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Comparative Pollutant Removal Capability of Stormwater Treatment Practices

Over the last two decades, an impressive amount of research has been undertaken to document the pollutant removal capability of urban stormwater treatment practices. The Center has recently developed a national database that contains more than 135 individual stormwater practice performance studies. The goals for this project, were to generate national statistics about the pollutant removal capability of various groups of stormwater practices and to highlight gaps in our knowledge about pollutant removal.

The database was compiled after an exhaustive literature search of past monitoring studies from 1990 to the present. About 60 earlier monitoring studies had been collected in prior literature syntheses (Strecker *et al*., 1992; Schueler, 1994). To be included in the database, a performance monitoring study had to meet three minimum criteria: a) collect at least five storm samples, b) employ automated equipment that enabled taking flow or time-based composite samples, and c) have written documentation of the method used to compute removal efficiency. A total of 139 studies in the current phase of the project met these criteria.

Once in the database, a few general conventions were needed to facilitate the statistical analysis. First, related measurements of water quality parameters were lumped together in the pollutant removal analysis (e.g., "soluble phosphorus" included ortho-phosphorus, biologically available phosphorus, and soluble reactive phosphorus; "organic carbon" lumps biological oxygen demand, chemical oxygen demand and total organic carbon removals, "hydrocarbons" can refer to oil/grease or total petroleum hydrocarbons and "soluble nitrogen" refers to nitrate + nitrite or nitrate alone.

Second, if more than one method was used to calculate pollutant removal, methods that compared the input and output of mass rather than concentrations were used. Third, if the monitoring study only recorded removal in terms of "no significant difference" in concentrations, these were registered as zero removals. Similarly, studies that reported unspecified negative removals were entered as minus 25% (mean of negative values where specified). Finally, performance studies reporting negative removals greater than 100% were limited to minus 100% to prevent undue bias in the data set.

Each study was then assigned to one of five general stormwater practice groups: ponds, wetlands, open channels, filters, and infiltration practices. Each group was further subdivided according to design variations. For example, the pond group includes detention ponds, dry extended detention (ED) ponds, wet ponds and wet ED ponds. Medians were used as the measure of central tendency for all stormwater practice groups and design variations, and are only reported if sample size exceeded five monitoring studies. In general, pollutant removal rates should be considered as *initial* estimates of stormwater practice performance as studies occurred within three years of practice construction.

As always, extreme caution should be exercised when stormwater management performance studies are compared. Individual studies often differ in the number of storms sampled, the manner in which pollutant removal efficiency is computed (e.g., as a general rule, the concentration-based technique often results in slightly lower efficiency than the mass-based technique), the monitoring technique employed, the internal geometry and storage volume provided by the practice design, regional differences in soil type, rainfall, latitude, and the size and land use of the contributing catchment. In addition,

Table 1: Seldom-Monitored Stormwater Management Practices (National Urban BMP Database, 1997)

Stormwater Practice Design	Number of Monitoring Studies
Biofilter	0
Filter/Wetland Systems	0
Filter Strips	0
Infiltration Basins	0
Bioretention	1
Wet Swale	2
Gravel-based Wetlands	2
Infiltration Trench	3
Porous Pavement	3
Perimeter Sand Filter	3

Table 2: Frequency that Selected Stormwater Pollutants Were Monitored In 123 BMP Performance Studies

Stormwater Parameter	Percent of Studies that Measured It
Total Phosphorus	94
Total Suspended Solids (TSS)	94
Nitrate-Nitrite Nitrogen	71
Total Zinc	71
Total Lead	65
Organic Carbon	56
Soluble Phosphorus	55
Total Nitrogen	54
Total Copper [a]	46
Bacteria	19
Total Cadmium [a]	19
Total Dissolved Solids	13
Dissolved Metals	10
Hydrocarbons	9

[a] Excludes studies where parameter was below detection limits.

pollutant removal percentages can be strongly influenced by the variability of the pollutant concentrations in incoming stormwater. If the concentration is near the "irreducible level" (see Schueler, 1996), a low or negative removal percentage can be recorded, even though outflow concentrations discharged from the stormwater practice were actually relatively low.

Gaps in the Stormwater Practice Performance Database

A key element of the database project was to identify current gaps in stormwater practice monitoring research. To this end, the entire database was analyzed to find practices that had seldom been monitored and identify key stormwater pollutants that were not frequently sampled. This information is helpful for setting future monitoring priorities in order to close these research gaps.

Key gaps in our current knowledge about urban stormwater management practice performance are shown in Table 1. As can be seen, the pollutant removal performance of 10 commonly-used practice designs have been tested less than four times. Consequently, we have less confidence in the computed removal rates for these practices. Perhaps the most critical gap in stormwater practice performance research exists for infiltration and bioretention practices, which, as of yet, have never been adequately monitored in the field. To some extent, the lack of performance monitoring reflects the fact that stormwater enters these practices in sheetflow and often leaves them by exfiltrating into the soil over a broad area. Since runoff is never concentrated, it is extremely difficult to collect representative samples of either flow or concentration that are needed to evaluate removal performance. This sampling limitation has also made assessment of filter strips problematic.

More research on the performance of water quality swales (i.e., dry swales and wet swales) appears warranted, because so few have been monitored, and the recorded removal rates are so different. The performance of other stormwater practices have not been scrutinized either because they are relatively new (i.e, organic filters and submerged gravel wetlands) or are smaller versions of frequently sampled practices (i.e., pocket wetlands and ponds).

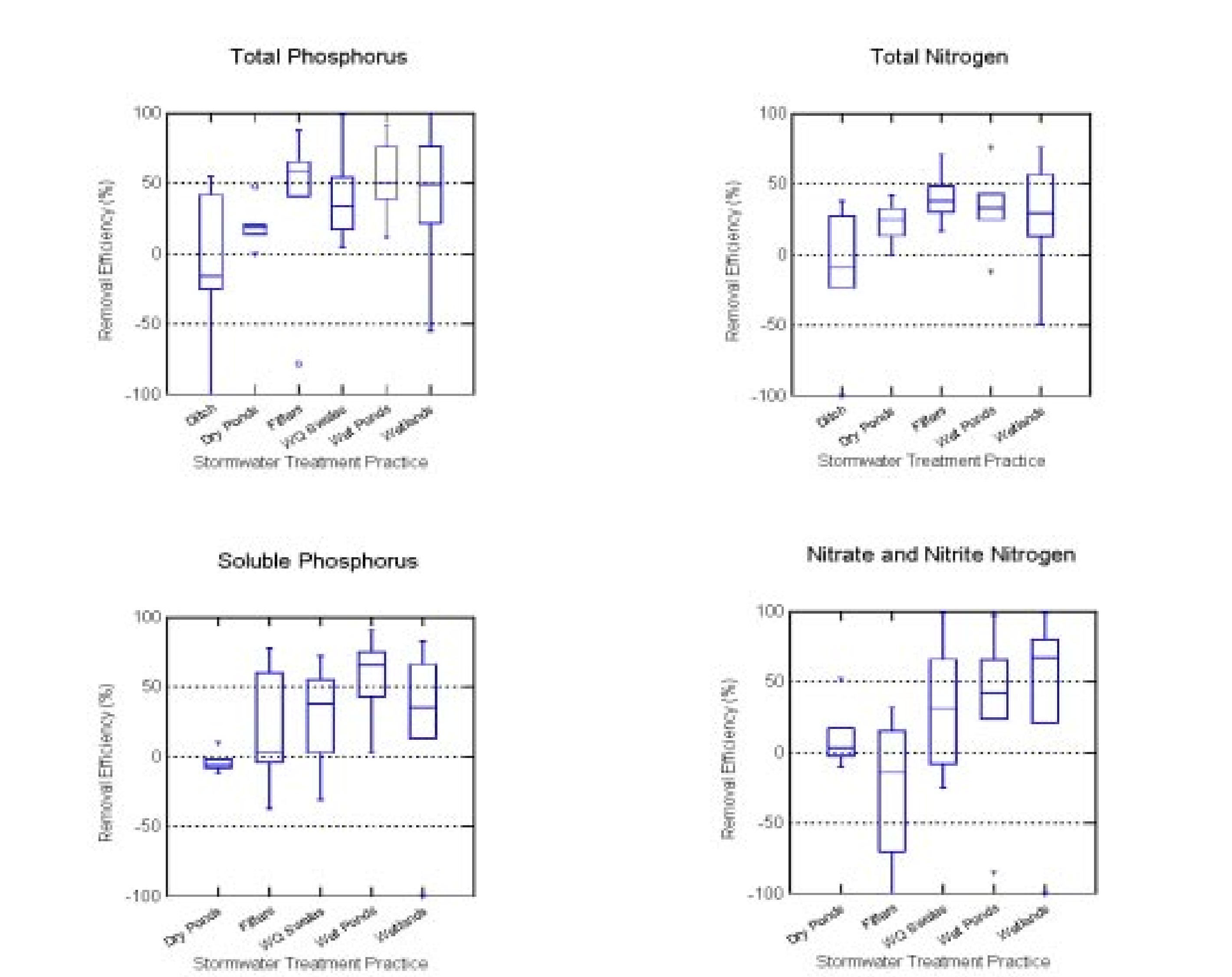
While ponds, wetlands, sand filters and open channels have been extensively monitored in the field (10 to 30 studies each), significant gaps exist with respect to individual stormwater parameters (Table 2). In particular, stormwater practice pollutant removal data is scarce with respect to bacteria, hydrocarbons, and dissolved metals. These three parameters have only been measured in 10 to 20% of all stormwater practice performance studies, despite their obvious implications for human health, recreation, and aquatic toxicity. A greater focus on these important parameters is warranted in future monitoring efforts.

Comparison of Stormwater Practice Pollutant Removal Performance

The comparative removal efficiency of stormwater practice groups is shown in Figures 1 and 2 for a series of commonly sampled parameters. These "box and whisker" plots depict the statistical distribution of removal rates: the "whiskers" show the minimum and maximum values, whereas the "box" delimits where half of all values lie (range between 25 and 75% quartile). Thus, the more compact the box, the less variable the data. The line inside the box denotes the median value. Medians and sample sizes are also shown in Tables 3 and 4.

As both plots clearly show, performance can be extremely variable for many parameters within a group of stormwater management practices. (This is in addition to similar variability frequently seen from storm to storm, within an individual stormwater practice). Consequently, estimates of stormwater practice performance should not be regarded as a fixed or constant value, but merely as a long-run average.

Figure 1: Comparative Distribution of Pollutant Removal Rates by Practice Group–Nutrients



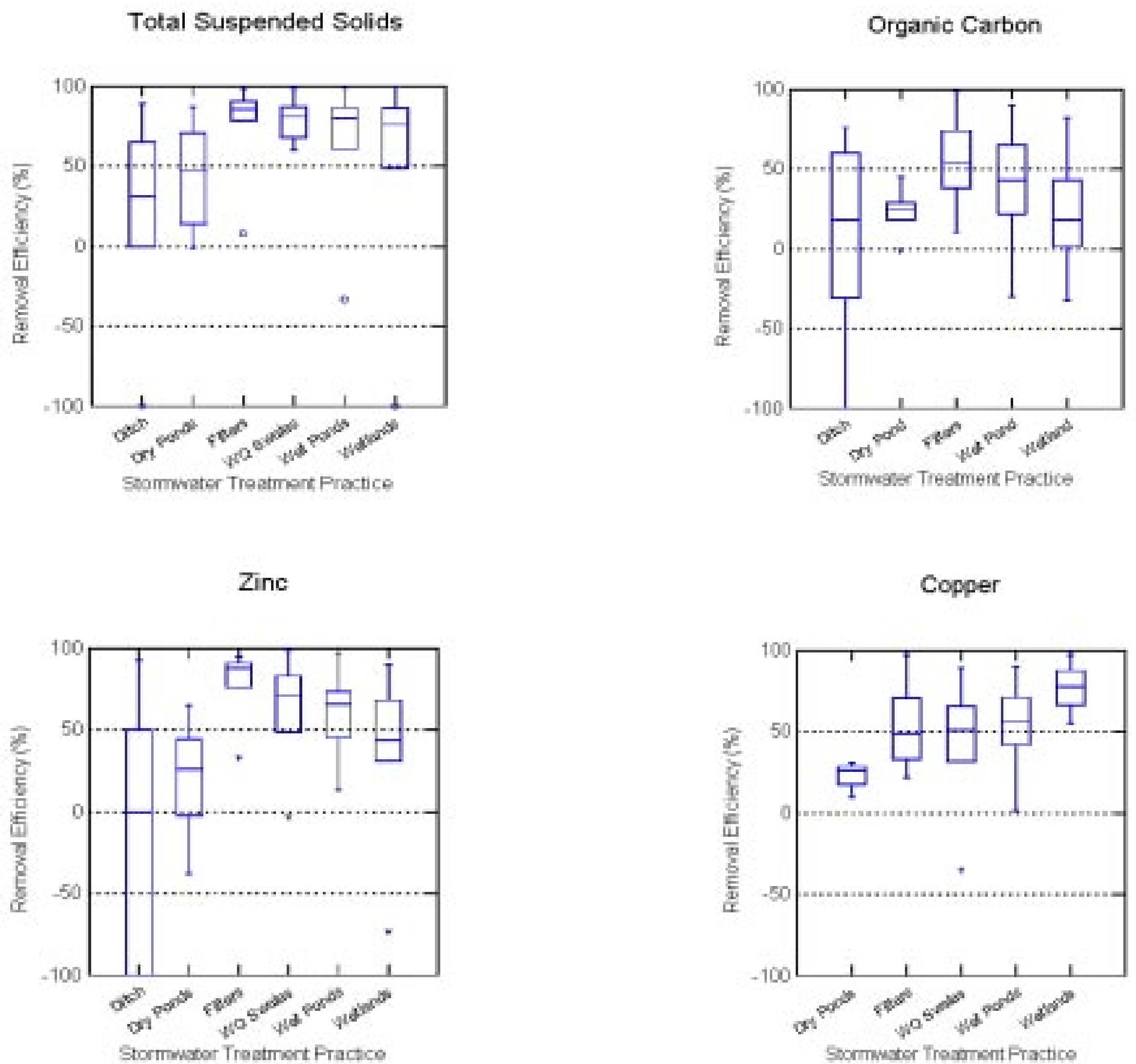
Phosphorus

While variable, most practice groups were found to have median removal rates in the 30 to 60% range for both soluble and total phosphorus. Once again, dry ponds and ditches showed low or negative ability to remove either phosphorus form. Interestingly, several practice groups exhibited very wide variation in phosphorus removal (e.g., note the large size of boxes for wetlands, water quality swales and sand filters). While sand filters were found to be effective in removing total phosphorus, they often exported soluble phosphorus.

Nitrogen

Most stormwater practice groups, on the other hand, showed a lower ability to remove total nitrogen, with typical median removal rates on the order 15 to 35%. In contrast to phosphorus, most practice groups showed relatively low variation in total nitrogen removal. The groups differed greatly in their ability to remove soluble nitrogen. In a broad sense, the stormwater practice groups could be divided into two categories: "nitrate leakers" and "nitrate-keepers." Nitrate leakers tend to have low or even negative removal of this soluble form of nitrogen, and included filters, ditches, and dry ponds. In these practices, organic nitrogen is converted to nitrate in the nitrification process, but conditions do not allow for subsequent denitrification. Thus, these "leakers" produce more nitrate than is delivered to them. Nitrate keepers tend to have moderate removal rates and include wet ponds, wet ED ponds and shallow marsh. In these practices, algal and other plants take up nitrate, and incorporate it into organic nitrogen. Thus, "keepers" tend to remove more nitrate than is delivered to them. Some practice groups, such as water quality swales and pond/wetland systems, exhibit such wide

Figure 2: Comparative Distribution of Pollutant Removal Rates for Practice Groups–TSS, Carbon, Zinc and Copper



variability, that it is likely that some practices are acting as nitrate leakers and others as nitrate keepers.

Suspended Sediment

Most stormwater practice groups exhibited a strong capability to remove suspended sediment, with median removals ranging from 60 to 85% for most groups. The highest median removal was noted for sand filters, water quality swales, infiltration practices, and shallow marsh systems (all slightly above 80%). Most pond and wetland designs approached but did not surpass the 80% TSS removal threshold specified in Costal Zone Act Reauthorization Amendments (CZARA) Section 6217 (g) guidance. Ditches exhibited the greatest variability, and had a median sediment removal rate of 31%.

Carbon

The ability of urban stormwater management practices to remove organic carbon or oxygen demanding material, while quite variable, was generally fairly modest, with median removal rates on the order of 20 to 40%. A notable exception was water quality swales, which exhibited median removal rates in excess of 65%. It should be noted that some variability in carbon removal rates could be due to the lumping of total organic carbon, BOD, and COD together.

Trace Metals

Most stormwater practice groups displayed a moderate to high ability to remove total lead, and zinc from urban runoff. Typical median removal rates were on the order of 50 to 80%. Exceptions included open

Table 3: Comparison of Median Pollutant Removal Efficiencies Among Selected Practice Groups: Conventional Pollutants

Practice Groups	N	Median Removal Rate For Stormwater Pollutants (%)					
		TSS	TP	Sol P	Total N	NOx	Carbon
Detention Pond	3	7	19	0	5	9	8
Dry ED Pond	6	61	20	(-11)	31	(-2)	28
Wet Pond	29	79	49	62	32	36	45
Wet ED Pond	14	80	55	67	35	63	36
PONDS [a]	**44**	**80**	**51**	**66**	**33**	**43**	**43**
Shallow Marsh	23	83	43	29	26	73	18
ED Wetland	4	69	39	32	56	35	ND
Pond/Wetland	10	71	56	43	19	40	18
WETLANDS	**39**	**76**	**49**	**36**	**30**	**67**	**18**
Surface Sand Filters	8	87	59	(-17)	32	(-13)	67
FILTERS [b]	**19**	**86**	**59**	**3**	**38**	**(-14)**	**54**
INFILTRATION	**6**	**95**	**70**	**85**	**51**	**82**	**88**
WQ SWALES [c]	**9**	**81**	**34**	**38**	**84**	**31**	**69**
DITCHES	**11**	**31**	**(-16)**	**(-25)**	**(-9)**	**24**	**18**

N = Number of performance monitoring studies. The actual number for a given parameter is likely to be slightly less.
Sol P = Soluble phosphorus, as measured as ortho-P, soluble reactive phosphorus or biologically available phosphorus.
Total N = Total Nitrogen. Carbon= Measure of organic carbon (BOD, COD or TOC).
[a] Excludes conventional and dry ED ponds.
[b] Excludes vertical sand filters and vegetated filter strips.
[c] Includes biofilters, wet swales and dry swales.

Table 4: Median Stormwater Pollutant Removal Reported for Selected Practice Groups – Fecal Coliform Bacteria, Hydrocarbons and Selected Trace Metals

Practice Groups	Median Stormwater Pollutant Removal [d]					
	Bacteria [e]	HC [f]	Cd	Copper	Lead	Zinc
Detention and Dry ED Ponds	78	ND	32%	26%	54%	26%
PONDS [a]	**70**	**81**	**50**	**57**	**74**	**66**
WETLANDS	**78**	**85**	**69**	**40**	**68**	**44**
FILTERS [b]	**37**	**84**	**68**	**49**	**84**	**88**
INFILTRATION	**ND**	**ND**	**ND**	**ND**	**98**	**99**
WQ SWALES [c]	**(-25)**	**62**	**42**	**51**	**67**	**71**
DITCHES	**5**	**ND**	**38**	**14**	**17**	**0**

[a] Excludes dry ED and conventional detention ponds.
[b] Excludes vertical sand filters and vegetated filter strips.
[c] Includes biofilters, wet swales and dry swale.
[d] N is less than 5 for some BMP groups for bacteria, TPH and Cd, and medians should be considered provisional.
[e] Bacteria values represent mean removal rates.
[f] HC = hydrocarbons measured as total petroleum hydrocarbons or oil/grease.

channels and dry ED ponds that were generally ineffective at promoting settling. Median copper removal rates ranged from 40 to 60%, with highest removals seen for the water quality swales, stormwater wet ponds, and filter groups. It should be noted that only 10% of all stormwater practice studies measured soluble metal removal which is widely thought to be a better indicator of potential aquatic toxicity than total metals (which includes metals that are tightly bound to particles). A quick review of the few studies that examined soluble metals suggests that while removal was usually positive, it was almost always lower than total metal removal.

Bacteria

The limited monitoring of fecal coliform did not allow for intensive statistical analysis of the effectiveness of stormwater practice groups in removing bacteria from urban runoff. Preliminary mean fecal coliform removal rates ranged from 65 to 75% for ponds and wetlands, and 55% for filters. Based on very limited data, ditches were found to have no bacteria removal capability, while water quality swales consistently exported bacteria. To put the removal data in perspective, a 95 to 99% removal rate is generally needed in most regions to keep bacteria levels under recreational water quality standards.

Hydrocarbons

The limited monitoring data available suggested that most stormwater practice groups can remove most petroleum hydrocarbons from stormwater runoff. For example, ponds, wetlands, and filters all had median removal rates on the order of 80 to 90%, and water quality swales were rated at 62%. In general, the ability of a practice group to remove hydrocarbons was closely related to its ability to remove suspended sediment. In nearly every case, hydrocarbon removal was within 15% of observed sediment removal.

Implications

This re-analysis of urban stormwater management practice performance has several implications for watershed managers. For the first time, there is enough data to select specific practice groups on the basis of their comparative ability to remove specific pollutants. A second implication is that the pond and wetland practice groups have similar removal capabilities, although the pollutant removal capability of wetlands appears to be more variable than ponds. Infiltration practices do appear to have the highest overall removal capability of any practice group, whereas dry ED ponds and ditches have extremely limited removal capability. Water quality swales show promise for some pollutants but not for biologically available phosphorus.

Significant gaps do exist in our knowledge in regard to the removal capability of certain practice designs and stormwater parameters. Filling these gaps should be the major focus of future stormwater practice monitoring research. For the more well-studied practice groups (ponds, wetlands, and filters) research should be re-directed to investigate internal factors (geometry, sediment/water column interactions, etc.) that can cause the wide variability in pollutant removal that is so characteristic of stormwater practice monitoring. Such research could be of great value in developing better design strategies to dampen pollutant removal variability, thereby improving reliability in achieving pollutant reduction goals at the watershed scale.

—TRS

References

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Note: The Center updated its natural stormwater treatment database in 2000. While the comparative pollutant removal performance did not change greatly, the reader may want to consult this far more expanded database which is available from the Center.