The Water Report

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STORMWATER MANAGEMENT

STATE-OF-THE-ART IN COMPREHENSIVE APPROACHES TO STORMWATER

by Eric Strecker, PE; Marcus Quigley PE; Ben Urbonas, PE; & Jonathan Jones, PE

Introduction

While much has been learned about the performance of stormwater Best Management Practices (BMPs), this information is only rarely used to improve how we actually manage stormwater. Regulatory programs, including the establishment of Total Maximum Daily Loads (TMDLs) under the federal Clean Water Act as well as local design standards, have been slow to respond.

Recently, there has been a growing trend of providing more sustainable and low-impact approaches to development. This trend is encouraging in its ability to improve stormwater quality as well as downstream habitat.

This article challenges some of the traditional thinking about stormwater management and provides some recommendations and guidance to practitioners.

Best Management Practices: What Have We Learned About Their Performance

The US EPA (Environmental Protection Agency)/ASCE (American Society of Civil Engineers) National Stormwater BMP Database has been in development since 1994 under a US EPA grant project with the Urban Water Resources Research Council (UWRRC) of ASCE (Urbonas, 1994).

The project was initiated to address:

- Inconsistent data reporting, which limits scientific comparison/evaluation of studies
- Differences in monitoring strategies and data evaluation methods that result in wide range of reported "effectiveness" (e.g. minus-to-plus percent removals)
- Widespread use of BMPs and faulty BMP performance information without sufficient understanding of performance and factors leading to performance

The project has included: the development of recommended protocols for BMP performance (Urbonas, 1994 and Strecker 1994); a compilation of existing BMP information and "loading" of suitable data into a specially designed database (www.bmpdatabase.org); and an initial assessment of the results of the analyses of the database (Strecker et. al., 2001). A detailed guidance document on BMP monitoring has also been developed, titled: *Urban Stormwater BMP Performance Monitoring: A Guidance Manual for Meeting the National Stormwater BMP Database Requirements* (download at: www.bmpdatabase.org).

Municipal **s**eparate **s**torm **s**ewer **s**ystem owners ("MS4s") and operators, industries, and transportation agencies need to identify and design effective BMPs for improving stormwater runoff water quality that directly target their "pollutants of concern." The protocols developed under this project and the *Urban Stormwater BMP Performance Monitoring* guidance address the need for improved information by helping to establish a standard basis for collecting water quality, flow, and precipitation data as part of a BMP monitoring program as well as watershed and BMP design information. The collection, storage, and analysis of this data will ultimately improve BMP selection and design.

Major findings of the EPA/ASCE BMP Database effort to date include how to best assess BMP pollutant removal performance for most pollutants (Strecker et. al., 2001).

Stormwater BMPs
Assessment

"Percent Removal"

"HSC"

"LID"

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BMP pollutant removal performance is best assessed by determining:

- How much stormwater runoff is prevented? (via evapotranspiration and/or infiltration; e.g. Hydrological Source Control)
- How much of the runoff that occurs is or is not treated by the BMP? (amount of flow not by-passed or exceeding BMP effective treatment rates)
- Of the runoff treated, what is the effluent quality? (Statistical characterization of effluent quality)

For some pollutants, the amount of material captured is also important, as well as how the BMP mitigates temperature and/or flow changes.

The most common performance measure used today is "percent removal" of pollutants. The database team has determined that percent removal is a highly problematic method for assessing performance and has resulted in some significant errors in BMP performance reporting (Strecker, et. al., 2001). Percent removals are not recommended as performance descriptors for stormwater BMPs.

An Updated Re-Evaluation of the National BMP Database

The project team has completed an assessment of the recently expanded database. Table 1 presents an overview of the structural BMPs currently in the database, including the number of data records for each structural BMP type. These are studies that meet the protocols established for BMP monitoring and reporting. The almost 200 studies now in the database compares with the total of just over 60 BMP studies in the database during the initial evaluation. New BMP information is being provided to the database team at about a rate of 15-to-30 studies per year. There are currently about 50 studies awaiting entry into the database (subject to funding).

Each study has been analyzed in a consistent manner (described in Strecker, et. al. (2001) & at project website). Data produced includes: lognormal distribution based summary statistics; comparisons of influent and effluent water quality through parametric and non-parametric hypothesis tests; and other summary statistics. The effects of BMPs on hydrology and effluent quality is also being investigated.

Hydrology Evaluation

One of the goals of the database was to provide better information on the effects of BMPs on hydrology and whether some BMPs may have some benefits over others in terms of reducing volumes of runoff (Hydrological Source Control or "HSC"). For example, one would expect that a wet pond might not significantly decrease the volume of runoff, but a biofilter might, given the contact with drier soils and resulting evapotranspiration and/or infiltration. Much of the premise of Low Impact Development (LID) is based upon reducing runoff volumes. Accurately measuring flow during storm conditions is very difficult (EPA, 2002). A field test of over 20 different flow measurement technologies and approaches by the Federal Highway Administration (2001) found that flow measurements of volume of runoff over a storm can be upwards of 50 percent or more off of the expected true flow. Therefore any assessments of the database will likely show some variability in flow changes. However, some trends are evident.

Table 1: Structural BMPs in the International BMP Database

BMP Totals by Category

BMP Category	Number Of BMPs
Structural	
Biofilter (Grass Swales)	32
Detention Basin	24
Hydrodynamic Device	17
Media Filter	30
Percolation Trench/Well	1
Porous Pavement	5
Retention Pond	33
Wetland Basin	15
Wetland Channel	14
Total	**171**
Non-Structural	
Maintenance Practice	28
Total	**28**
Grand Total	**199**

BMP Totals by State/Country

State (Domestic)	Number of BMPs
AL	13
CA	41
CO	4
FL	24
GA	2
IL	5
MD	5
MI	5
MN	7
NC	6
NJ	3
OH	1
OR	3
TX	19
VA	29
WA	20
WI	10
International	
Sweden	1
Canada	1

Stormwater BMPs

Volume & Pollutant Reduction

FIGURE 1 presents plots of inflow vs. outflow for Biofilters (swales and filter strips), Detention Basins (dry ponds), Retention Ponds (wet ponds) and Wetland Basins. Hydrodynamic devises and filters were not included as they do not reduce runoff volumes. Biofilters showed an average of about 40 percent less volume of outflows as compared to inflows for the storms monitored. Dry-extended detention systems showed 30 percent less volume of such outflows. The other BMPs showed a large scatter, but generally showed an increase in runoff volumes.

TABLE 2 (see page 4) presents the results of removing the smaller more insignificant storms from the analyses (storms less than 0.2 watershed inches). It is apparent that detention basins (dry-ponds) and biofilters (vegetated swales, overland flow, etc.) appear to contribute significantly to volume reductions, even though they were likely not specifically designed to do so. Based upon the recommended criteria above for assessing BMP performance, it appears that there is a basis for factoring in volume and resulting pollutant load reductions into BMP performance. This has significant implications for TMDL implementation planning and other stormwater management planning. As BMPs that are specifically designed to reduce runoff volumes (e.g., lower impact development, etc.) are tested and information added into the database, these results will improve.

Water Quality Performance

Assessment Levels

The analysis of BMP water quality performance data is comprised of three levels:

1) a comprehensive evaluation of effluent vs. influent water quality for each BMP study
2) comparisons of effluent quality amongst BMP types
3) comparisons of performance vs. design attributes for BMP types and individual BMPs

Even with the increase in data in the database since the last evaluation, the total number of BMPs in any one category is still relatively small as compared to the number of design parameters and other regional factors that can be potentially investigated (Table 1).

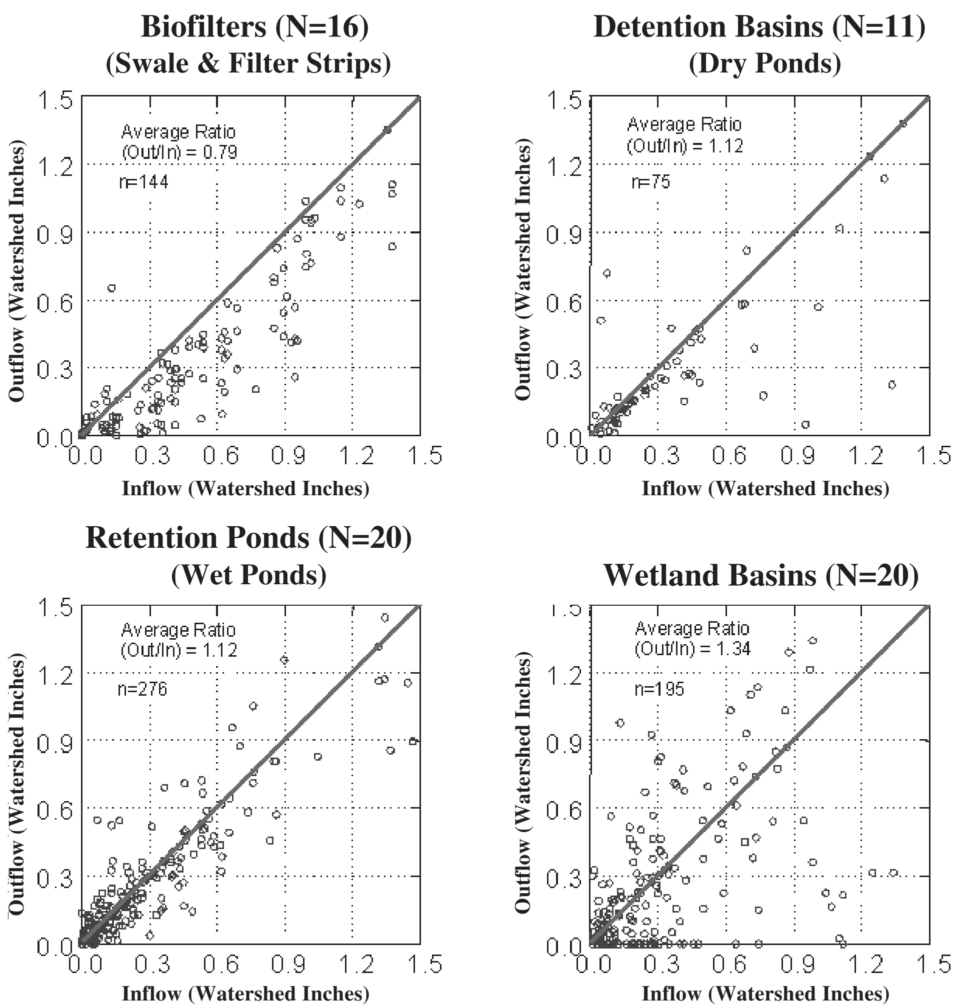


Figure 1: Comparison of Individual Storm Inflow and Outflow Volumes for Indicated BMPs
(N= number of BMPs included; n= number of storm events)

Stormwater BMPs

Problematic Results

Effluent Quality

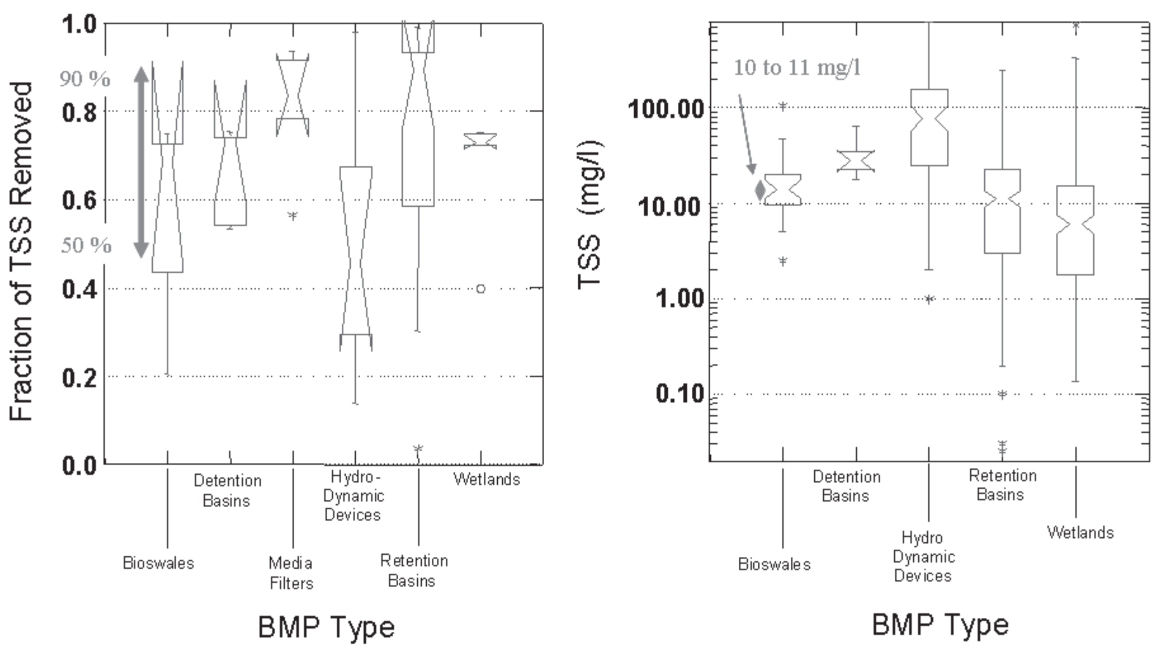
Effluent quality is much less variable than the percent removed (or fraction removed) for BMP studies, as shown in Figure 2, which shows box plots by BMP types of the fractions of **t**otal **s**uspended **s**olids (TSS) removed and box plots of TSS effluent quality. The box plots present the median, the upper and lower 95 percent confidence intervals of the median, and the 25th and 75th percentiles.

As has been found previously (Strecker et. al., 2001), it appears that percent removal is more-or-less a function of how "dirty" the inflow is. That is, even with a high percent removal, a treatment system handling highly polluted inflow may well result in problematic — though "treated" — effluent quality. What is new from the analyses of the expanded database is that effluent quality can now be assumed to be different amongst different BMP types for some parameters. It appears that Retention Ponds (wet ponds) and Wetlands can achieve lower concentrations of TSS (and other parameters) than other BMPs, while hydrodynamic devices were the lowest performers (higher effluent concentrations) on average for TSS. As a comparison, the 95% confidence interval for the median wet pond removal is between about 50 and 90 percent (a little better than 0-to-100), while the median effluent quality 95% confidence range is between approximately 11-to-18 mg/l (milligram per liter).

Table 2: Ratio of Mean Monitored Storm Event Outflow to Inflow for inflow Storms Greater than 0.2 watershed inches.

BMP Type	Mean Monitored Outflow/Mean Monitored Inflow for Events Greater Than or Equal to 0.2 Watershed Inches
Detention Ponds	0.70
Biofilters	0.62
Media Filters	1.0
Hydrodynamic Devices	1.0
Wetland Basins	0.95
Retention Ponds (wet)	0.93
Wetland Channels	1.0

Figure 2: Box plots of the fractions of total suspended solids (TSS) removed and of effluent quality of selected BMP types, by BMP Study



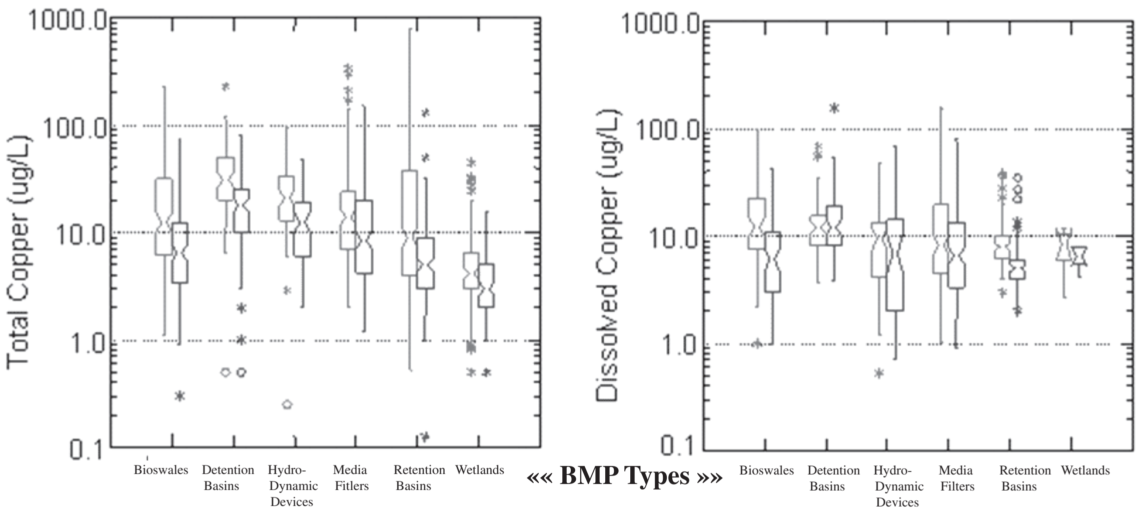
Stormwater BMPs

Figure 3
Paired Box Plots of Influent & Effluent Quality
(Inflow: Lighter Shade On Left
Outflow: On Right)
Selected BMPs: Total and Dissolved Copper
- By Event -

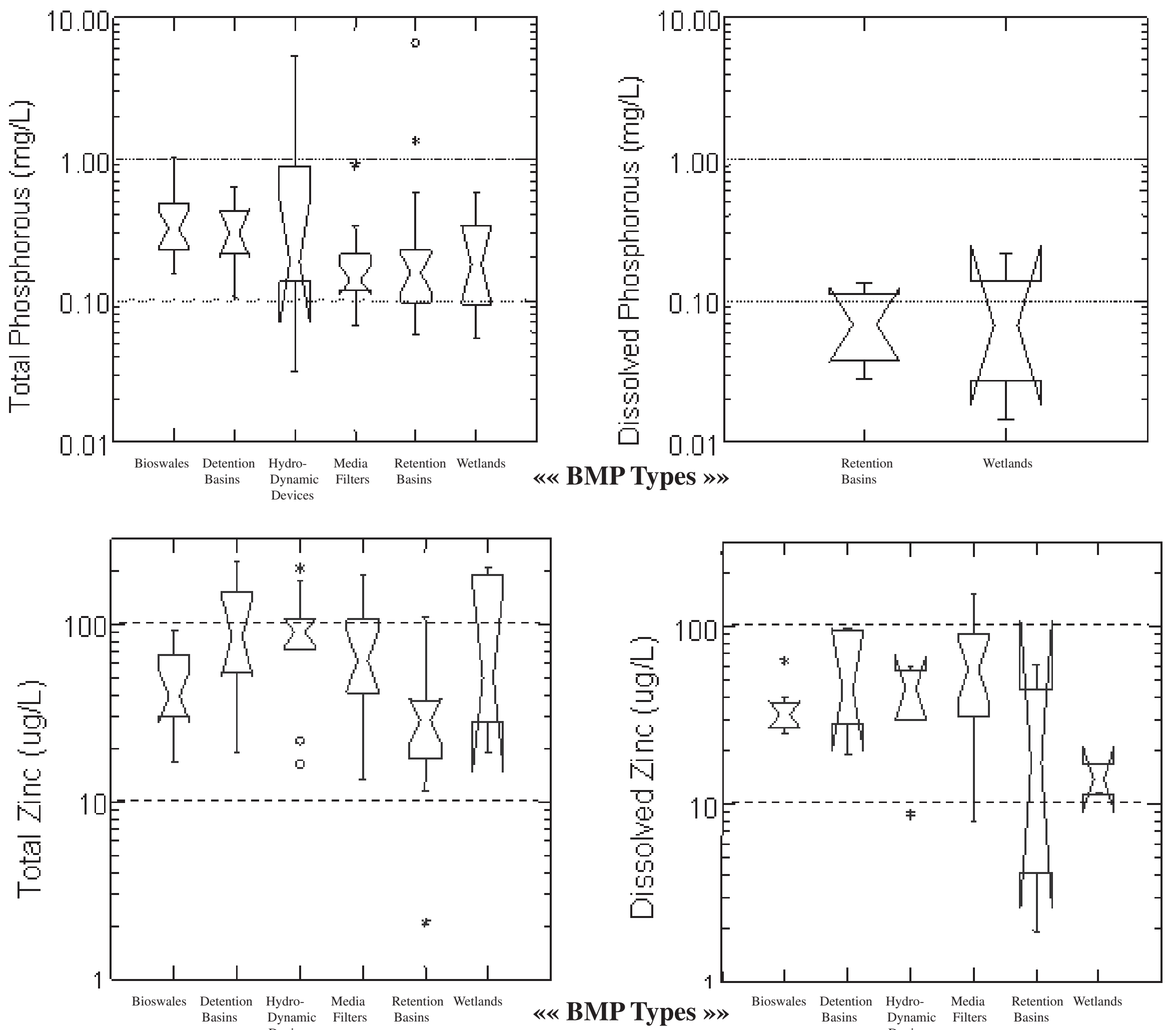
Figure 4
Box Plots of Effluent Quality of Selected BMPs for Total & Dissolved Phosphorus and Zinc
- By BMP Type -
(further desciption on next page)

Figure 3 shows the influent and effluent box total and dissolved copper box plots for event data (each event considered separately). For all BMP types, total copper influent and effluent can be assumed to be different for all BMP Types. However, for dissolved Copper concentrations only bioswales and wet ponds appear to have effected concentrations. Note that incoming dissolved concentrations are quite low and therefore this effects "efficiency."

— Figure 3 —



— Figure 4 —



Stormwater BMPs

Phosphorus

FIGURE 4 (previous page) shows the effluent quality results for comparing total and dissolved zinc and phosphorus for the same BMP categories weighted by BMP study (each BMP Study is a single data point). For dissolved constituents, data is still somewhat sparse. In these plots, the effluent quality of hydrodynamic devices is somewhat more consistent with other BMP types; this may be a confirmation of the work by Sansalone et. al. (1998) which showed that a sizable proportion of some pollutants are associated with fractions that may be removable via limited detention time devices. Some of his current work is demonstrating this in more detail (Sansalone, 2004). It is interesting to note that the lowest effluent quality achieved for phosphorus is about 50-to-60 ug/l (micrograms per liter). This contrasts with TMDLs or other water quality programs where the ultimate phosphorus goal has been set to 10-to-20 ug/l and then showing achievement of such goals by misapplication of percent removal approaches. For example, in some TMDL implementation efforts, BMPs are “assigned” certain percent removals. In order to assert that a BMP program for a site meets these low levels, designers have sometimes resorted to “daisy-chaining” BMPs to apply multiple percent removals to meet the requirements (e.g., employing three wetlands in a series and then applying a 60 percent removal for each). However, an effluent quality of 50-to-60 ug/l is a significant reduction as compared to typical urban runoff concentrations.

Fecal Coliform

Performance Ranges

Human pathogens are increasingly of concern in stormwater discharges. Debate continues over the usefulness of the fecal coliform test as an indicator of human pathogen levels in urban stormwater. FIGURE 5 shows a comparison of influent and effluent fecal coliform box plots for the indicated BMP types and a more detailed look at wet ponds. It should be noted that this is grab sample data. From the plot, it is apparent that some BMPs appear to be able to reduce fecal coliform concentrations (including media filters and retention ponds) while others cannot yet demonstrate reductions. The second plot for retention ponds demonstrates the influent and effluent quality observed for wet ponds — where the wet ponds appear to have a significant effect. It should be noted that in cases where there is heavy wildlife use, increases have been found.

— Figure 5 —

Various BMPs
Inflow: Lighter Shade / On Left**; Outlow/**Right

Retention Ponds
Inflow/Left**; Outlow/**Right

Fecal Coliform Concentrations (MPN/100ml)

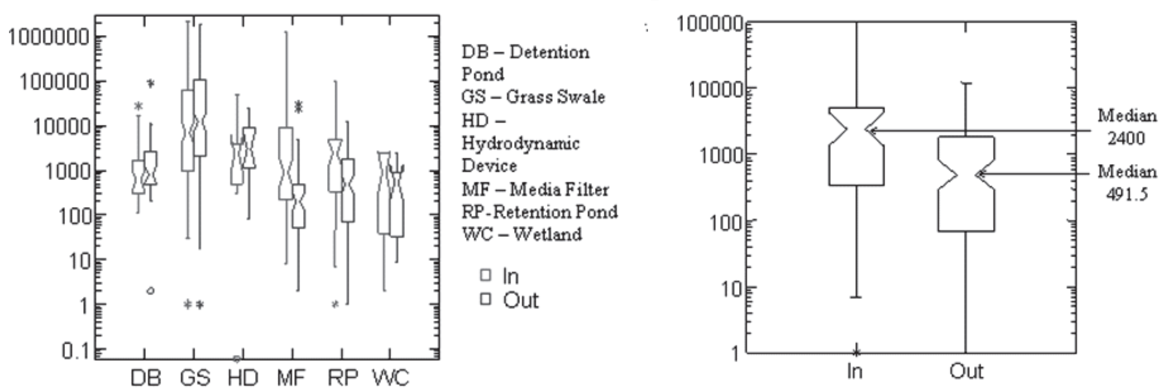


Figure 5. Box plots of effluent quality of selected BMP types for Fecal Coliform and Fecal Coliform inflow and outflow highlighted by event.

Water Hardness

Some of the other assessments that are being performed are the potential reductions in toxicity of heavy metals by BMPs. More recent BMP studies have been collecting data on water hardness and therefore there is an ability to assess potential toxicity issues via comparisons of effluent quality with EPA acute and chronic criteria values (as benchmarks as the criteria apply in receiving waters). One trend that your authors have noticed in the data is that for many BMPs, hardness levels are increased in BMP effluent (compared to influent). This hardness increase could contribute, along with concentration reductions, to reduced toxicity (as defined by EPA’s Acute Criteria for Aquatic Life). We will also be looking at the effects of BMPs on load reductions considering both hydrological source control performance as well as effluent quality.

Stormwater BMPs

Pond Size & Treatment Volume

DESIGN VS. PERFORMANCE

During the initial evaluation no statistically significant relationships between design parameters and performance were found (Strecker, et. al., 2001). This included retention ponds and wetlands and their treatment volume relative to measured storm events.

FIGURE 6 shows box plots of Retention Pond mean influent and effluent quality for sites with ratio less than one and greater than one ratio of the treatment volume to mean monitored storm event volume — e.g. how big the pond is as compared to average volumes of storms measured. The plots clearly demonstrate that at those sites where the wet pool treatment volume was greater than the average size storm event inflows monitored, the effluent quality was significantly lower. In addition, the variability of effluent quality for the larger retention ponds was lower. These results are expected, but it is one of the first times that they have been demonstrated statistically.

— Figure 6: TSS Influent and Effluent —

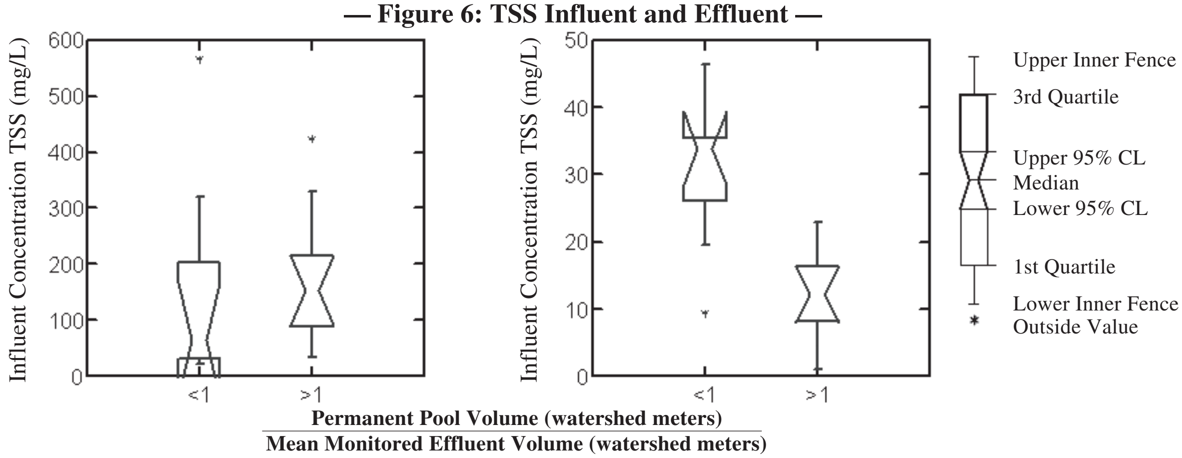


Figure 6. Box plots of the TSS influent and effluent quality of sites grouped by a ratio of less than or greater than 1 for the ratio of the permanent pool volume to mean monitored effluent volume by BMP study.

Assessment Basis

FIGURE 7 shows effluent comparisons for the same ratio for total phosphorus and total zinc. Note that for phosphorus, for the sites with a ratio less than one, it cannot be concluded that the BMP had an effect. For sites that are of the average size inflow, performance is better. It should be noted that this ratio is based upon the average size inflow volume and not the average sized rain event. One should not use the average size event at a rain gage as a basis for asserting BMP sizing; an average rain event would include many events that did not produce runoff or very little runoff.

Figure 7
Paired Box Plots
Inflow: Lighter Shade (On Left)
Outflow: On Right

— Figure 7: Total Phosphorus and Total Zinc Effluent Quality —

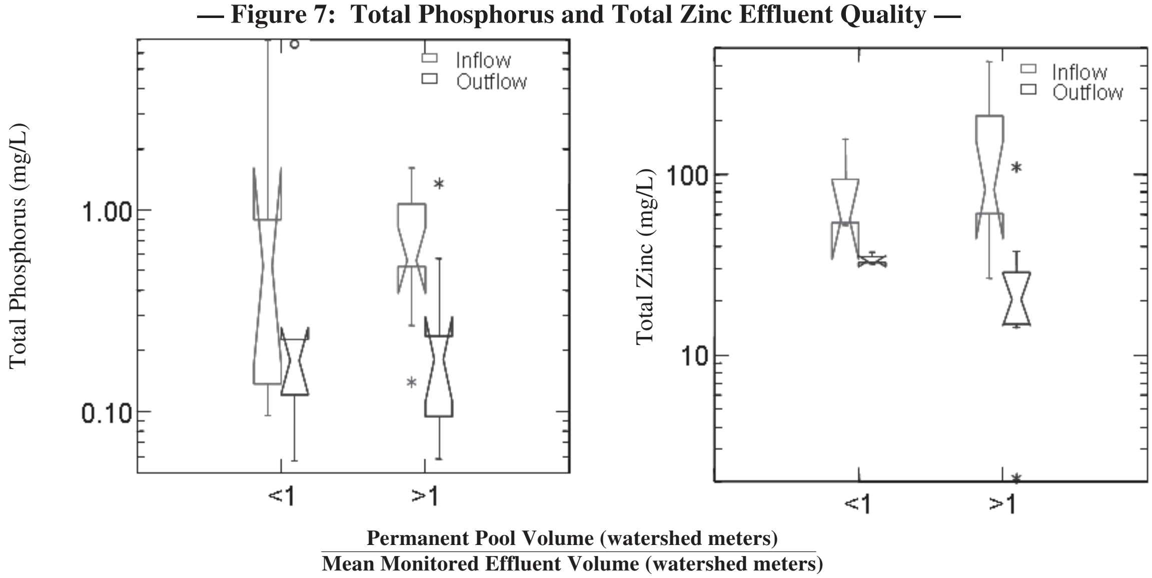


Figure 7. Box plots of the total phosphorus and total zinc effluent quality of sites grouped by a ratio of less than or greater than 1 for the ratio of the permanent pool volume to mean monitored effluent volume by BMP study.

Stormwater BMPs
"HSC"

Simulation

Standards Considerations

Targeted Pollutants

Defensible Acceptance

Implications for Setting of BMP Design Requirements and TMDLs

The analysis of water quantity and water quality performance of BMPs is very useful in the consideration of setting of stormwater design standards and development of TMDL implementation plans.

SOME RECOMMENDATIONS INCLUDE:

- Design standards should account for the hydrologic losses (HSC) that can occur with some BMP types to encourage their use. Both biofiltration systems and dry extended detention ponds appear to show significant reductions in the runoff routed through them.
- Continuous simulation techniques should be employed to assess potential BMP design sizing (as opposed to "percent capture") to ascertain what the potential hydraulic performance of BMPs will be over long-time periods. Given the expenditures of resources by the private and public sector on BMPs, it is imperative that those setting standards should conduct these more detailed assessments with more local rain gages to assess the hydrologic and hydraulic performance of BMPs. Using a 24-hour rainfall analysis to set standards is problematic.
- BMP types should be considered in setting standards. For example, a storm depth (volume) measurement is relatively meaningless for a vegetated swale. For "flow-through" BMPs, an analysis of hourly or 15 minute data is more appropriate.
- BMPs should be targeted based upon expected performance of BMPs with regard to "pollutants-of-concern." For example, if TSS and dissolved copper are the constituents of concern, then a hydrodynamic device alone is not likely to address the issues. Several efforts are under way to develop "unit processes" descriptions of BMP performance. The results of these efforts, together with other updated BMP performance information, should be used to evaluate the potential results of employing various BMP types. It is likely that given the wide mixture of pollutants-of-concern, that multiple, sequential BMPs ("treatment train" approaches) will prove most effective.
- BMP "Acceptance" is becoming a larger issue for communities. Are all "BMPs" acceptable regardless of performance? One problem that BMP vendors face is regulatory requirements that appear to state that one selected treatment BMP for any area must "do it all"—when in fact, in most cases a well designed treatment train is sufficient and may be preferable. Vendors, to stay in business, seem encouraged to make claims to be all encompassing. Developing acceptance standards that are defensible and which result in well-performing BMPs, will become an increasing goal of BMP requirement programs. An example of the problems of BMP acceptance is presented in Figure 8. By almost all current BMP acceptance criteria, this BMP would be accepted for its greater than 80 percent removal. One has to consider, though, whether an average effluent quality of over 100 mg/l is acceptable. Compared to other BMPs' effluent quality, it is not. That is not to say that this BMP type might not serve a valuable role as initial treatment in conjunction with stormwater wetlands.

Table 3. George Field Study Evaluation of a Vortechs model 11000

Runoff	TSSin (mg/L)		TSSout (mg/L)		% Reduction	
Event #	Interpolated	Arithmetic	Interpolated	Arithmetic	Interpolated	Arithmetic
1	987.48	693.52	263.18	205.98	73%	70%
2	128.73	88.57	59.23	59.18	54%	33%
3	1040.04	882.42	337.87	486.75	68%	45%
4	213.73	225.42	359.14	388.08	-68%	-72%
5	1673.57	1217.53	71.39	102.84	96%	92%
6	535.16	603.54	70.14	85.23	87%	86%
7	180.81	132.22	29.76	34.88	84%	74%
8	2491.55	2202.78	35.41	35.47	99%	98%
9	89.99	76.60	31.98	33.14	64%	57%
10	1047.02	2257.46	37.08	31.22	96%	99%
11	439.45	344.86	16.57	13.83	96%	96%
12	445.19	291.58	17.36	14.91	96%	95%
13	1156.16	674.94	44.72	37.91	96%	94%
Averages	802.2215	745.4954	105.6792	117.6477	87%	84%

(Winkler and Guswa 2002)

Stormwater BMPs

CONCLUSIONS

An evolving tool is available to practitioners who are assessing the performance of BMPs via the International Stormwater Best Management Practices Database Project. Practitioners can perform their own evaluations via downloading of information from the web site.

Best Description Criteria

Results of the analyses of the now expanded database have reinforced the initial findings that BMPs are best described via: their ability to reduce runoff volumes; how much of the runoff record is treated (and not treated); and, of the treated runoff, what does the effluent quality and characteristics (potential toxicity) look like. Differences in the effluent quality of various BMP types can be statistically characterized. BMPs design factors, including sizing, are becoming more statistically discernible in the BMP type data sets as the number of studies assessed grows. Continued expansion of the BMP database with additional studies will improve the ability to discern performance when considering BMP selection and design. The BMP database provides a useful tool to develop more accurate design requirements for stormwater BMPs as well as implementation plans for TMDLs that will be more targeted at achieving desired outcomes.

Goals Supported

These Basic BMP performance description elements can be utilized to:
- assess the concentrations that BMPs are able to achieve (concentration TMDLs)
- more accurately assess effects on total loadings (TMDLs), including how much runoff is prevented or treated and more realistic estimates of resulting loads
- determine the frequency of potential exceedances of water quality criteria or other targets
- establish/utilize other desired water quality performance measures.

Train Preferred

For now, designers are urged to utilize a treatment train approach for BMPs wherever possible. The approach should consider: the pollutants of concern and their form; the unit processes that are needed to remove those pollutants; and the unit processes that occur in significance in various BMP types. For example, as Figure 8 shows, if one is interested in removing multiple pollutant types, then a treatment train has many advantages. Using a treatment train will help to account for the inherent variability and uncertainties that are associated with BMP performance. Designers should employ conservative criteria, including sizing and focusing on longer residence times for volume based BMPs, as well as larger sizing of filters and other flow-through BMPs (see ASCE/WEF *1998 Water Quality Manual of Practice*).

— Figure 8 —

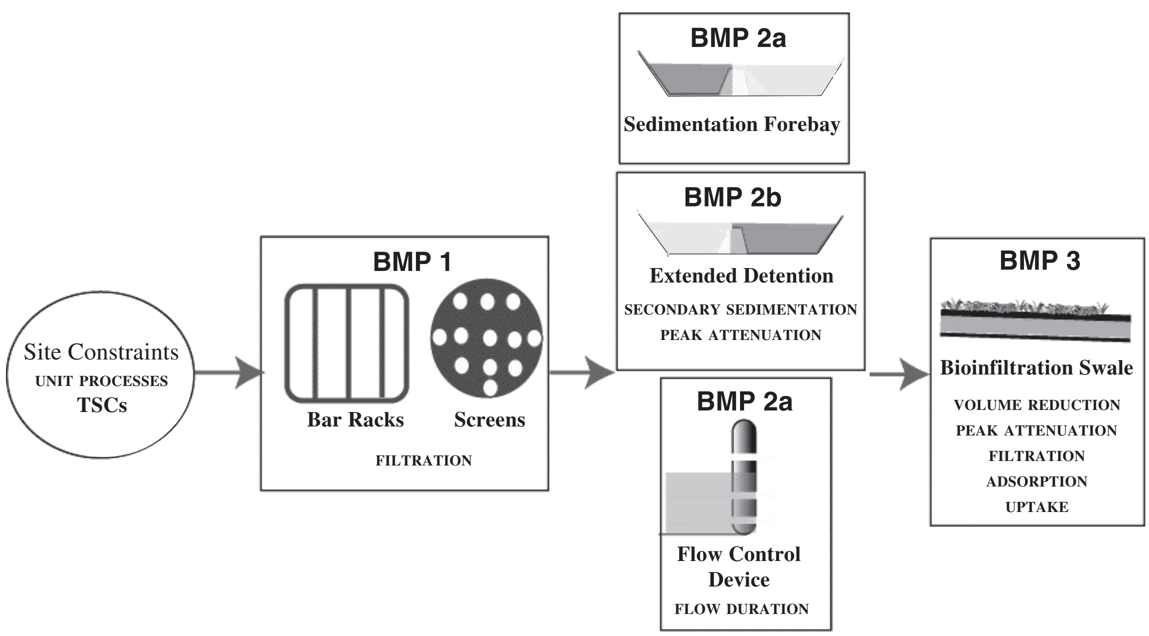


Figure 8. A treatment Train designed to remove Trash/Debris, TSS and Dissolved Copper

Minimizing Runoff

Finally, it is important to minimize the increase in runoff. Typical urban development has severely reduced **e**vapo**t**ranspiration (ET) and infiltration. Too often, we think infiltration could be the answer in areas where pre-development infiltration was minimal, but is eliminated due to soils and/or slope conditions concerns. We need to look at ways of mimicking pre-development evapotranspiration rates as the first step in stormwater management. It is often the case that pre-development evapotranspiration may be as high as 80+ percent of rainfall. If we infiltrate all of that water, then we will have increased infiltration greatly over pre-development.

To increase ET, the "sponge" should be restored which includes more:
• Trees, Shrubs and Grasses
• Shallow soils (non compacted)
• EcoRoofs

Stormwater Management is a difficult task, but we need to keep applying new knowledge that is carefully evaluated for specific situations.

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Eric Strecker, Ben Urbonas, and Jonathon Jones are the Principal Investigators for the International BMP Database Project. Marcus Quigley assisted with the data analysis. The project team was awarded the National 2003 State-of-the-Art in Civil Engineering Award by the American Society of Civil Engineers for this project.

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