful emptying time	•	•	•		•	•	•
	Bottom stage/infiltrating surface area and type			•	•			•
Pretreatment	Forebay volume and surface area	•	•	•		•	•	•
	Relationship to other BMPs upstream	•	•	•	•	•	•	•
Wetland plant	Wetland/swale type, surface area, length, and side slope (bottom width for swales and channels)			•	•			
	Percent of wetland surface between 0 and 12 in., 12–24 in., and 24–48 in.			•	•			
	Plant species and age of facility	•	•	•	•			

tomization of the functional aspects of the front end. The complete package is currently being distributed on CD-ROM as an Access run-time version and the search engine module of the database is available over the Internet (www.bmpdatabase.org).

ESTIMATION OF BMP POLLUTANT REMOVAL EFFICIENCY AND EFFECTIVENESS

BMP pollutant-removal efficiency and effectiveness estimations are not straightforward and a wide variety of methods have been employed. Martin and Smoot (1986) discussed three types of methods to compute efficiencies, including an efficiency ratio, sum of loads, and regression of loads. Many researchers have utilized an efficiency measure based upon storm pollutant loads in and out of the BMP on a storm-by-storm basis. This weights the effectiveness considering that all storms are "equal" in computing the average removal. However, it is readily apparent that all storm volumes and their associated concentrations are not equal. For example, one factor that complicates the estimation of the effectiveness is that for wet ponds and wetlands (and other BMPs where there is a permanent pool), comparing effectiveness on a storm-by-storm basis neglects the fact that the outflow for a particular event being measured may have little or no relationship to the inflow for that same event. Based upon a national characterization of rainfall (Driscoll et al. 1989), if a basin were sized to have a permanent pool equal to the average storm volume from the watershed, about 60–70% of the storms would be less than this volume. Therefore, due to many storms not being large enough to displace the permanent pool volume, storm-by-storm comparisons are probably not valid. It is more appropriate to utilize statistical characterizations of the inflow and outflow concentrations to evaluate effectiveness or, if enough samples are collected (i.e., almost all storms monitored), to utilize total loads in and out of the BMP.

Three methods are compared for an example site in Table 3, including percent removal by storm, a statistical characterization of inflow and outflow concentration, and a simple comparison of total loads in and out. The removals estimated differ by up to 18 percentage points. In this record, there are several storm events where inflow concentrations were relatively low and therefore the system was not "efficient"; however, effluent quality is not appreciably degraded for these events.

Based upon these factors, it is recommended that a statistical characterization of inflows versus outflows be utilized to determine if the BMP has had a measurable effect on water quality. This is especially recommended for BMPs with significant storage. Use of the log transformation of event mean concentrations (EMCs) is also recommended. Urban storm water runoff EMCs for many constituents have been shown to be well fit by a lognormal distribution [USEPA 1983; Harremoes 1988; Van Buren et al. 1997], and justified theoretically by Chow (1954). The assumption that both influent and effluent EMCs are well fit by the lognormal distribution was explored for the initial database data set. The lognormal assumption was found to be a valid approximation of the distribution of the water quality data examined. In all cases, tests of the applicability of a log transformation should be made to support the transformation of data when sufficient data are available. Standard descriptive statistics, hourglass box-and-whisker plots, and normal probability plots of the transformed data, for both the inflow and outflow, should be employed to clearly demonstrate not only the differences in the mean EMCs, but also the effectiveness of the BMP throughout the range of influent and effluent EMCs. The plots that are recommended were chosen based on their ability to quickly and accurately depict BMP efficiency and convey information that is statistically relevant, e.g., central tendency, confidence in mean values, and variability. In addition, this approach provides the ability to determine whether any apparent differences in inflow and outflow EMC populations are statistically different than zero. The hourglass box-and-whisker plot is equivalent to a nonparametric analysis of variance. Normal probability plots containing two sample data sets can quickly indicate median concentrations, differences in median concentrations, how well each data set is approximated by the lognormal distribution, and variability. If enough data on storms are collected (e.g., continuous samples over an extended period including base flow measurements where significant), an analysis of the total loads in and out may also be an acceptable method. A graphical look at the distribution of contributing storms will often provide insight into the applicability of the method (e.g., do a small number of large storms dominate the resulting effectiveness value?).

The variability in runoff concentrations from event to event is large. If one is attempting to statistically characterize a BMP influent (and effluent) concentration, the more data, the better the characterization. A rigorous statistical approach should be applied in selecting the number of samples to be collected to help assure detection of a given level of change in the EMC.

As an example of the number of samples required to detect a "true" difference, Table 4 presents an analysis of two Portland, Ore., monitoring stations (Woodward-Clyde 1993) where 10 flow-weighted composite samples were collected. The Fanno Creek station is a large (about 485 ha or 1,200 acres) residential catchment that is in an open channel, while the M1 station is a smaller (about 40 ha or 100 acres) mixed land use station that is contained in a pipe. An analysis of variance-based test was utilized with the existing data to estimate how many samples are estimated to be needed to detect a 5, 20, and 50% change in the mean concentration at the station. The test was performed considering an 80% probability that the difference will be found to be significant, with a 5% level of significance (Sokal and Rohlf 1969). This analysis did not consider potential seasonal effects on the collection of data as a factor. Even so, quite a large number of samples would be required to detect a 5–20% difference in concentrations. In many locations, given that there may be only 10–20 storm events per year that are large enough to monitor, it would take a number of years of sampling all storm events to be able to detect small differences. There are numerous examples in the literature where small differences (1–5% positive and negative) have been reported based upon much fewer samples than indicated by this analysis. This highlights the need to be rig-

TABLE 3. Comparison of BMP Pollutant Removal Efficiency Estimation Techniques

Storm	Volume of flow (ft^3) [m^3(ft^3)] inflow = outflow	Statistical Characterization of Inflow and Outlfow Concentrations [mg/l]	In	Out	Inflow and Ouflow Pollutant Loads [kg(lb_m)] In	Out	Percent removal by storm
1	12,609 (445,300)		352	24	4,436 (9,780)	304 (670)	93
2	18,400 (649,800)		30	25	553 (1,220)	458 (1,010)	17
3	12,915 (456,100)		99	83	1,279 (2,820)	1,070 (2,360)	16
4	9,857 (348,111)		433	141	4,268 (9,410)	1,388 (3,060)	67
5	20,678 (730,261)		115	63	2,376 (5,240)	1,302 (2,870)	45
		Median	139	65	Total In	Total Out	
		Coefficient of variation	1.48	0.86	12,914 (28,470)	4,522 (9,970)	
		Mean	249	85			
Pollutant Removal Estimation			66%		65%		48%

Note: 1 lb_m = 2.2046 kg and 1 ft^3 = 0.028317 m^3.

TABLE 4. Analysis of Sample Sizes Needed to Statistically Detect Changes in Mean Pollutant Concentrations from Two Stations in Portland, Ore.

Monitoring site	Parameter	Number of Samples Required to Detect Indicated Percent Reduction in Site Mean Concentration[a] 5%	20%	50%
R1—Fanno Creek residential	Total suspended solids	202	14	4
	Copper	442	29	6
	Phosphorus	244	16	4
M1—NE 122nd Columbia Slough mixed use	Total suspended solids	61	5	2
	Copper	226	15	4
	Phosphorus	105	8	3

[a]80% certain of detecting indicated percent reduction in mean of EMCs.

orous with regard to statistical testing of reported effectiveness estimates. To detect larger changes, the number of samples estimated to be required becomes reasonable.

Another approach that this study has evaluated is the use of effluent data to measure the influence of certain design criteria on BMP efficiency. It has been suggested by some researchers that BMPs may be able to only treat to a given concentration; therefore, if relatively clean water is entering a BMP, performance based upon removal efficiency may not fully characterize whether a BMP is well designed. An example of this is based upon Ruston et al. (1997). The storm water management facility (pond/wetland) was located downstream of the Southwest Florida Water Management District service office and parking lot in Tampa. The drainage basin was 2.6 ha or 6.5 acres with about 30% of the watershed covered by rooftops and asphalt parking lots, 6% by a crushed limestone storage compound, and the remaining 64% was a grassed storage area. The pond/wetland was modified twice after initial construction, and therefore, there are three periods of monitoring data for three different designs. The researchers reported that the first system had an average retention time of 2 days, the second 5 days, and the third 15 days. The second design increased volume and reduced vegetation (35% vegetated), while the third utilized a significantly larger pool in combination with replanting of the littoral zone.

Fig. 1 shows the input and output median concentrations in a log base-10 scale as well as the 95% confidence limits of the median. The study reported that efficiency of the pond (measured as percent removal) decreased after the first modification. The data indicate that the average inflow concentrations were much lower during the second period, while the outflow concentrations were about the same (less, but not statistically different than the first design). It appears that with the original and first modified designs that the effluent concentrations were not decreased significantly. However, one could not say that the BMP was significantly less effective from an effluent quality standpoint. The last design appears to have lowered the effluent concentration, but the major difference in efficiency came from the significantly higher inflow concentrations during the third sampling period. This example points out the need to carefully think about whether pollutant removal efficiency, particularly when it is expressed as a percent removal, is an accurate representation of how well a BMP does or does not perform.

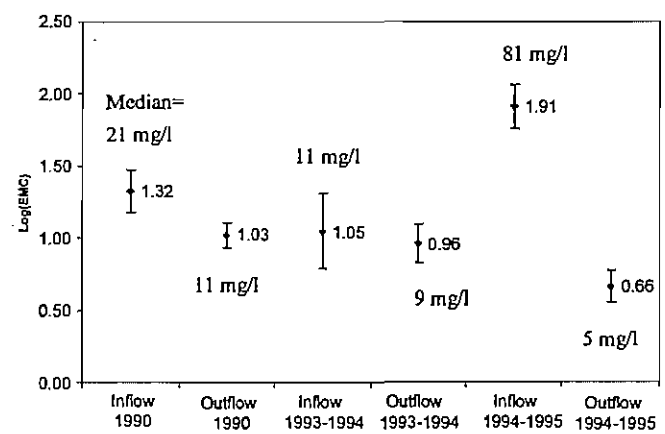

FIG. 1. Inflow and Outflow Log Mean TSS Concentrations (mg/L) and 95% Confidence Limits for Different Designs of Wet Pond Located at SWFWMD Service Office in Tampa, Fla.

EVALUATION OF EXISTING DATABASE

Available and "Missing" Design and Monitoring Study Information

As described above, the protocols for the database outline a detailed set of information describing the design of the BMP in addition to water quality, quantity, and rainfall data. In the studies that are part of the initial release of the database, specific effectiveness-related design information was often missing. Parameters missing from one or more studies included transferable measures of storage volume, surcharge detention volumes, stage/storage data, watershed characteristics, and land use information. For wetlands, the situation was particularly acute, presumably as a result of the lack of existing protocols for reporting wetland design criteria. In addition to missing information, translation of available design parameters was often difficult. For example, a number of dry pond studies provided average detention times in lieu of brim-full or half-brim-full emptying times. In many of these cases, without more detailed information, a translation between these two measures of storage volume and outlet design could not be made. As most of the studies were completed prior to development of the reporting partials under this research program it was expected that this data would be incomplete.

Despite the lack of some parameters that may be important when relating design of BMPs to efficiency, a significant amount of information was available for analysis of the initial data set. The information that was available for analysis almost universally included

- Flow volumes for monitored storm at the inflow(s) and outflow(s)
- Water quality detention volume (dry ponds) and permanent pool volume (wet ponds)
- Ratio of mean monitored storm volume to permanent pool volume or water quality detention volume for wet and dry ponds
- Comprehensive climatic data from synoptic analysis of rainfall
- Detailed water quality data

Analysis Methodologies

BMP water quality data stored in the database were analyzed in two different ways—first individually—then in groups by BMP type. The individual analysis had two components: a rigorous statistical analysis and a corresponding graphical analysis. The individual analysis was conducted for each parameter for each BMP. The statistical analysis included

- Descriptive statistics of the influent and effluent EMCs both log transformed and in arithmetic space, including determination of the mean, median, standard deviation, coefficient of variation, and upper and lower confidence limits on the mean and median
- Percent removals using the efficiency ratio method based on estimates of the arithmetic mean using log-transformed influent and effluent EMCs

- Parametric and nonparametric analyses of variance including the ANOVA, Mann-Whitney, and Kolmogorov-Smirnov tests
- Percentiles for influent and effluent EMCs
- Percent difference in percentiles (10th and 90th) at the influent and effluent
- Estimates of the minimum and maximum possible removal efficiencies based on the confidence interval about the mean EMC

The graphical analysis included

- Time series scatter plots of influent and effluent event mean concentration
- Graphical nonparametric analysis of variance utilizing box-and-whisker plots showing influent and effluent EMCs on the same plot
- Normal probability plots of log transformed water quality data showing overlays of the influent and effluent EMCs

The BMP group analysis looked at the results for all BMPs of a particular type, e.g., wetland basins, or retention ponds. The group analysis was primarily graphical and included the following:

- Box-and-whisker plots of influent and effluent EMCs for each water quality constituent showing all BMPs of that type on one plot
- Normal probability plots showing mean influent and effluent concentrations by BMP type
- Box-and-whisker plots showing the distribution of effluent quality for a variety of BMP types on one plot
- Scatter plots showing measures of efficiency (e.g., effluent quality or percent removal) as a function of a design parameter (e.g., the ratio between mean runoff volume and storage volume)

These statistical and graphical analyses are available in the Web site.

Initial Results from Analysis of Existing Database

The quantity of data initially stored in the database limits the number of BMP types that could be examined in detail; however, a number of conclusions were reached as a result of the analysis of this data base including

- Removal percentages are not very useful for characterizing effectiveness, unless looked at much more carefully (e.g., only at "dirty" sites for example). As a result, it is the authors opinion that general BMP efficiency requirements should not be specified in terms of percent removal, unless carefully thought through. The concern here is that source controls could be discouraged if requirements specify that the BMPs must remove some percentage of pollutants.
- Some BMP types may have potentially been mischaracterized as less effective because of cleaner influent. Most BMPs that rely on settling as a primary removal mechanism typically have lower percent removals for total suspended solids where the concentration of these materials is low in the influent. The dry pond effluent quality in the database cannot be shown to be statistically different from that of effluent from wet ponds.
- Much more data are needed for many BMP types.
- Effluent quality may be a better way to characterize efficiency, although at an individual site, it is important to test whether the BMP had a statistically significant effect on water quality.

Other Measures of BMP Effectiveness

Although the current focus of the database project is on constituent concentrations and loads, biological and downstream physical habitat assessments such as aquatic invertebrate sampling and habitat classification should be explored as an alternative to simply utilizing chemical measures of effectiveness (Maxted 1999). Long-term trends in receiving water quality, coupled with biological assessments, would likely be a much better gauge of the success of the implementation of BMPs, especially on an area-wide basis.

SUMMARY AND RECOMMENDATIONS

There is a great need for consistency with regard to the constituents and methods utilized for assessing BMP effectiveness. It is recommended that researchers who undertake BMP effectiveness studies consider the recommendations suggested here, by Urbonas (1995) and other recommendations developed, based upon further analysis of this subject. It is the authors' opinion that the EPA should require studies receiving federal funding to conduct BMP effectiveness studies that utilize standard methods as suggested here combined with much still needed, detailed guidance on data collection and sampling methods to improve data transferability.

ACKNOWLEDGMENTS

The authors wish to thank Gene Driscoll, Bob Pitt, Bill Snodgrass, and Larry Roesner for their helpful discussions and comments on the subject. John O'Brien from Wright Water Engineers was instrumental in the development and implementation of the database software. The Urban Water Resources Research Council provided very beneficial review, support, and feedback. Finally, the assistance by the EPA in funding this cooperative agreement is acknowledged as well as the helpful participation of Eric Strassler and Jesse Pritts in reviewing our work.

REFERENCES

Chow, V. T. (1954). "The lognormal distribution and its engineering applications." *Proc., Am. Soc. Civ. Engrs.*, 110, 607–628.

Driscoll, E., Palhegyi, G., Strecker, E., and Shelley, P. (1989). "Analysis of storm event characteristics for selected rainfall gauges throughout the United States." *Draft Rep. Prepared for U.S. Environmental Protection Agency*, Woodward-Clyde Consultants, Oakland, Calif.

Harremoes, P. (1988). "Stochastic models for estimations of extreme pollution from urban runoff." *Water Resour. Bull.*, 22, 1017–1026.

Martin, E. H., and Smoot, J. L. (1986). "Constituent-load changes in urban storm water runoff routed through a detention pond-wetland system in central Florida." *Water Resour. Investigation Rep. 85-4310*, U.S. Geological Survey.

Maxted, J. (1999). *Proc., 1st Int. South Pacific Conf. on Urban Storm Water.*

Ruston, B. T., Miller, C. H., Hull, H. C., and Cunningham, J. (1997). "Three design alternatives for storm water detention ponds." Southwest Florida Water Management District, Brooksville, Fla.

Sokal, R. R., and Rohlf, F. J. (1969). *Biometry: The principles and practice of statistics in biological research*, W. H. Freeman and Co., San Francisco.

Strecker, E. (1994). "Constituents and methods for assessing BMPs." *Proc., Engrg. Found. Conf. on Storm Water Related Monitoring Needs*, ASCE, New York.

Strecker, E. W., Kersnar, J. M., Driscoll, E. D., and Horner, R. R. (1992). "The use of wetlands for controlling storm water pollution." The Terrene Institute, Washington, D.C.

Urbonas, B. R. (1994). "Parameters to report with BMP monitoring data." *Proc., Engrg. Found. Conf. on Storm Water Monitoring-Related Monitoring Needs*, ASCE, New York.

Urbonas, B. R. (1995). "Recommended parameters to report with BMP monitoring data." *J. Water Resour. Plng. and Mgmt.*, ASCE, 121(1), 23–34.

U.S. Environmental Protection Agency (USEPA). (1983). "National urban runoff program." *Final Rep., Water Plng. Div.*, Washington, D.C.

U.S. Environmental Protection Agency (USEPA). (1993). *Memo.*, Ofc. of Water Policy and Tech. Guidance on Interpretation and Implementation of Aquatic Life Metals Criteria, Washington, D.C.

Van Buren, M. A., Watt, W. E., and Marsalek, J. (1997). "Applications of the lognormal and normal distributions to storm water quality parameters." *Water Res.*, 31(1), 95–104.

Woodward-Clyde Consultants. (1993). "Data from storm monitored between May 1991 and January 1993." *Final Data Rep. prepared for Bureau of Environmental Services, City of Portland, Oregon*, Portland, Oreg.