WASHINGTON STATE DEPARTMENT OF ECOLOGY

Efficiency of Urban Stormwater Best Management Practices: A Literature Review

Abstract

This report is a literature review of urban stormwater best management practices (BMPs) efficiency studies.

Efficiency studies are seldom conducted using common methods, so results are not directly comparable. Nevertheless, BMP performance data from different studies have been compiled. Some of these compilations are reviewed in this document.

One compilation produced an Access© database of BMP performance. This database can be used to help identify suitable BMPs. This report summarizes some of the results in the database along with confidence limits for different BMP types.

Not all BMP types consistently improve water quality. Even when average efficiency of a particular type is positive (i.e., water quality is improved by the average BMP), 90% confidence limits frequently include 0.

By Dave Hallock
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For more information contact:

Publications Coordinator
Environmental Assessment Program
P.O. Box 47600
Olympia, WA 98504-7600

E-mail: csme461@ecy.wa.gov
Phone: 360-407-6677

Author: David Hallock
Environmental Assessment Program
Washington State Department of Ecology
PO Box 47600
Olympia, WA 98504-7710
E-mail: daha461@ecy.wa.gov
Phone: (360) 407-6681

Background

The Washington State Department of Ecology's Water Quality Program requested that the Environmental Assessment Program do a literature review and compile the efficiencies of various urban stormwater best management practices (BMPs). The ultimate goal of the project is to identify suitable BMPs for different urban land uses. The original scope of work (Project ID 06-96) involves much more; this literature review is an initial step.

Introduction

There have been many studies of BMP effectiveness, but few have been comprehensive enough, or are similar enough, to allow detailed and rigorous assessments and comparisons among different types of BMPs. Different programs collect different analytes at different frequencies. Even when studies are similar, inconsistency in sampling and assessment methods can yield wildly different efficiencies (Strecker et al., 2001). For example, efficiency can vary greatly depending on whether storm events were sampled exclusively, whether results were flow-weighted (or weighted by some measure of precipitation), or whether efficiency was based on averaged concentrations or an average of efficiency of each storm event.

Furthermore, even if monitoring and assessment methods were comparable, BMP performance is dependent on site-specific details that many studies do not report. Even when descriptive information is adequately reported, this information is rarely used when comparing efficiencies. For example, two identical wet ponds could easily have very different efficiencies due to different retention times, different catchment ratios, or any number of other factors.

The point, of course, is that the performance of any given BMP is difficult to predict accurately without a detailed evaluation of design and site characteristics. Still, there are many studies that, in aggregate, may provide some modestly useful generalizations for both BMP efficiency and expected pollutant concentrations for different land uses. A number of sources have compiled results from various studies of BMP performance. The following four may be particularly useful:

1. **National Stormwater Best Management Practices Database**: Results are available online at www.bmpdatabase.org. This is an ongoing project. In 2000 there were 71 BMPs in the database. Effluent concentrations have been summarized but not efficiency because the project managers do not believe that is the best way to assess BMP performance.
2. **National Pollutant Removal Performance Database**: This is a compilation of 139 studies (as of 2000), 18 of which are from Washington State. Winer (2000) summarizes removal efficiencies by BMP type and constituent.
3. **STEPL**: STEPL is a TetraTech/EPA model that can be used to determine pollutant load (bering.tetratech-ffx.com/stepl/). The model accepts land use information and urban BMP type and calculates the resultant pollutant load of Nitrogen (N), Phosphorus (P), Biological Oxygen Demand (BOD), and Total Suspended Solids (TSS) using "known BMP

efficiencies." Efficiencies used by the model were not explicitly given, but could probably be back-calculated. Seven sources for urban BMP efficiencies are listed in a hidden worksheet.

4. **Stormwater Best Management Practices Effectiveness Review:** CH2M Hill, under contract to the Oregon Association of Clean Water Agencies, compiled results from more than 300 effectiveness studies in an Access© database.

BMP Efficiency

Of the four sources of compiled BMP performance data listed above, the database developed by CH2M Hill (2005) is the most complete, the most current, and the most user friendly. Table 1 summarizes removal efficiencies from this database for fecal coliform bacteria, total phosphorus, and total suspended solids.

Removal efficiencies, however, are only part of the story and can be misleading. For example, studies with few or no major storm events may report low removal efficiencies because both influent and effluent concentrations were low. Other problems with comparing efficiencies are discussed in the Introduction, above. The real question, according to (Strecker et al., 2001), is whether effluent concentrations from the BMP are acceptable. Although CH2M Hill (2005) includes effluent concentrations, at least when reported by the original authors, Table 1 summarizes efficiency for several reasons:

1. Effluent concentrations are also subject to some of the same criticisms as efficiency, such as inconsistent sampling protocols.
2. CH2M Hill did not include influent concentrations, so the direct impact of the BMP on the influent water could not be evaluated. (Were effluent concentrations low because the BMP was effective or because influent concentrations were low?)
3. Far more studies reported removal efficiencies than effluent concentrations.

All BMP types compiled by CH2M Hill (2005) were more or less effective at removing total suspended solids based on average percent efficiency (Table 1). However, a negative lower bound for several of the 90^{th} percent confidence intervals indicates low confidence that these BMP types will work at all sites, at least when performance is measured as percent efficiency. A negative efficiency indicates an increase in concentration through the BMP. For suspended sediment, BMP types with the highest likelihood of success (when measured by percent efficiency) were wetlands, dry ponds, filter strips, and porous pavement.

For total phosphorus control, a number of BMP types had positive average efficiency, but only porous pavement, street sweeping, and wet ponds had a high likelihood of success (based on the lower 90th percentile of efficiencies). However, the first two types had only two studies each included in the database.

For fecal coliform bacteria, constructed wetlands, filters, soakage trenches, and wet ponds all had a high likelihood of success (based on the lower 90th percentile of efficiencies), though only filters had more than a few studies included in the database.

Table 1. Average percent efficiency for various BMP types.

Bold type indicates positive efficiency or the lower 90th percent confidence interval greater than 0. (Avg = average percent efficiency, ±90Pct CI = plus and minus the 90th percent confidence interval on the average, N = number of studies.)

BMP Type	Avg[1]	±90Pct CI	N	WA Avg[2]	N	WA Avg[3]	N
Fecal Coliform							
Catch Basin Type	**14**	NA	1				
Constructed Wetlands (surface flow)	**94**	**87.7 - 99.3**	2			55	1
Dry Ponds - Vegetated	**78**	NA	1				
Filter Strips	-25	NA	1				
Filters (sand / leaf / other media)	**60**	**32.8 - 87.4**	9				
Soakage Trenches / Infiltration Basins	**86**	**77.5 - 95**	4				
Vegetative Swales	-30	NA	1			-50	3
Wet Ponds	**87**	**65.9 - 107.1**	2				
Total Phosphorus							
Catch Basin Type	**18**	NA	1				
Centrifugal Separator	**57**	-10.4 - 124.4	2				
Constructed Wetlands (subsurface flow)	-8	-47.8 - 32.8	2				
Constructed Wetlands (surface flow)	**37**	-3.6 - 76.6	16			10	3
Drain Inlet Devices	**97**	NA	1				
Dry Ponds - Non-Vegetated	-13	NA	1				
Dry Ponds - Vegetated	**26**	-18.5 - 70.5	9				
Filter Strips	-77	-288.6 - 135.4	8				
Filters (sand / leaf / other media)	**26**	-20.1 - 73.1	25	-9	3	6	4
Oil/Water Separator	-7	NA	1				
Porous Pavement	**66**	**56.5 - 74.5**	2				
Soakage Trenches / Infiltration Basins	**60**	NA	1			94	1
Street Sweeping	**57**	**29 - 85**	2				
Vegetative Swales	-34	-130.2 - 61.7	27			29	4
Wet Ponds	**48**	**12.4 - 84**	32	17	1	60	5
Total Suspended Solids							
Catch Basin Type	**52**	**12.8 - 90.2**	2				
Centrifugal Separator	**12**	-38.7 - 61.7	2				
Constructed Wetlands (surface flow)	**72**	**44.9 - 100**	13			30	3
Dry Ponds - Non-Vegetated	**25**	NA	1				
Dry Ponds - Vegetated	**69**	**50.7 - 86.7**	7				
Filter Strips	**64**	**44.2 - 83.3**	7				
Filters (sand / leaf / other media)	**34**	-194.1 - 262.2	28	44	3	59	4
Oil/Water Separator	**31**	**0.1 - 60.9**	2				
Porous Pavement	**71**	**39.6 - 102.9**	8				
Soakage Trenches / Infiltration Basins	**85**	**71 - 98.5**	4			97	1
Street Sweeping	**74**	**42.7 - 105.3**	2				
Vegetative Swales	**51**	-3.7 - 104.7	28			72	5
Wet Ponds	**56**	-52.8 - 163.9	31	59	1	81	5

[1] Average of efficiencies from study averages reported in the Stormwater Best Management Practices Effectiveness Review (CH2M Hill, 2005).
[2] Average of efficiencies for studies in Washington State from the Stormwater Best Management Practices Effectiveness Review (CH2M Hill, 2005).
[3] Average of efficiencies for studies in Washington State from the National Pollutant Removal Performance Database (Winer, 2000).

Pollutant Sources

Pollutant levels expected from various land uses are harder to come by than BMP efficiencies, at least in compiled form. Expected concentrations from a few compilations are given in Table 2. Other compilations provide expected pollutant levels from various land uses expressed as loads (e.g., Burton and Pitt, 2002: EPA 1999: Horner et al., 1994).

Pitt et al. (2004) gives the median and coefficient of variation for various constituents, but the data are not segregated by land use. Lubliner (2007) has also summarized pollutant concentrations (see her Appendix D).

Table 2. Expected pollutant concentrations for various land uses.
(These measures of central tendency include means, medians, and event mean concentrations, depending on the source; ranges are given in parentheses; see footnotes.)

Parameter		Use			
		Residential	Commercial	Industrial	Freeway
Total Suspended Solids mg/L	1	200	340	128	185
	2				45-798
	3	100 (100-228)	75 (69-168)		150 (142-242)
	4	101	67	108-124 (120)	
	5	60 (42-86)	79 (62-98)	134 (92-192)	170 (122-227)
	6	48	43	77	99
Biological Oxygen Demand mg/L	1	15	75		
	2				12.7-37
	4	10	7.8		
	5	8.8 (6-12)	9.9 (6.1-14.2)	39.3 (25-56)	16.4 (9.2-27)
	6	9	11.9	9	8
Phosphorus, total mg/L	2				0.113-0.998
	3	0.4 (0.26-0.62)	0.2 (0.20-0.29)	0.4 (0.42)	0.5 (0.4-0.59)
	4	0.383	0.263		
	5	0.34 (0.21-0.48)	0.4 (0.2-0.71)	0.61 (0.49-0.73)	0.37 (0.29-0.46)
	6	0.3	0.22	0.26	0.25
Soluble Phosphorus mg/L	4	0.143	0.056		
	6	0.17	0.11	0.11	0.2
Nitrogen mg/L	3	2.2 (1.5-2.6)	2.0 (1.75-2.3)	2.5 (2.53)	3.0 (2.72-3.48)
	4	2.64	1.85		
E. coli #/100mL	5	1783 (1064-2710)	1839 (1063-2976)	717 (381-1255)	1430 (643-2887)
Oil/grease mg/L	1	0.8-13	8-31	10-20	27-44
Arsenic μg/L	1	10	ND	23	3
Cadmium μg/L	1	3	5	5	0.6
	6	0.5	0.9	2	1
Copper μg/L	1	41	24	106	41
	4	33	27		
	6	12	17	22	35
Lead μg/L	1	230	381	247	862
	2				73-1780
	4	144	114		
	6	12	18	25	25
Nickel μg/L	1	12			
	6	5.5	7	16	9
Zinc μg/L	1	123	274	273	481
	4	135	135		
	6	73	150	210	200

[1] Resource Planning Associates, 1989, Table A.1. Mean value of several storms. (TSS was given in μg/L, presumed to be mg/L)
[2] EPA, 2006, Table 7.2. Range of average values. Total Phosphorus and BOD concentration were incorrectly reported in Table 7.2; results here are from the original source.
[3] www.stormwatercenter.net 2006. (Numbers are those used by their model. Range of results from 2 to 10 different studies is given in parentheses.)
[4] Burton and Pitt, 2002. Results are medians from National Urban Runoff Program. Nitrogen is sum of TKN and NO_{2+3}. Coefficients of variation and other parameters were also provided in Table 2.4.
[5] www.portlandonline.com 2006. Mean (range in parentheses).
[6] Pitt et al, 2004, Table 3. Median values and event mean concentrations from the National Stormwater Quality Database.

Select Annotated Bibliography

Water Quality BMP Manual (City of Seattle) (Resource Planning Associates, 1989): Although similar to the Ecology Stormwater Manual in that it provides lists of urban uses and of BMPs by business, this Seattle manual does not tie them together well and it does not include expected control efficiencies. However, this manual does include a consumer reports-type chart showing relative effectiveness of different treatment systems (three types of oil separators, five treatment systems, e.g., biofilter) for different pollutants (solids and oil) (pg 4.3). The appendices list stormwater data (BOD, oil, TSS, various metals) for four land uses (residential, commercial, industrial, freeway) from Metro and Bellevue studies (Table A.1) and predicted removal of TSS in a wet pond as function of runoff coefficient and catchment ratio (Fig 1.1). Also included is a literature review (n~40) indicating, among other things, which sources discuss removal efficiency.

Preliminary Data Summary of Urban Stormwater Best Management Practices (EPA 1999): This document discusses effectiveness of BMPs in managing urban runoff (Section 5.5), including a narrative discussion of the effectiveness of non-structural BMPs, and quantitative discussions of efficiency of structural BMPs. EPA cites Brown and Schueler (1997), which was the first edition of the National Pollutant Removal Performance Database (See Winer, 2000). (www.epa.gov/waterscience/guide/stormwater/)

National Management Measures to Control Nonpoint Source Pollution from Urban Areas (EPA, 2006): This document lists general methodologies for modeling loads (p 2-6 to 2-7); modeling effectiveness of treatment (for urban watersheds, "Watershed Treatment Model" is available online for $25) (p 2-10); residential site development (e.g., conventional vs. LID) (p 4-6+); runoff controls, pros and cons (p 5-54); effectiveness of runoff controls—the source of this is Winer (2000) (p 5-59); loading from various residential sources (e.g., garbage disposal) (p 6-51) and highways (p 7-4); and effectiveness of erosion controls (p 8-13, 23) (e.g., PAM) (p 8-21).

Determining Urban Storm Water BMP Effectiveness (Strecker et al., 2001): "However, in attempting to review and summarize the information gathered from …BMPs," for various reasons, "wide-scale assessments" were "difficult if not impossible." This 2001 paper compares various assessment techniques, recommends consistency in methods, and proposes data to be reported (BMP type, design, and methods) for determining efficiency. Recommended assessment methods include an analysis of various plots, p-value from an ANOVA, and an evaluation of distribution by comparing, for example, 10, 50, and 90^{th} percentiles, and mean and confidence intervals. Simply comparing percent efficiency was not recommended. Based on "event mean concentration" data from two Portland, Oregon stations, detecting a 20% change in Total Phosphorus will require samples from 8 to 16 storm events. (This report is an outgrowth of the BMPDatabase project.)

Analysis of Treatment System Performance (GeoSyntec Consultants, 2006): This document gives median (and confidence interval) effluent concentrations for data in the BMPDatabase. It also indicates whether effluent was statistically different than influent, but it does not give the difference, efficiencies, or the influent data.

National Pollutant Removal Performance Database 2nd Edition (Winer, 2000): This second edition (Brown and Schueler (1997) was the first edition) is a compilation of 139 studies. As far as I can tell, it is independent of the BMPDatabase. Conclusions include:

- Most designs can remove significant amounts of sediment and Total Phosphorus but removal of Total Nitrogen is less successful.
- Dry ponds perform worse than any other group.
- Infiltration practices have the highest removal rates.
- In general, ponds and wetlands have similar removal rates.
  - Ponds had higher removal rates for metals and soluble phosphorus.
  - Wetlands had higher removal rates for soluble nitrogen.
- Filters removed total nutrients well but soluble nutrients poorly.
- Vertical sand filters and ditches performed poorly.
- Figures 3.1 and 3.2 show removal efficiency box plots for different treatment practices and constituents.
- There is not much available data on internal factors (e.g., geometry and sediment/water column interactions). That may explain the large variability in efficiencies.

The Simple Method to Calculate Urban Stormwater Loads (www.stormwatercenter.net): This is a short paper that proposes calculating loads by the following formula:

$$(\text{annual runoff})*(\text{pollutant concentration})*\text{area}$$

Runoff is based on rainfall and impervious fraction. Tables provide pollutant concentrations (total suspended solids, total phosphorus, and total nitrogen) from several studies by land use (residential, commercial, roadway, and industrial). Another table gives National Urban Runoff Program concentration averages for various pollutants.

Ecology Stormwater Manual (Ecology, 1999): This document may be useful providing in lists of urban uses and of BMPs, although it does not tie them together well and does not include expected efficiencies. Volume 1 gives flow charts for determining general requirements by parcel size (small and large). Volume 2 lists specific BMPs (separated by source control and runoff/conveyance/treatment) with design and maintenance information (e.g., BMPC201, Grass-lined Channels). Volume 3 is the “how to” for designing flow-related BMPs (e.g., using Darcy’s Law to size an infiltration BMP). Volume 4 guides source control BMP selection by urban land use (e.g., railroad yard: don’t discharge from toilets while train is in motion; Urban streets: sweep promptly). Volume 5 provides runoff treatment BMP selection, design, and maintenance information and ties to requirements in Volume 1.

Dana Point, CA, Urban Runoff Requirements for Development (www.danapoint.org/water/urban.html)**:** The WQMP (Water Quality Management Plan) Template contains a matrix of urban uses vs. potential pollutants (p. 5); however, neither quantification nor references are provided. Tables 6.1 and 6.2 (beginning on page 10) list and describe various BMPs for treatment controls and source controls. (Also see www.cabmphandbooks.com for CA guidance on BMPs.)

Evaluation and Management of Highway Runoff Water Quality (Young, et al., 1986): This is a highly detailed analysis of various structural and non-structural BMPs with application beyond highway runoff. It includes engineering design considerations and expected effectiveness, and explains factors that can affect effectiveness.

Stormwater Best Management Practices Effectiveness Review (CH2M Hill, 2005): This project reviewed 310 effectiveness studies from 17 references, some local, some national. Results are provided in an Access© database group-able by BMP type or by constituent. One can, for example, select total phosphorus and see a list of BMP studies and various measures of effectiveness for each study.

Effectiveness Evaluation of Best Management Practices for Stormwater Management in Portland (www.portlandonline.com): This report provides a table showing several BMPs, in order of effectiveness (but without quantification), for various management goals. For example, to reduce nutrients, the most effective structural BMPs were wetlands, wet ponds, and swales, in that order.

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