National Pollutant Removal Performance Database for Stormwater Treatment Practices

2nd Edition

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Disclaimer

Executive Summary

The second edition of the *Stormwater Treatment Practice (STP) Pollutant Removal Performance Database* (the "Database") modifies, clarifies, and expands upon the original *National Database of BMP Pollutant Removal Performance* (the First Edition) by Brown and Schueler (1997).

The First Edition included 129 studies and spanned a 19-year period; the minimum storm sampling criteria was four sampling events, and little effluent concentration data was included. Major changes to the First Edition include the following:

- Addition of 24 studies
- Elimination of studies that did not meet the new minimum storm sample criteria of five
- Update of existing entries to include effluent concentration and other data where available
- Addition of new fields

Eight of the studies included in the First Edition were deleted because of insufficient storm sample size. In addition, concentration data were added to existing studies to make the database a more powerful analysis tool. More than half of the original studies included both influent and effluent concentration data, and these data were not consistently included in the First Edition. Finally, several fields were added since the First Edition, including *Age of the Facility*, *Drainage Class* (based on drainage area), *Land Use Quantification* (e.g., percent commercial, residential, etc.), and storage in *Watershed* and *Impervious Inches*. Unfortunately, many studies did not report these data explicitly. Consequently, the database does not currently have sufficient data to develop relationships between specific site or design characteristics and performance. One exception is the *Drainage Class* field, which classifies ponds and wetlands as Pocket, Regular, or Regional. Although the results are not conclusive, sufficient data are available to characterize each data class.

Table E.1 Median Pollutant Removal (%) of Stormwater Treatment Practices							
	TSS	**TP**	**Sol P**	**TN**	**NOx**	**Cu**	**Zn**
Stormwater Dry Ponds	47	19	-6.0	25	4.0	26[1]	26
Stormwater Wet Ponds	80 (67)	51 (48)	66 (52)	33 (31)	43 (24)	57 (57)	66 (51)
Stormwater Wetlands	76 (78)	49 (51)	35 (39)	30 (21)	67 (67)	40 (39)	44 (54)
Filtering Practices[2]	86 (87)	59 (51)	3 (-31)	38 (44)	-14 (-13)	49 (39)	88 (80)
Infiltration Practices	95[1]	70	85[1]	51	82[1]	N/A	99[1]
Water Quality Swales[3]	81 (81)	34 (29)	38 (34)	84[1]	31	51 (51)	71 (71)

1. Data based on fewer than five data points
2. Excludes vertical sand filters and filter strips
3. Refers to open channel practices designed for water quality

NOTES:
- Data in parentheses represent values from the First Edition (Schueler, 1997; Appendix D).
- Shaded regions indicate a difference of at least ± 5% from the First Edition.
- N/A indicates that the data are not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; Sol P= Soluble Phosphorus; TN = Total Nitrogen; NOx = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

The statistical reanalysis of the First Edition revealed some changes in the pollutant removal efficiencies of STPs (Table E.1). These changes can be attributed to the addition of new studies and revisions to the older studies. Most of the shaded regions represent a pollutant removal increase of at least 5%. Three exceptions are nitrogen removal for filtering practices, which decreased by 16%; and zinc and soluble phosphorus removal of stormwater wetlands, which decreased by 18% and 10% respectively. The STP group with the greatest change over original data is filtering practices. This result is not surprising, since a significant number of changes were made to this group (five studies were added to the original 14). In particular, the negative soluble phosphorus in the original was caused by a few values from organic filters, and from one perimeter filter that had become submerged, releasing soluble phosphorus.

Table E.2 Median Effluent Concentration (mg/L)[1] of Stormwater Treatment Practice Groups

	TSS	TP	OP	TN	NOx	Cu	Zn
Stormwater Dry Ponds	28[2]	0.18[2]	0.13[2]	0.86[2]	N/A[3]	9.0[2]	98[2]
Stormwater Wet Ponds	17	0.11	0.03	1.3	0.26	5.0	30
Stormwater Wetlands	22	0.20	0.09	1.7	0.36	7.0	31
Filtering Practices[3]	11	0.10	0.08	1.1[2]	0.55[2]	10	21
Infiltration Practices	17[2]	0.05[2]	0.003[2]	3.8[2]	0.09[2]	4.8[2]	39[2]
Water Quality Swales[4]	14	0.19	0.08	1.1[2]	0.35	10	53

1. Units for Zn and Cu are micrograms per liter
2. Data based on fewer than five data points
3. Excludes vertical sand filters and filter strips
4. Refers to open channel practices designed for water quality

NOTES:
- N/A indicates that the data is not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; OP = Ortho-Phosphorus; TN = Total Nitrogen; NOx = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Median effluent concentrations by STP groups are summarized in Table E.2. Effluent concentration data were added to the Database as a supplement to the pollutant removal capability of STPs. In some instances, pollutant removal percentage may not be a good indicator of the overall removal capability of a STP. 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" (Schueler, 1996), a low or negative removal percentage can be recorded even though outflow concentrations discharged from the STP were relatively low. Although these data represent a median, unlike the group mean reported in Schueler (1996), the data suggest that the typical concentration data reported in this initial study and are high compared with the results from the Database (see Appendix E).

The data presented in this study support the contention that most STP designs can remove significant amounts of sediment and total phosphorus in urban runoff. Most STP groups, on the other hand, showed a lower ability to remove nitrogen. This result suggests that non-structural nutrient reduction methods, in addition to stormwater STPs, may be needed to meet nutrient reduction targets.

Section 1.0 Introduction

Since the First Edition was compiled in 1997, a significant number of new monitoring studies have been performed. The Center recognized the need to incorporate the new studies and reevaluate the quality of the previous entries. The Database is a national compilation of 139 individual STP performance studies. The Database is intended for use by engineers, planners, and municipal officials as they consider STPs in conjunction with watershed restoration and protection efforts, stormwater management strategies, and stormwater design manuals and criteria.

The First Edition included 123 studies and spanned a 19-year period; the minimum storm sampling criteria was four storm sampling events and little effluent concentration data was included. Major changes to the Database include the addition of 24 new performance monitoring studies, the elimination of eight studies which did not meet the new minimum storm sample criteria of five, an update of existing entries to include concentration and other data where available, and the addition of new fields.

The research summaries are presented in Microsoft Access® format. Included in each summary are general site and location information, bibliographic information, and pollutant removal and concentration data for a variety of nutrient, metal, bacteria, organic and other parameters. These summaries are presented in Appendix A.

We have used the Database to update national pollutant removal statistics for various STP groups (e.g., wetlands, filters) as individual design variations (e.g., wet extended detention pond, perimeter sand filter) and to identify performance research needs. This report describes the methodology used to compile and update the Database and presents the summary pollutant removal data.

The Database consists of two components: (1) a dynamic computer database and (2) a series of STP pollutant removal efficiency summaries. The first component is described in detail in the following discussion. Section 3 provides the pollutant removal summaries.

The Database includes 139 data sheets cataloged in Microsoft® Access format. The Microsoft® Access format allows users to extract specific data, perform statistical analysis and enter additional study data. Each data sheet corresponds to an individual study or research effort. Each study is categorized according to STP group and design variation as shown in Table 1.1. Additional information provided on the data sheet includes bibliographic references, facility name and location, site descriptions, drainage class, STP design characteristics, and pollutant removal data. A complete listing of information provided on each data sheet is provided in Table 1.2.

Table 1.1 Stormwater Treatment Practices Group and Design Variation		
Group	**Design Variation**	
Stormwater Pond		
	Quantity Control Pond	Wet Extended Detention Pond
	Dry Extended Detention Pond	Wet Pond
	Multiple Pond System	
Stormwater Wetland		
	Shallow Marsh	Pond/Wetland System
	Extended Detention Wetland	Submerged Gravel Wetland
Open Channel Practice		
	Grass Channel	Dry Swale
	Ditch*	Wet Swale
Filtering Practice		
	Perimeter Sand Filter	Bioretention
	Surface Sand Filter	Organic Filter
	Vertical Sand Filter	Multi-Chambered Treatment Train
Infiltration Practice		
	Porous Pavement	Infiltration Trench
Other STPs		
	Stormceptor	Oil-grit separator

* Refers to an open channel practice not explicitly designed for water quality

Table 1.2 Pollutant Removal Data Sheet Fields	
Field	**Description**
Study Number	Unique number assigned to each study
Facility	STP or development name
State	State where STP is located
STP Group	Pond, wetland, filter, infiltration practice, open channel, or other
STP Design Variation	Specific type of STP (e.g., vertical sand filter or wet pond)
Drainage Class	Based on drainage area; STP is classified as pocket, regular, or regional
Author	Study author and year of publication
Reference	Bibliographic reference
No. of Storms	Number of storms or samples represented by data
Treatment Volume	Criteria for design and sizing of the STP
Watershed Inches	Runoff inches STP was designed to treat off entire drainage area
Impervious Inches	Runoff inches STP was designed to treat off the impervious portion of the drainage area
Drainage Area	STP catchment area (acres)
Slope	Slope of the STP (applicable to open channel practices)
Land Use	Dominant land use in the STP catchment area
Soil Type	Description of the underlying soil at site
STP Size	STP dimensions
Age of Facility	Number of years since installation of STP
STP Notes	Additional information regarding the STP
Performance Notes	Additional information regarding the study
% Efficiency Mass	Removal efficiency reported as mass or load reduction
% Efficiency Conc.	Removal efficiency reported as a concentration reduction
% Efficiency Other	Removal efficiency determined using a non-specified method
Concentration Inflow	Measurement of a specific pollutant concentration at the inflow
Concentration Outflow	Measurement of a specific pollutant concentration at the outflow
Organic Name	Specific organic parameter: BOD, TOC, or COD
Bacteria Type	Specific bacteria parameter: fecal coliform, total coliform, E. coli, streptococci or enterococci

Section 2.0 Methodology

The Database was compiled through a comprehensive literature search focusing on STP monitoring studies from 1990 to the present. In addition, approximately 60 previously collected STP monitoring studies from 1977 and 1989 were included in the Database (Strecker *et al.*, 1992 and Schueler, 1994). All STP studies considered for inclusion were reviewed with respect to three target criteria:

1. Five or more storm samples were collected
2. Automated equipment that enabled flow or time-based composite samples were used
3. The method used to compute removal efficiency was documented

All 139 studies included in the Database meet the second and third criteria. With respect to the number of storms sampled, more than three-quarters of the studies explicitly stated that they were based on five or more storm samples. Although the remaining studies did not report sample size, they were included if report text suggested a significant sampling effort.

2.1 Changes in the 2nd Edition

The primary purpose of this project was to improve upon the quality and size of the First Edition. Changes in the number of studies included in the Database are presented in Table 2.1. As previously stated, 24 studies were added since the First Edition, and eight studies were deleted because of insufficient storm sample size.

Pollutant removal percentages can be strongly influenced by the concentration of the pollutant in the incoming stormwater. If the concentration is near the "irreducible level" (Schueler, 1996), a low or negative removal percentage can be recorded, even though outflow concentrations discharged from the STP are relatively low. For this reason, concentration data was added to STP studies where available. Over half of the studies provided pollutant concentration data.

Several fields were added to provide a more comprehensive summary of each study, including *Age of Facility, Land Use Quantification, Drainage Class, Watershed Inches,* and *Impervious Inches*. The age of the facility is an important consideration, as factors such as sedimentation and maintenance needs can decrease pollutant removal efficiency over time. Unfortunately, less then 25% of the studies documented age. In order to provide a quantitative description of the land draining to the STP, the land use category was further divided into four classes: percent impervious cover, percent residential, percent commercial, and percent industrial. The new *Drainage Class* field classified ponds and wetlands as either Pocket, Regular or Regional based on their contributing drainage area. Stormwater ponds and wetlands that served a drainage area less than 10 acres were classified as Pocket; those with drainage areas greater than 10 acres but less than 300 acres were classified as Regular; and those with a drainage areas greater than 300 acres were classified as Regional. This new field eliminated the need for the pocket wetland design variation that was included in the First Edition, and thus it was removed as a STP type. Additional reorganization of STPs included the reclassification of the Filter/Wetland Systems into a more descriptive subcategory: Submerged Gravel Wetlands.

2.2 Conventions

During the development of the Database, several conventions were used to facilitate and simplify statistical analysis. These conventions are described below.

Database Entry Conventions

1. When more than one method was used to calculate pollutant removal in a specific STP study, mass- or loading-based measurements of removal efficiency were entered into the Database rather than concentration-based measurements.

2. Removal efficiency data generally correspond to the median values reported in the studies. When removal efficiencies were reported as a range of values, the average of the range was recorded in the Database.

3. Removal data reported as "no significant difference" were entered into the Database as zero removals. Removal data reported as "not detected" were not included in the Database.

4. Removal data reported as unspecified negative removals were entered as negative 25%. Negative removal data greater than 100% in magnitude were entered as negative 100% to prevent undue weighting in subsequent statistical analysis.

5. Organic carbon data included biological oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC) removal data.

6. Nitrate-Nitrite (NO_x) data include removal data for nitrate as well as combined nitrate-nitrite.

7. Ammonium (NH_4) data include ammonium and ammonia data.

8. Bacteria data include fecal streptococci, enterococci, fecal coliform, *E. coli* and total coliform.

9. Soluble phosphorus used to calculate efficiencies represented lumped data that includes ortho-phosphorus and dissolved phosphorus. Effluent concentrations, on the other hand, were calculated based only on ortho-phosphorus.

Table 2.1 Number of Studies by Stormwater Treatment Practice Group and Design Variation			
STP Type	**First Edition # of Studies (1997)**	**Database # of Studies (2000)**	**# of Studies with Concentration Data**
Pond			
Quantity Control Pond	2	3	0
Dry Extended Detention Pond	6	6	3
Wet Extended Detention Pond	7	14	11
Multiple Pond System	0	1	0
Wet Pond	29	29	15
Total	***44***	***53***	***29***
Wetland			
Shallow Marsh	17	23	9
Extended Detention Wetland	4	4	2
Pond/Wetland System	10	10	7
Pocket Wetland	1	0	0
Submerged Gravel Wetland	0	2	0
Filter/Wetland System	3	0	0
Total	***35***	***39***	***18***
Filtering Practice			
Organic Filter	5	7	5
Perimeter Sand Filter	3	3	3
Surface Sand Filter	6	8	2
Vertical Sand Filter	2	2	2
Vegetated Filter Strip	2	0	0
Bioretention	0	1	1
Total	***18***	***21***	***13***
Infiltration Practice			
Infiltration Trench	3	3	3
Porous Pavement	2	3	1
Total	***5***	***6***	***4***
Open Channel Practice			
Grass Channel	3	3	3
Ditch	11	9	3
Dry Swale	4	4	2
Wet Swale	2	2	2
Total	***20***	***18***	***10***
Other			
Oil-Grit Separator	1	1	1
Stormceptor	0	1	1
Total	***1***	***2***	***2***
Total for All STP Types	**123**	**139**	**76**

Statistical Conventions

The median removal efficiencies and effluent concentrations were computed for each STP group and each STP design variation for select pollutants. The box and whisker plot computations, including median, and 75^{th} and 25^{th} percentile values, are presented in Section 3. Computations for the box and whisker plots were performed only for water quality parameters that were sampled in five or more studies.

Monitoring Methodology

Monitoring methodology refers to field methods, laboratory analysis techniques, number of storms sampled, and pollutant removal efficiency computations. All of the studies included in the Database used automated sampling equipment. With respect to laboratory methods, it was assumed that appropriate analysis methods and quality assurance and quality controls were used. Individual studies often differed in the number of storms sampled, ranging from five to 81 storm events.

Efficiency Calculations

Pollutant removal efficiency, usually represented by a percentage, specifically refers to the pollutant reduction from the inflow to the outflow of a system. The two most common computation methods are event mean concentration (EMC) efficiency and mass or load efficiency. EMC efficiency is calculated by averaging the inflow and outflow concentrations for all storm events. This method gives equal weight to both small and large storms and does not account for water volume. Rainfall input is not considered. Event mean concentration efficiency is typically calculated as follows:

EMC efficiency (%) = $[(Conc_{in} - Conc_{out})/Conc_{in}] * 100$

where:

$Conc_{in}$ is the average of EMC at inflow.
$Conc_{out}$ is the average of EMC at outflow.

Mass efficiency is influenced by volume of water entering the STP and water losses within the STP (e.g., evapotranspiration and infiltration). Mass efficiency is typically calculated as follows:

Mass Efficiency (%) = $[(SOL_{in} - SOL_{out})/(SOL_{in})] * 100$

where:

SOL_{in} is the sum of incoming loads. This value may include sources other than the inflow such as rainfall or atmospheric deposition.
SOL_{out} is the sum of all outgoing loads at the outfall, calculated by multiplying the pollutant concentration by the outgoing volume of water from the STP.

The two equations presented above are methodologies to calculate efficiencies using EMC and mass techniques, but there are many variations of these two equations. As Table 2.2 illustrates, the specific methodology chosen can influence pollutant removals.

Table 2.2 Example EMC and Mass Efficiency Calculations

Storm No.	Flow in Fi (ft3)	Flow Out Fo (ft3)	Concentration In Ci (mg/L)	Concentration Out Co (mg/L)	Event Efficiency Concentration E(c)	Mass In (Ci*Fi)	Mass Out (Co*Fo)	Event Efficiency Mass (F)
1	16200	13680	0.35	0.13	63%	5670	1778	69%
2	7560	7200	0.12	0.15	-25%	907	1080	-19%
3	21960	19800	0.80	0.26	68%	17568	5148	71%
4	19080	19080	0.48	0.33	31%	9158	6296	31%
5	32760	31680	0.19	0.10	47%	6224	3168	49%
Avg.			**0.39**	**0.19**	**37%**			**40%**
Sum	**97560**	**91440**				**39528**	**17471**	

***Method 1:* 50%**
The average Ci and Co for all five storm events was applied to the EMC equation presented above. (0.39 - 0.19)/0.39
***Method 2:* 37%**
In this method, an average was taken of the EMCs calculated for individual storm events.
***Method 3:* 56%**
Method 3 used the average Fi and Fo in the Mass Efficiency equation provided above. (39528 - 17471)/39528
***Method 4:* 40%**
This removal efficiency was derived by taking an overall average of the Mass Efficiency calculated for each storm event.

Other methods that do not fall within the two categories presented above may also be used to compute removal efficiency. Methods classified as "Other" included mass balance and flux analysis. Several studies classified as "Other" determined the removal efficiency using inflow and outflow regression curves based on field data.

Strecker *et al.* (2000) also reported the discrepancies described in Table 2.2, and recommended that future monitoring efforts be standardized to yield fair comparisons between practices. When developing the Database, we did not adjust the technique used in the original study. However, when concentration data were reported, we did add the concentration-based efficiency as a field in the Database.

2.3 Caveats

The statistical analysis results should be used to examine the general removal capability of various groups and design variations of STPs. The computed median removal values are based on the broad spectrum of studies entered in the Database and represented removal capability under a variety of climatic and physiographic conditions. Furthermore, the data used to determine general removal capability are based on "best condition" values. In particular, most of the studies focused on STPs that were constructed within three years of monitoring.

The actual performance of a specific STP in the field may be influenced by a variety of factors, including the following:

- STP geometry
- Site characteristics
- Monitoring methodology (see Table 2.2)
- Influent pollutant concentrations

It is suspected that removal capability is influenced by the internal geometry and storage volume provided by the STP. Inappropriate internal geometry can sharply limit STP pollutant removal mechanisms. For example, closely located inlet and outlet may "short-circuit" the STP, allowing stormwater to exit before being treated. Site characteristics that can also influence removal capability include soil type, rainfall, latitude, catchment size, watershed land use, and percent impervious. However, it is not possible to quantify the relative influence of each of these factors on reported STP performance with currently available data.

2.4 Research Gaps in STP Performance

A key element of the 2nd Edition was the identification of current gaps in STP monitoring research. To this end, the entire Database was analyzed to identify the STP groups and design variations that have seldom been monitored and key stormwater pollutants that are infrequently sampled in monitoring studies. This information can be used to set future monitoring and research priorities.

The number of studies included in the Database for various STP groups and design variations and key stormwater pollutants are shown in Table 2.1. This table reveals critical gaps in current knowledge about urban STP performance. Several STPs have been tested fewer than four times. Given the limited number of research studies available for these STPs, there is less confidence in the computed removal rates for these practices. The STP designs that have been tested fewer than four times include the following:

- All Infiltration Practices
- Bioretention
- Swales (dry swales, wet swales, and grass channels)
- Filters (except for surface sand filters)
- Proprietary Products

While proprietary products have been extensively studied, many of the studies were restricted because they were conducted in the lab, rather than field-tested. Further, many proprietary products have been tested only by the manufacturer. Only independent monitoring studies were included in the database.

Perhaps the most critical gap in STP performance research exists for infiltration and bioretention practices, which have not yet 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 exfiltration into the soil over a broad area. Since runoff is never concentrated, it is extremely difficult to collect the 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 (e.g., biofilters, dry swales and wet swales) appears warranted, not only because so few have been monitored, but because of the wide removal variability among those that have been sampled. Other STPs have been the subject of scant performance research either because they are relatively new (e.g., organic filters and submerged gravel wetlands) or are smaller versions of frequently sampled practices (e.g., pocket wetlands and ponds).

While ponds, wetlands 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 2.3). In particular, bacteria and hydrocarbons, and dissolved metal data are scarce. Despite well-established correlations with human health, recreation, and aquatic toxicity, these three parameters were measured in only 10 to 20% of the STP performance studies included in the Database. A greater focus on these important parameters is warranted in future STP monitoring efforts.

Table 2.3 Frequency of Monitoring in Stormwater Treatment Practice Performance Studies for Select Stormwater Pollutants

Stormwater Pollutant	% of Studies Monitored
Bacteria	19
Cadmium, Total	19
Copper, Total	46
Hydrocarbons	9
Lead, Total	65
Nitrate-Nitrite Nitrogen	71
Nitrogen, Total	54
Organic Carbon	56
Phosphorus, Soluble	55
Phosphorus, Total	94
Total Dissolved Solids	13
Total Suspended Solids	94
Zinc, Total	71

Another remaining research gap is the ability to determine the relative benefits of various design features. For example, while it is assumed that increasing storage volume will improve treatment capability, it is not possible to develop a statistically significant relationship using the Database in its current form. One reason for this result is that storage in "impervious inches" is rarely reported. This value would most likely provide the best regression. Descriptions of other design features are also rarely reported.

Section 3.0 Results

In this section, pollutant removal and effluent data are presented in both tabular and graphical format. Tables 3.1 and 3.2 include pollutant removal efficiencies for various STP group and design variations. Table 3.3 presents pollutant removal data for ponds and wetlands of different drainage classes. Finally, Tables 3.4 and 3.5 include effluent concentration data for various STPs.

Removal and effluent concentration data are presented graphically in Figures 3.1-3.6. In these "box and whisker" plots, the "whiskers" represent the maximum and minimum values. The "box" represents the first and third quartile values, as well as the median.

As Figures 3.1 and 3.2 show, STP removal efficiency can vary significantly both between STP groups and among STPs within the same design variation. Consequently, estimates of STP efficiency should not be regarded as a fixed or constant value, but rather as a general estimate of long-term performance. Nevertheless, some generalizations can be made regarding the relative performance of STP groups based on the data in these figures, and in Tables 3.1 and 3.2. Overall, dry ponds perform worse than any other STP group, particularly for soluble pollutant forms. Infiltration practices appear to have the highest removal rates. This result should be viewed with some scrutiny, however, because of the difficulties associated with monitoring infiltration practices, and the fact that few have been monitored. Ponds and wetlands appear to have similar removal rates, with a few exceptions. Ponds have higher removal rates for metals. In addition, while the two groups have similar removal rates for total nutrient removal, ponds have much higher removal rates for soluble phosphorus, while wetlands are more effective at removing soluble nitrogen (i.e., NO_x).

Filters perform relatively well, with the exception of removals for soluble forms of nutrients. Filters do have reasonably high rates for total nitrogen and total phosphorus, however. Most likely, nutrients are transformed from the organic or sediment-bound form of the nutrient within the filter, and flushed out during subsequent storm events. This phenomenon would explain the very low removals for soluble phosphorus and nitrate. Water quality swales appear to perform similarly to ponds or wetlands. Some of these removal rates for TN are very high, and are based on very few data points.

In general, it is difficult to distinguish between specific design variations due to limited data. A few exceptions are the vertical sand filter and the ditch, which consistently perform poorly when compared with other design variations within the same STP group.

Table 3.1 Median Pollutant Removal (%) of Stormwater Ponds and Wetlands

	TSS	TP	Sol P	TN	NO_x	Cu	Zn
Stormwater Dry Ponds							
Quantity Control Pond*	3	19	0	5	9	10	5
Dry Extended Detention Pond	61	20	-11	31*	-2*	29*	29*
Group Median ± 1 St. Dev	**47** ±32	**19** ±13	**-6** ±8.7	**25** ±16	**3.5** ±23	**26***	**26** ±37
Stormwater Wet Ponds							
Wet Extended Detention Pond	80	55	67	35	63	44	69
Multiple Pond System*	91	76	69	N/A	87	N/A	N/A
Wet Pond	79	49	62	32	36	58	65
Group Median ± 1 St. Dev	**80** ±27	**51** ±21	**66** ±27	**33** ±20	**43** ±39	**57** ±22	**66** ±22
Stormwater Wetlands							
Shallow Marsh	83	43	29	26	73	33	42
Extended Detention Wetland*	69	39	32	56	35	N/A	-74
Pond/Wetland System	71	56	43	19	40	58*	56
Submerged Gravel Wetland*	83	64	-10	19	81	21	55
Group Median ± 1 St. Dev	**76** ±43	**49** ±36	**36** ±45	**30** ±34	**67** ±54	**40** ±45	**44** ±40

* Data based on fewer than five data points
NOTES:
- N/A indicates that the data is not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; Sol P = Soluble Phosphorus; TN = Total Nitrogen; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Table 3.2 Median Pollutant Removal (%) of Stormwater Filtering, Infiltration, Open Channel, and Other Practices							
	TSS	TP	Sol P	TN	NO_x	Cu	Zn
Filtering Practices[1]							
Organic Filter	88	61	30[2]	41[2]	-15	66[2]	89
Perimeter Sand Filter[2]	79	41	68	47	-53	25	69
Surface Sand Filter	87	59	-17[2]	32	-13	49	80
Vertical Sand Filter[2]	58	45	21	5	-87	32	56
Bioretention[2]	N/A	65	N/A	49	16	97	95
Group Median ± 1 St. Dev	**86** ±23	**59** ±38	**3** ±46	**38** ± 16	**-14** ±47	**49** ±26	**88** ±17
Infiltration Practices							
Infiltration Trench[2]	N/A	100	100	42	82	N/A	N/A
Porous Pavement[2]	95	65	10	83	N/A	N/A	99
Group Median ± 1 St. Dev	**95**[2]	**80** ±24	**85**[2]	**51** ±24	**82**[2]	N/A	**99**[2]
Open Channels							
Ditches[3]	31	-16	-25[2]	-9	24[2]	14[2]	0[2]
Grass Channel[2]	68	29	40	N/A	-25	42	45
Dry Swale[2]	93	83	70	92	90	70	86
Wet Swale[2]	74	28	-31	40	31	11	33
Group Median[4] ± 1 St. Dev	**81** ±14	**34** ±33	**38** ±46	**84**[2]	**31** ±49	**51** ±40	**71** ±36
Other							
Oil-Grit Separator[2]	-8	-41	40	N/A	47	-11	17
Stormceptor®[2]	25	19	21	N/A	6	30	21

1. Excludes vertical sand filters and filter strips
2. Data based on fewer than five data points
3. Refers to open channel practices not designed for water quality
4. Median value excludes ditches

NOTES:
- N/A indicates that the data is not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; Sol P = Soluble Phosphorus; TN = Total Nitrogen; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Figure 3.1 Stormwater Treatment Practice Pollutant Removal Efficiencies: Total Suspended Solids, Total Nitrogen, Total Khedjahl Nitrogen, and Nitrate and Nitrite Nitrogen

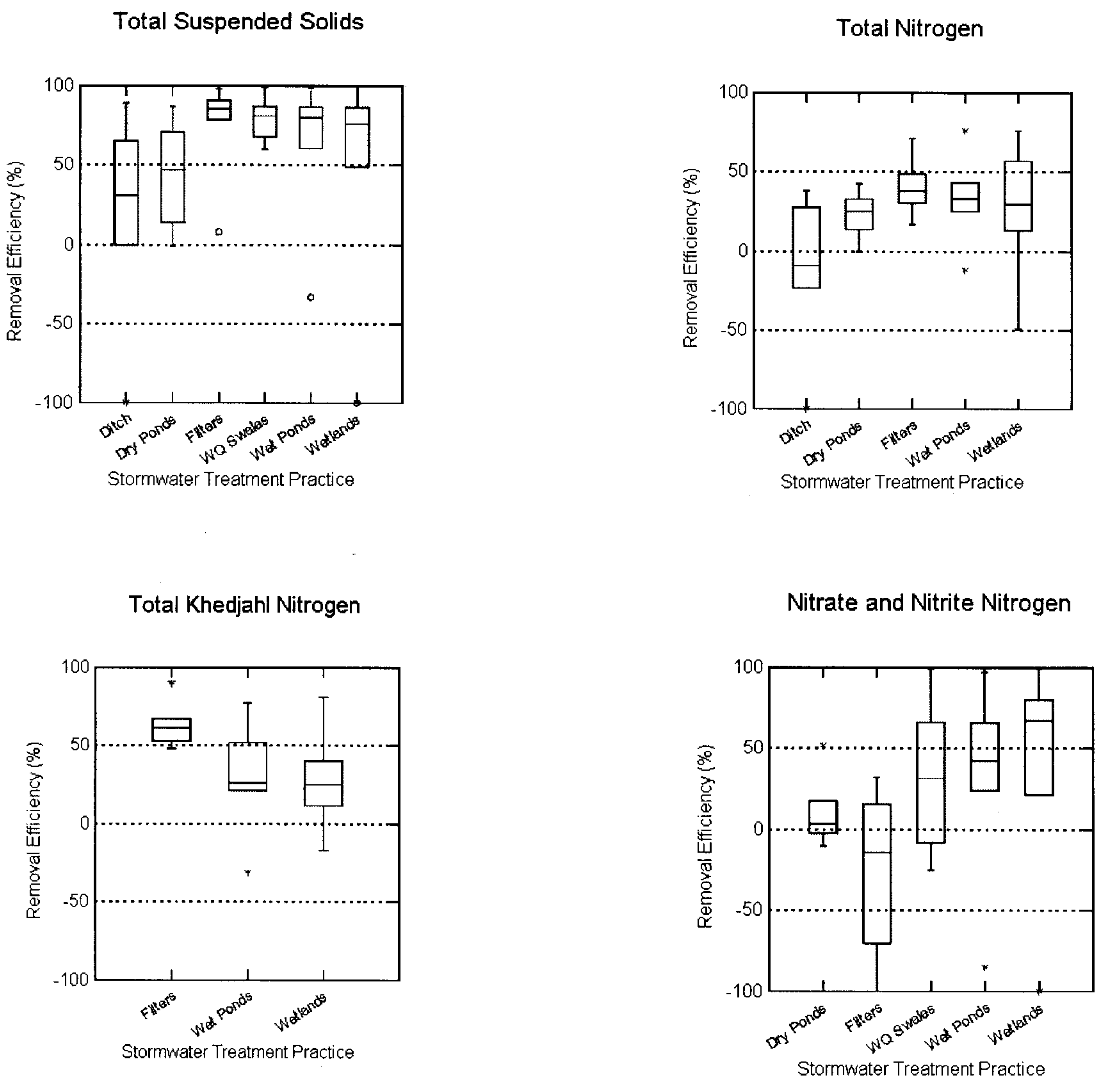
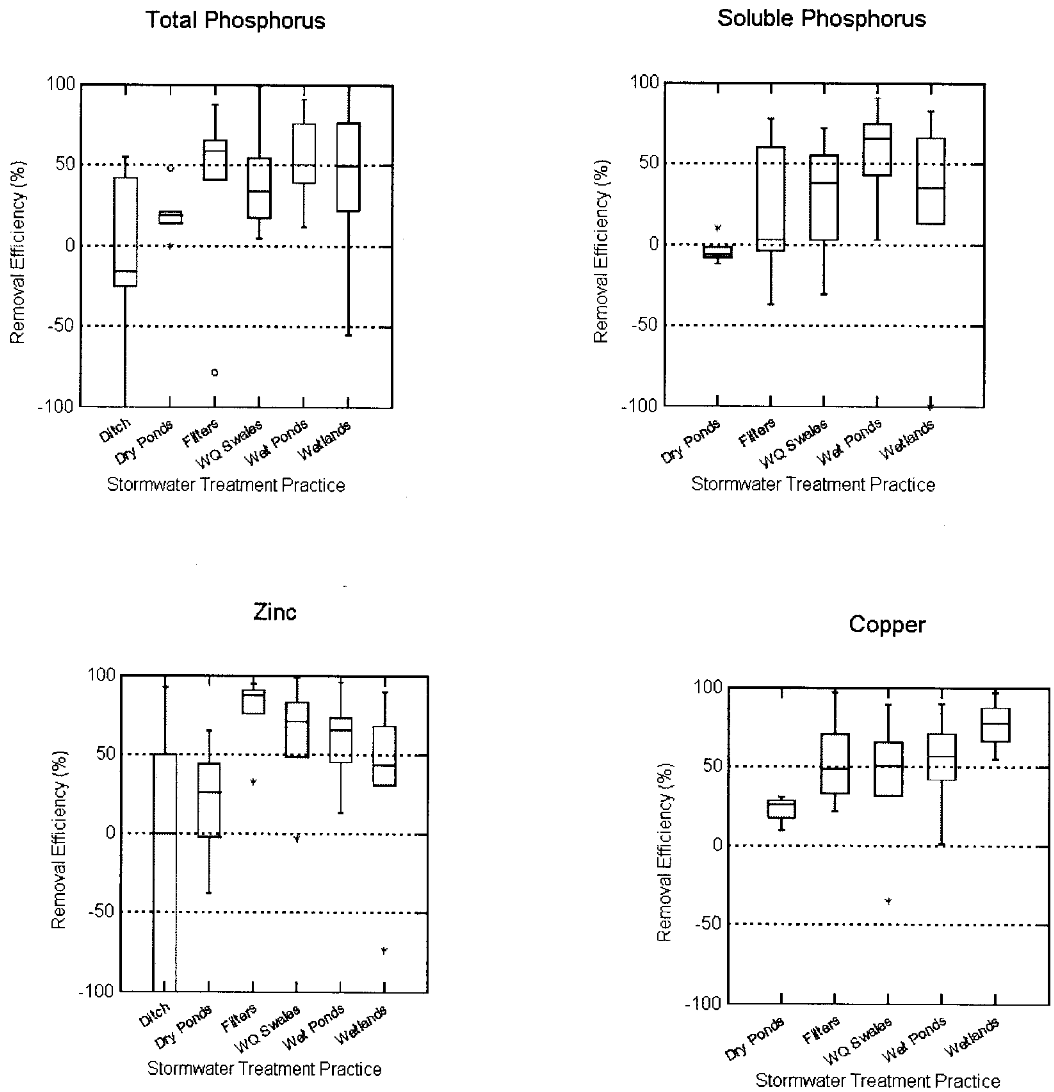


Figure 3.2 Stormwater Treatment Practice Pollutant Removal Efficiencies: Total Phosphorus, Soluble Phosphorus, Zinc, and Copper



A supplementary analysis compared removal rates of ponds and wetlands in different drainage classes (Table 3.3). Overall, these data do not support many conclusions regarding pollutant removal differences between drainage classes. In particular, data for Pocket ponds are sparse, with fewer than five studies represented. Based on the limited analysis conducted here, it appears that Regional wetlands have higher pollutant removal overall than other wetland designs. Regional ponds, on the other hand, have slightly lower efficiencies. The poor performance of Regional ponds may be caused by the influence of baseflow on these larger systems.

Table 3.3 Median Pollutant Removal (%) of Stormwater Treatment Practices by Drainage Class

		TSS	TP	Sol P	TN	NO_x	Cu	Zn
Stormwater Wet Ponds	Pocket[1]	87	78	65[2]	28[2]	67[2]	55	65
	Regular[3]	80	49	70	32	62	58	66
	Regional[4]	70	48	42	37	23	55[2]	43
Stormwater Wetlands	Pocket[1]	57[2]	57[2]	66[2]	44[2]	67[2]	25[2]	52[2]
	Regular[2]	61	36	37	15	45	60	36
	Regional[3]	80	43	35	35	68	57[2]	52[2]

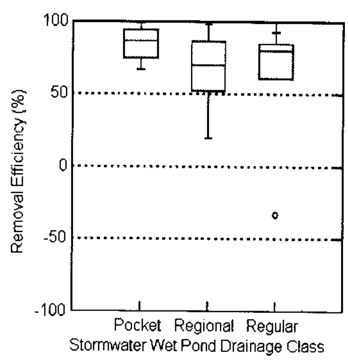
1. Drainage area < 10 acres
2. Data based on fewer than five data points
3. Drainage area <= 300 acres and >= 10 acres
4. Drainage area > 300 acres

NOTES:

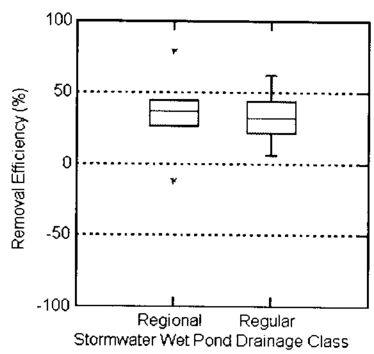
- TSS = Total Suspended Solids; TP = Total Phosphorus; Sol P = Soluble Phosphorus; TN = Total Nitrogen; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Figure 3.3 Median Pollutant Removal (%) by Drainage Class: Total Suspended Solids, Total Nitrogen, Total Khedjahl Nitrogen, and Nitrate and Nitrite Nitrogen

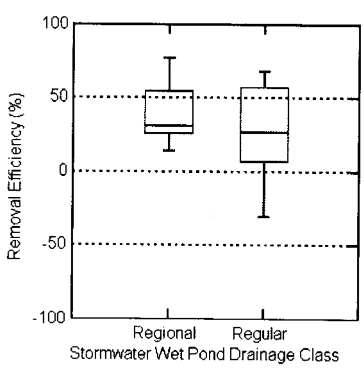
Total Suspended Solids



Total Nitrogen



Total Khedjahl Nitrogen



Nitrate and Nitrite Nitrogen

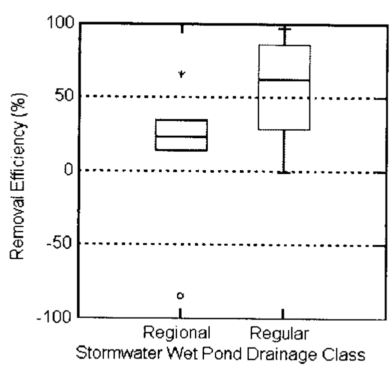
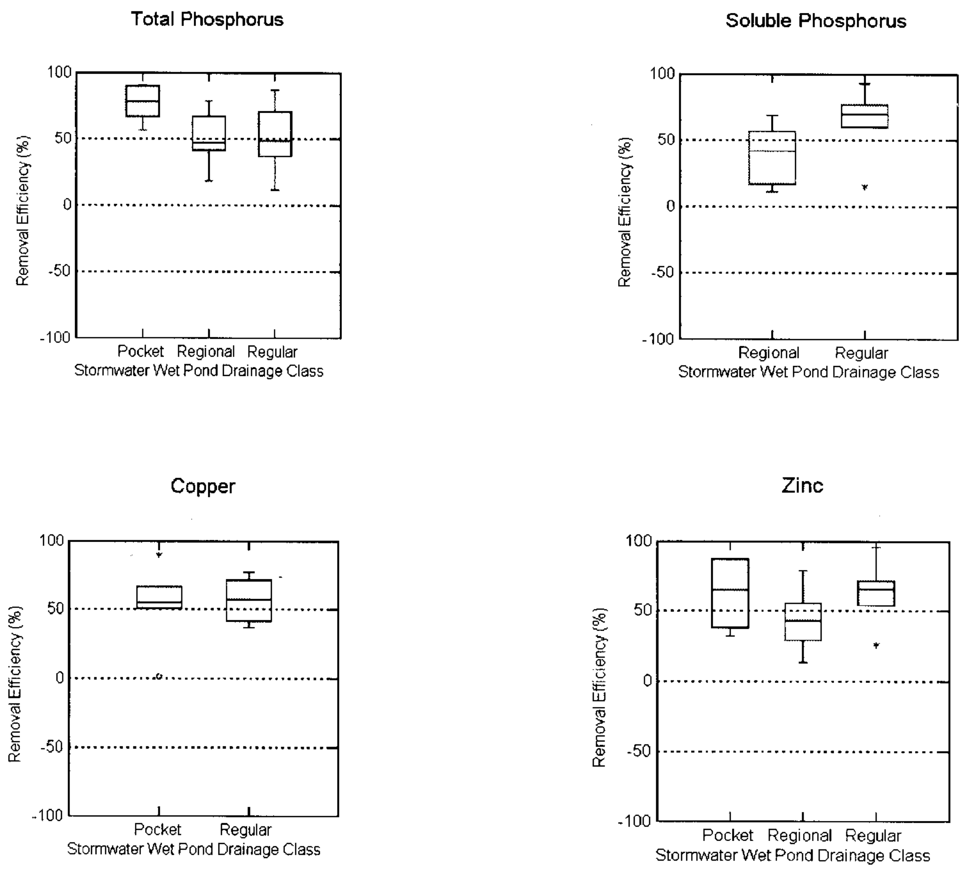


Figure 3.4 Median Pollutant Removal (%) by Drainage Class: Total Phosphorus, Soluble Phosphorus, Copper, and Zinc



A final analysis compared effluent concentrations in various STP groups and design variations. The effluent concentration is an important measure of practice performance, and some research suggests that this parameter may reflect practice performance better than removal efficiency (Schueler, 1996; Strecker *et al.*, 2000). Overall, the data reported in Tables 3.4 and 3.5 and in Figures 3.3 and 3.4 suggest that, for the studies included in the database, practices with high removal efficiencies also tend to have lower effluent concentrations. It is important to note that the removal data are highly variable. Furthermore, only a few studies were available to characterize each STP design variation, and some STP groups. Like efficiencies reported in this document, the effluent concentration represents a general trend in performance, and cannot be used to predict results from an individual practice.

For the most part, the effluent concentrations derived from the database are lower than those reported by Schueler (1996), who evaluated *irreducible concentrations* from stormwater treatment practices (see Appendix E). Part of this discrepancy may be caused by the fact that medians, rather than group means, are presented here.

Table 3.4 Median Effluent Concentration (mg/L)[1] from Stormwater Ponds and Wetlands

	TSS	TP	OP	TN	NO_x	Cu	Zn
Stormwater Dry Ponds[2,3]	**28**	**0.18**	**N/A**	**0.86**	**N/A**	**9.0**	**98**
Stormwater Wet Ponds							
Wet Extended Detention Pond	14	0.11	0.03	1.0	0.08	4.5	26
Wet Pond	18	0.12	0.03	1.5	0.30	6.0	30
Group Median ± 1 St. Dev	**17** ±17	**0.11** ±0.08	**0.03** ±0.03	**1.3** ±0.8	**0.26** ±0.6	**5.0** ±5.7	**30** ±16
Stormwater Wetlands							
Shallow Marsh	12	0.12	0.09[3]	1.7	0.90	4.5	30
Extended Detention Wetland[3]	29	0.27	N/A	1.6	0.84	N/A	N/A
Pond/Wetland System	23	0.20	0.05[3]	1.7	0.31	7.0	28
Group Median ± 1 St. Dev	**22** ±14	**0.20** ±0.81	**0.07** ±0.03	**1.7** ±8.8	**0.36**[3]	**7.0** ±5.0	**31** ±14

1. Units for Zn and Cu are micrograms per liter
2. Data available for Dry Extended Detention Ponds only
3. Data based on fewer than five data points

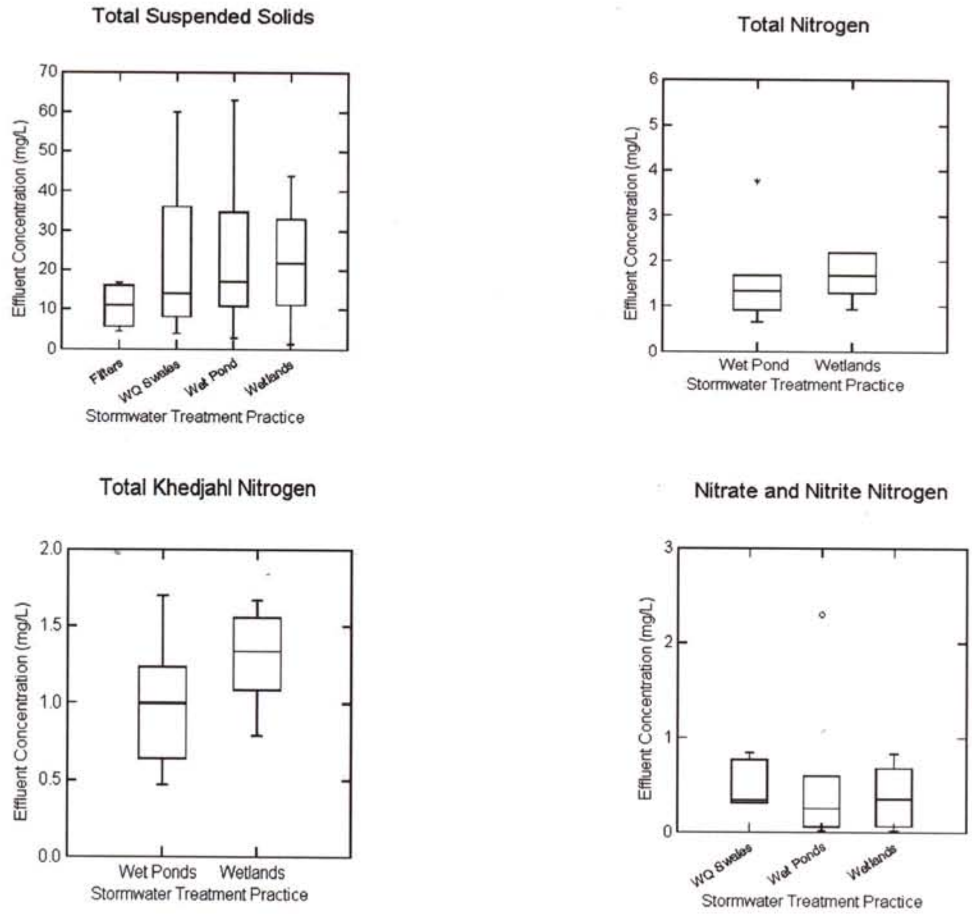
NOTES:
- N/A indicates that the data is not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; OP = Ortho-Phosphorus; TN = Total Nitrogen; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Table 3.5 Median Effluent Concentration (mg/L)[1] from Stormwater Filtering, Infiltration, Open Channel, and Other Practices							
	TSS	**TP**	**OP**	**TN**	**NO_x**	**Cu**	**Zn**
Filtering Practices[2]							
Organic Filter	12	0.10	0.50[3]	0.99[3]	0.60[3]	10[3]	22
Perimeter Sand Filter[3]	12	0.07	0.09	3.8	2.0	49	21
Surface Sand Filter[3]	38	0.13	N/A	1.8	N/A	2.9	23
Vertical Sand Filter[3]	74	0.14	0.04	1.3	0.60	5.5	20
Bioretention[3]	N/A	0.18	N/A	1.7	N/A	2.0	25
Group Median ± 1 St. Dev	**11** ±4.8	**0.10** ±0.14	**0.07**[3]	1.1[3]	0.60[3]	**9.7** ±0.3	**21** ±23
Infiltration Practices							
Infiltration Trench[3]	N/A	0.63	0.01	3.8	0.09	N/A	N/A
Porous Pavement[3]	17	0.10	0.01	N/A	N/A	N/A	39
Group Median ± 1 St. Dev	**17**[3]	**0.05**[3]	**0.003**[3]	**3.8**[3]	**0.09**[3]	**4.8**[3]	**39**[3]
Open Channels							
Ditch[3, 4]	29	0.31	N/A	2.4	0.72	18	32
Grass Channel[3]	15	0.14	0.09	N/A	0.07	10	60
Dry Swale[3]	16	0.40	0.24	1.4	0.35	23	87
Wet Swale[3]	8.2	0.13	0.08	0.96	31	13	39
Group Median ± 1 St. Dev	**14** ±19	**0.19** ±0.15	**0.09**[3]	**1.1**[3]	**0.35** ±0.27	**10** ±10	**53** ±46
Other							
Oil-Grit Separator[3]	48	0.41	0.05	1.9	0.20	13	170
Stormceptor®[3]	7.5	0.02	N/A	N/A	0.27	3.0	19
ALL Stormwater Treatment Practices	**17** ±19	**0.15** ±3.1	**0.04** ±0.05	**1.6** ±1.0	**0.38** ±0.70	**7** ±13	**30** ±41

1. Units for Zn and Cu are micrograms per liter
2. Excludes vertical sand filters
3. Data based on fewer than five data points
4. Refers to open channel practices not designed for water quality
5. Excludes ditches

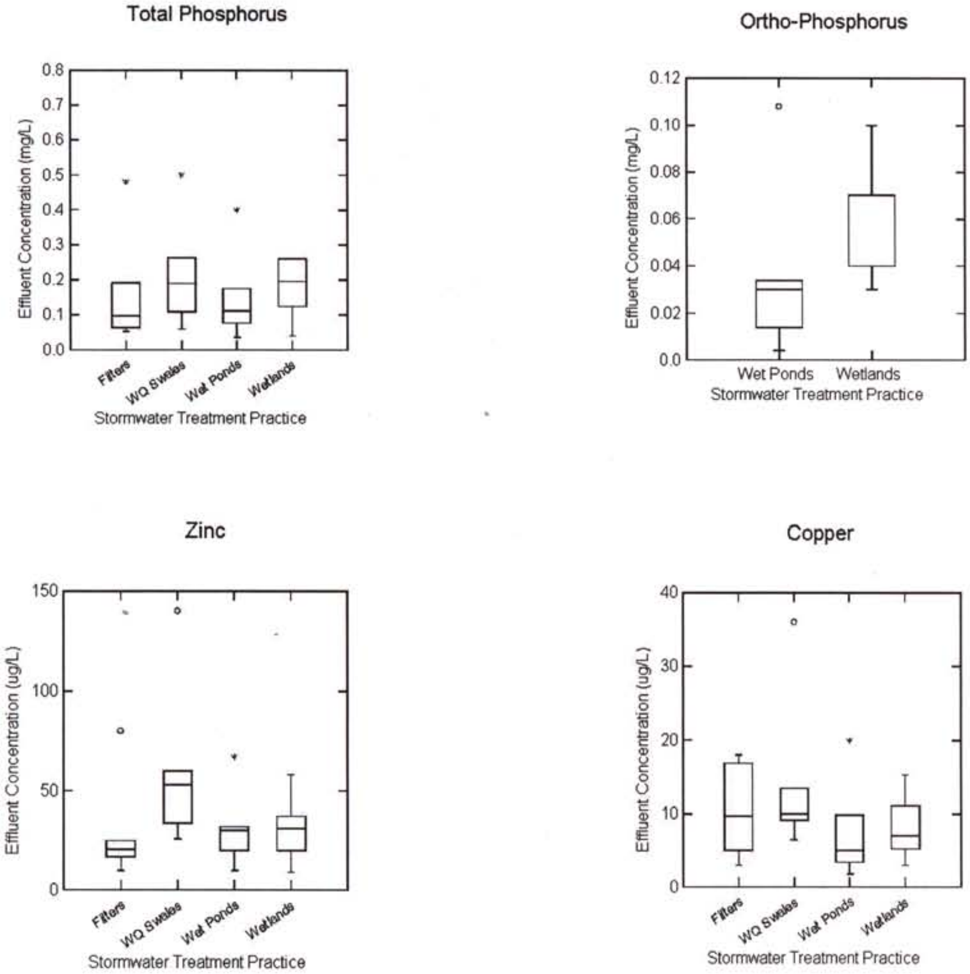
NOTES:
- N/A indicates that the data is not available.
- TSS = Total Suspended Solids; TP = Total Phosphorus; OP = Ortho-Phosphorus; TN = Total Nitrogen; NO_x = Nitrate and Nitrite Nitrogen; Cu = Copper; Zn = Zinc

Figure 3.5 Stormwater Treatment Practice Median Pollutant Effluent Concentrations: Total Suspended Solids, Total Nitrogen, Total Khedjahl Nitrogen, and Nitrate and Nitrite Nitrogen*



* The maximum wetland total nitrogen effluent concentration is 34.5 mg/L.

Figure 3.6 Stormwater Treatment Practice Median Pollutant Effluent Concentrations: Total Phosphorus, Ortho-Phosphorus, Zinc, and Copper*



* The maximum wetland total phosphorus effluent concentration is 26.5 mg/L.

3.1 Phosphorus

While results are variable, most STP design variations had median removal rates in the 30 to 60% range for both soluble and total phosphorus. Water quality swales showed poor removal relative to other practices. Pocket ponds appear to have the highest removal rate among the drainage classes at 78%. While submerged gravel wetlands were effective in removing total phosphorus, this STP was very ineffective in removing soluble phosphorus. Groups that exhibited very wide variation in phosphorus removal included wetlands, water quality swales, and ditches.

While there is some variability between outflow concentrations, most of the outliers have a low sample size of fewer than five studies. The median value for all studies containing phosphorus effluent concentrations is 0.15 mg/L. The median ortho-phosphorus concentration is 0.04 mg/L.

3.2 Nitrogen

Most STP design variations exhibited a limited ability to remove total nitrogen, with typical median removal rates on the order of 15 to 35%. With respect to soluble forms of nitrogen (e.g. nitrate), the STP groups differed greatly in their pollutant removal ability. In a broad sense, the STP 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 include filtering practices and dry ponds. In these practices, organic nitrogen is converted to nitrate in the nitrification process, but conditions do not allow for the subsequent denitrification process. Thus, these "leakers" produce more nitrate than is delivered to them. "Nitrate keepers" tend to have moderate removal rates and include wet ponds, wet extended detention ponds and shallow marshes. In these STPs, algae and other plants take up nitrate and incorporate it into organic nitrogen. Thus, "keepers" tend to remove more nitrate than is delivered to them.

Median effluent concentration for total nitrogen and nitrate and nitrite nitrogen are 1.60 mg/L and 0.38 mg/L respectively. In this case, there does not appear to be a strong correlation between low effluent concentrations and low removal efficiencies.

3.3 Suspended Sediment

Most STP groups exhibit strong ability to remove suspended sediment, with median removals ranging from 60 to 85% for most STP groups. Highest median removals were noted for sand filters, water quality swales, infiltration practices, and shallow marshes (all slightly above 80%). Most pond and wetland designs approached, but did not surpass, the 80% TSS removal threshold specified in CZARA 6217 guidance. Ditches exhibited the greatest removal variability, and had a median sediment removal rate of 31%. All pond drainage classes exhibited fairly high removal rates for suspended solids.

The majority of the effluent concentrations range from 10 to 30 mg/L with an overall median concentration of 16.7 mg/L.

3.4 Carbon

The ability of stormwater STPs to remove organic carbon or oxygen-demanding material was generally modest, with median removal rates in the order of 20 to 40% (Table 3.6). A notable exception was water quality swales, which exhibited median removal rates in excess of 65%. However, water quality swale carbon removal data were only based on three studies. It should be noted that variability in carbon removal rates could be attributed to the combination of total organic carbon, BOD and COD data.

3.5 Metals

Most STP groups displayed moderate to high pollutant removal rates for zinc. Typical median removal rates were on the order of 50 to 80%. Exceptions included open channels and dry ED ponds that were generally ineffective at promoting settling. Median copper removal rates ranged from 40 to 60%, with highest removals noted for the water quality swales, stormwater wet ponds, and filter groups. Figure 3.6 shows that regional ponds were ineffective at reducing zinc. Zinc and copper median effluent concentrations for all STPs are seven and 30 ug/L. It should be noted that only 10% of all STP studies measure soluble metal removal. Soluble metal concentration is 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 STP studies that examined soluble metals suggests that while removal is usually positive, it is almost always lower than total metal removal.

3.6 Bacteria

Bacteria median removal rates for select STPs are also provided in Table 3.6. The limited bacteria monitoring data did not allow for intensive statistical analysis. Preliminary mean bacteria 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 (Schueler, 1999).

Table 3.6 Median Bacteria and Organic Carbon Removal (%) by Stormwater Treatment Practice			
	Bacteria[1]	Organic Carbon[2]	Hydrocarbons
Stormwater Wet Ponds	70	43	81[5]
Stormwater Dry Ponds	78[5]	25	N/A[6]
Stormwater Wetlands	78[5]	18	85[5]
Filtering Practices[3]	37	54	84[5]
Water Quality Swales	-25[5]	69[5]	62[5]
Ditches[4]	5	18	N/A

1. Bacteria data include fecal streptococci, enterococci, fecal coliform, *E. coli.* and total coliform
2. Organic carbon data includes BOD, COD, and TOC removal data
3. Excludes vertical sand filters and filter strips
4. Refers to open channel practices not designed for water quality
5. Data based on fewer than five data points
6. N/A indicates that the data are not available

3.7 Hydrocarbons

The limited monitoring data available suggest that most STP groups can remove most petroleum hydrocarbons from stormwater runoff (Table 3.6). 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 STP 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.

3.8 Implications

This analysis of stormwater STP removal efficiency has several implications for the watershed manager:

- Pond and wetland STPs have similar removal capabilities, although the pollutant removal capability of wetlands appears to be more variable than ponds.
- Infiltration practices appear to have the highest overall removal capability of any STP group, although this is based on only a few data points.
- Dry ED ponds and ditches have extremely limited removal capability.
  Water quality swales show promise for most pollutants, but not for biologically available phosphorus.

Significant gaps do exist in our knowledge of the removal capability of certain STP designs and stormwater parameters. Filling these gaps should be the major focus of future STP monitoring research. The more well-studied STP groups (ponds, wetlands, and filters) should be re-directed to investigate internal factors (i.e., geometry and sediment/water column interactions) that may create the wide variability in pollutant removal that is characteristic of STP monitoring. Finally, more research is needed with respect to bacteria, dissolved metals, and hydrocarbons; all of these are pollutants associated with human health impacts. Such research could be of great value in developing better designs and reducing pollutant removal variability, allowing for more reliable pollutant reduction at the watershed scale.

The Center will continue to maintain and update the Database as new studies become available. Studies and research submitted to the Center for inclusion into the Database will be incorporated subject to examination for accuracy and appropriateness.

References

Schueler, T. 1994. "Review of Pollutant Removal Performance of Stormwater Ponds and Wetlands." Technical Note 6. *Watershed Protection Techniques*. 1(1):17-18. Center for Watershed Protection, Ellicott City, Maryland.

Schueler, T. 1996. "Irreducible Pollutant Concentrations Discharged from Urban BMPs." Technical Note 75. *Watershed Protection Techniques*. 2(2):369-371. Center for Watershed Protection, Ellicott City, Maryland.

Strecker, E., J. Kersnar, E. Driscoll, and R. Horner. 1992. *The Use of Wetlands for Controlling Stormwater Pollution.* EPA/600. Prepared for U.S. EPA, Region V Water Division. Woodward-Clyde. Portland, Oregon.

Strecker, E., M. Quigley, and B. Urbonas. 2000. *Determining Stormwater BMP Effectiveness*. National Conference on Tools for Urban Water Resource Management and Protection: February 7-10, 2000. Proceedings. U.S. Environmental Protection Agency. Washington, District of Columbia.

Appendix A: STP Pollutant Removal Database Summaries

UNDER CONSTRUCTION

Appendix B: Bibliography

BMP Category	BMP Type	Reference
Filtering Practice	Bioretention	Davis, A.; M. Shokouhian; H. Sharma; and C. Minami. 1998. Optimization of Bioretention Design for Water Quality and Hydrologic Characteristics. Department of Civil Engineering, University of Maryland, College Park.
Filtering Practice	Organic Filter	Corsi, S. and S. Greb. 1997. Demonstration project of Wisconsin Department of Natural Resources, United States Geological Survey and the City of Milwaukee. Personal communication with R. Pitt. 1997. In: Multi-Chamber Treatment Train Developed for Stormwater Hot Spots. Watershed Protection Techniques. Center for Watershed Protection. February 1997. 2(3): 445-449.
Filtering Practice	Organic Filter	Leif, W. 1999. Compost Stormwater Filter Evaluation. Snohomish County Public County Works. Everett, WA.
Filtering Practice	Organic Filter	Lower Colorado River Authority. 1997. Innovative NPS Pollution Control Program for Lake Travis in Central Texas. LCRA.
Filtering Practice	Organic Filter	Lower Colorado River Authority. 1997. Innovative NPS Pollution Control Program for Lake Travis in Central Texas. LCRA.
Filtering Practice	Organic Filter	Pitt, R. 1996. The Control of Toxicants at Critical Source Areas. The University of Alabama at Birmingham. 22 pp. (paper presented at the ASCE/Engineering Foundation Conference, August 1996 at Snowbird, Utah. Will be published by ASCE in 1997. Also in: Multi-Chamber Treatment Train Developed for Stormwater Hot Spots. Watershed Protection Techniques. Center for Watershed Protection. February 1997. Vol. 2(3): 445-449.

BMP Category	BMP Type	Reference
Filtering Practice	Organic Filter	Pitt, R. 1997. Multi-Chamber Treatment Train Developed for Stormwater Hot Spots. Watershed Protection Techniques. Center for Watershed Protection. February 1997. Vol. 2(3): 445-449.
Filtering Practice	Organic Filter	Stewart, W. 1992. Compost Stormwater Treatment System. W&H Pacific Consultants. Draft Report. Portland, OR. Also in: Innovative Leaf Compost System Used to Filter Runoff at Small Sites in the Northwest. Watershed Protection Techniques. Center for Watershed Protection. February 1994. Vol. 1(1): 13-14.
Filtering Practice	Sand Filter (P)	Bell, W., L. Stokes, L.J. Gavan and T.N. Nguyen. 1995. Assessment of the Pollutant Removal Efficiencies of Delaware Sand Filter BMPs. Final Report. Department of Transportation and Environmental Services. Alexandria, VA. 140 p. Also in: Performance of Delaware Sand Filter Assessed. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 291-293.
Filtering Practice	Sand Filter (P)	Horner, R.R., and C.R. Horner. 1995. Design, Construction and Evaluation of a Sand Filter Stormwater Treatment System. Part II. Performance Monitoring. Report to Alaska Marine Lines, Seattle, WA. 38 p. Also in: Performance of Delaware Sand Filter Assessed. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 291-293.
Filtering Practice	Sand Filter (P)	Horner, R.R., and C.R. Horner. 1995. Design, Construction and Evaluation of a Sand Filter Stormwater Treatment System. Part II. Performance Monitoring. Report to Alaska Marine Lines, Seattle, WA. 38 p. Also in: Performance of Delaware Sand Filter Assessed. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 291-293.

BMP Category	BMP Type	Reference
Filtering Practice	Sand Filter (S)	Barrett, M.; M. Keblin; J. Malina; R. Charbeneau. 1998. Evaluation of the Performance of Permanent Runoff Controls: Summary and Conclusions. Center for Transportation Research. Texas Department of Transportation. University of Texas. Austin, TX.
Filtering Practice	Sand Filter (S)	City of Austin, TX. 1990. Removal Efficiencies of Stormwater Control Structures. Final Report. Environmental Resource Management Division. 36 p. Also in: Developments in Sand Filter Technology to Improve Stormwater Runoff Quality. Watershed Protection Techniques. Center for Watershed Protection. Summer 1994. Vol. 1(2): 47-54.
Filtering Practice	Sand Filter (S)	City of Austin, TX. 1990. Removal Efficiencies of Stormwater Control Structures. Final Report. Environmental Resource Management Division. 36 p. Also in: Developments in Sand Filter Technology to Improve Stormwater Runoff Quality. Watershed Protection Techniques. Center for Watershed Protection. Summer 1994. Vol. 1(2): 47-54.
Filtering Practice	Sand Filter (S)	City of Austin, TX. 1990. Removal Efficiencies of Stormwater Control Structures. Final Report. Environmental Resource Management Division. 36 p. Also in: Developments in Sand Filter Technology to Improve Stormwater Runoff Quality. Watershed Protection Techniques. Center for Watershed Protection. Summer 1994. Vol. 1(2): 47-54.
Filtering Practice	Sand Filter (S)	City of Austin, TX. 1990. Removal Efficiencies of Stormwater Control Structures. Final Report. Environmental Resource Management Division. 36 p. Also in: Developments in Sand Filter Technology to Improve Stormwater Runoff Quality. Watershed Protection Techniques. Center for Watershed Protection. Summer 1994. Vol. 1(2): 47-54.

BMP Category	BMP Type	Reference
Filtering Practice	Sand Filter (S)	City of Austin, TX. 1996. Evaluation of Non-point Source Controls; a 319 Grant Project. Final Report. Water Quality Report Series. COA-ERM-1996-03.
Filtering Practice	Sand Filter (S)	Harper, H. and J. Herr. 1993. Treatment Efficiency of Detention With Filtration Systems. Environmental Research and Design, Inc. Final Report Submitted to Florida Department of Environmental Regulation. Orlando, FL 164 p.
Filtering Practice	Sand Filter (S)	Welborn, C. and J. Veenhuis. 1987. Effects of Runoff Controls on the Quantity and Quality of Urban Runoff in Two Locations in Austin, TX. USGS Water Resources Investigations Report. 87-4004. 88 p.
Filtering Practice	Sand Filter (V)	Barton Springs/Edwards Aquifer Conservation District. 1996. Final Report: Enhanced Roadway Runoff Best Management Practices. City of Austin, Drainage Utility, LCRA, TDOT. Austin, TX. 200 p.
Filtering Practice	Sand Filter (V)	Tenney, S.; M. Barrett; J. Malina; R. Charbeneau; and G. Ward. 1995. An Evaluation of Highway Runoff Filtration Systems. Center for Research in Water Resources. University of Texas at Austin.
Infiltration Practice	Infiltration Trench	Kuo, C.Y., G.D. Boardman and K.T. Laptos. 1990. Phosphorous and Nitrogen Removal Efficiencies of Infiltration Trenches. Dept. of Civil Engineering. VA Polytechnic Institute and State University. Prepared for: No. VA Planning District Commission, Occoquan Technical Advisory Committee and VA State Water Control Board. 129 p.

BMP Category	BMP Type	Reference
Infiltration Practice	Infiltration Trench	Kuo, C.Y., G.D. Boardman and K.T. Laptos. 1990. Phosphorous and Nitrogen Removal Efficiencies of Infiltration Trenches. Dept. of Civil Engineering. VA Polytechnic Institute and State University. Prepared for: No. VA Planning District Commission, Occoquan Technical Advisory Committee and VA State Water Control Board. 129 p.
Infiltration Practice	Infiltration Trench	Kuo, C.Y., G.D. Boardman and K.T. Laptos. 1990. Phosphorous and Nitrogen Removal Efficiencies of Infiltration Trenches. Dept. of Civil Engineering. VA Polytechnic Institute and State University. Prepared for: No. VA Planning District Commission, Occoquan Technical Advisory Committee and VA State Water Control Board. 129 p.
Infiltration Practice	Porous Pavement	Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments. Department of Environmental Programs. Also in: Weand, B., Grizzard, T. 1986. Interim Progress Report-Davis Ford Park-Urban BMP Demonstration Project. Occoquan Watershed Monitoring Laboratory-Department of Civil Engineering-Virginia Polytechnic Institute and State University.
Infiltration Practice	Porous Pavement	Schueler, T.R. 1987. Controlling Urban Runoff: A Practical Manual for Planning and Designing Urban BMPs. Metropolitan Washington Council of Governments. Department of Environmental Programs.
Infiltration Practice	Porous Pavement	St. John, M. 1997. Effect of Road Shoulder Treatments on Highway Runoff Quality and Quantity. University of Washington.

BMP Category	BMP Type	Reference
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Stormwater Wetland	Shallow Marsh	Reinelt et al., 1992. In: The Use of Wetlands for Controlling Stormwater Pollution. Strecker, E.W., J.M. Kersnar and E.D. Driscoll (Eds.). Woodward-Clyde Consultants. Portland, Oregon. Prepared for U.S EPA, Region V, Water Division, Watershed Management Unit. EPA/600 February 1992.
Stormwater Wetland	Shallow Marsh	Rushton, B. and C. Dye. 1993. An In-Depth Analysis of a Wet Detention Stormwater Sytem. Southwest Florida Water Management District. Brooksville, FL. 60 p. Also in: Pollutant Removal Capability of a "Pocket" Wetland. Watershed Protection Techniques. Center for Watershed Protection. Spring 1996. Vol. 2(2): 374-376.
Stormwater Wetland	Shallow Marsh	Urbonas, B., J. Carlson and B. Vang. 1994. Joint Pond-Wetland System in Colorado. An Internal Report of the Denver Urban Drainage and Flood Control District. Also in: Performance of a Storage Pond/Wetland System in Colorado. Watershed Protection Techniques. Center for Watershed Protection. Summer 1994. Vol. 1(2): 68-69.

BMP Category	BMP Type	Reference
Stormwater Wetland	Shallow Marsh	Yu, S; G. Fitch; and T. Earles. 1998. Constructed Wetlands for Stormwater Management. Virginia Transportation Research Council. Charlottesville, VA.
Stormwater Wetland	Shallow Marsh	Yu, S; G. Fitch; and T. Earles. 1998. Constructed Wetlands for Stormwater Management. Virginia Transportation Research Council. Charlottesville, VA.
Stormwater Wetland	Submerged Gravel Wetland	Egan, T., J.S. Burroughs and T. Attaway. 1995. Packed Bed Filter. Proceedings of the 4th Biennial Research Conference. Southwest Florida Water Management District. Brookeville, FL p. 264-274. Also in: Vegetated Rock Filter Treats Stormwater Pollutants in Florida. Watershed Protection Techniques. Center for Watershed Protection. Spring 1996. Vol. 2(2):372-374.
Stormwater Wetland	Submerged Gravel Wetland	Reuter, J., T. Djihan and C. Goldman. 1992. The Use of Wetlands for Nutrient Removal From Surface Runoff in a Cold-Climate Region of California: Results From a Newly Constructed Wetland at Lake Tahoe. Journal of Environmental Management. Vol. 36: 35-53. Also in: Performance of a Gravel-Based Wetland in a Cold, Hugh Altitude Climate. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 297-299.
Stormwater Wetlandf	Shallow Marsh	Carr, D. and B. Rushton. 1995. Integrating a Herbaceous Wetland into Stormwater Management. Stormwater Research Program. Southwest Flordia Water Management District. Brooksville, FL.

Appendix C: Eliminated STP Pollutant Removal Studies

Eliminated Stormwater Treatment Practice Pollutant Removal Studies[1]
Barton Springs/Edwards Aquifer Conservation District. 1996. Final Report: Enhanced Roadway Runoff Best Management Practices. City of Austin, Drainage Utility, LCRA, TDOT. Austin, TX. 200
Yu, S., M. Kasnick and M. Byrne. 1992. A Level Spreader/Vegetative Buffer Strip System for Urban Stormwater Management. Integrated Stormwater Management. p. 93-104. R. Field et al. Editors. Lewis Publishers. Boca Raton, FL. Also in: Level Spreader/Filter Strip System Assessed in Virginia. watershed Protection Techniques. Center for Watershed Protection. February 1994. Vol. 1(1): 11-12.
Yu, S., M. Kasnick and M. Byrne. 1992. A Level Spreader/Vegetative Buffer Strip System for Urban Stormwater Management. Integrated Stormwater Management. p. 93-104. R. Field et al. Editors. Lewis Publishers. Boca Raton, FL. Also in: Level Spreader/Filter Strip System Assessed in Virginia. watershed Protection Techniques. Center for Watershed Protection. February 1994. Vol. 1(1): 11-12.
Dorman, M.E., J. Hartigan, R.F. Steg and T. Quasebarth. 1989. Retention, Detention and Overland Flow for Pollutant Removal From Highway Stormwater Runoff. Vol. 1. Research Report. Federal Highway Administration. FHWA/RD 89/202. 179 p. Also in: Performance of Grassed Swales Along East Coast Highways. Watershed Protection Techniques. Center for Watershed Protection. Fall 1994. Vol. 1(3): 122-123.
Yousef, Y., M. Wanielista, H. Harper, D. Pearce and R. Tolbert. 1985. Best Management Practices: Removal of Highway Contaminants By Roadside Swales. Final Report. University of Central Florida. Florida Department of Transportation. Orlando, FL. 122 p. Also in: Pollutant Removal Pathways in Florida Swales. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 299-301.
Yousef, Y., M. Wanielista, H. Harper, D. Pearce and R. Tolbert. 1985. Best Management Practices: Removal of Highway Contaminants By Roadside Swales. Final Report. University of Central Florida. Florida Department of Transportation. Orlando, FL. 122 p. Also in: Pollutant Removal Pathways in Florida Swales. Watershed Protection Techniques. Center for Watershed Protection. Fall 1995. Vol. 2(1): 299-301.
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Maristany, A.E., R.L. Bartell. 1989. Wetlands and Stormwater Management: A Case Study of Lake Munson. Part I: Long-term Treatment Efficiencies. Wetlands: Concerns and Successes. American Water Resources Association. p. 215-229.
1: All studies were eliminated because they did not meet the new minimum storm sampling criteria of five.

Appendix D: Comparative Pollutant Removal Cabability of STPs

Appendix E: Irreducible Pollutant Concentrations Discharged from STPs