Determining Urban Stormwater Best Management Practice (BMP) Removal Efficiencies

Task 3.4 – Final Data Exploration and Evaluation Report

Prepared by

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Scope of Report

This memorandum is the first analysis of data contained in the National Stormwater Best Management Practices (BMP) Database. The task of quantifying the performance, effectiveness, and efficiency of the BMPs stored in the database and elucidating the relationship between and efficiency and static and state variables is a broad and complex subject. As a first analysis, given the existing data, the goal of this work was to "explore and evaluate" these relationships to the extent possible given the current data set and its limitations. The results shed light on the current state of the practice, underscore the need for detailed national guidance on BMP monitoring, and point in the direction of the need for high quality BMP monitoring and reporting.

1 Introduction

The purpose of this cooperative agreement between EPA and the American Society of Civil Engineers (ASCE) is to develop a more useful set of data on the performance and effectiveness of individual best management practices (BMPs). BMP monitoring data should not only be useful for a particular site, but should also be useful for comparing data collected in studies of both similar and different types of BMPs in other locations and with different design attributes. Most past BMP monitoring studies have provided very limited data that is useful for comparing BMP design and selection.

The initial data set and the Database on which it resides, are work products of Phases I and II of the cooperative agreement. During Phase I, protocols for the collection and storage of BMP information were established as part of a conceptual design for the Database. Phase I also included the compilation of an annotated bibliography for the identification of existing urban stormwater BMP monitoring documents. Phase II, Task 1 included the creation of the Database structure and software front end. Task 2 addressed the collection and review of BMP monitoring studies identified in the Phase I bibliography. The Task 2 collection of documents yielded ~500 references that were subsequently reviewed for inclusion in the database. This multileveled review of the collected documents produced ~71 BMPs that contained event based water quality data suitable for inclusion in the database. The extent of the design information for a number of the documents did not meet the detailed protocol for submission of design information to the Database. Primarily due to this shortfall, the evaluation of the relationship between design and efficiency will be limited until a significantly larger data set is compiled. Some of the data collected and stored in the initial data set were not comparable and were not explored utilizing the rigorous statistical methods described in this document.

This report describes the results of exploration and evaluation (Task 3 of Phase II) of the initial data set (Version 1.0) of the National Stormwater Best Management Practices Database. The primary goals of the data exploration and evaluation are to:

- Evaluate the efficiency and effluent quality the BMPs stored in the Database using a uniform statistical approach to the event based water quality data to obtain comparable estimates of efficiency and effluent concentrations, as appropriate.
- Utilize the results of the statistical evaluation of efficiency and mean effluent quality to quantitatively elucidate the relationships between efficiency and static and state variables (i.e., design, environmental, and climatic).

This document is broken down into five primary sections: description of the methodology used, an overview of the results of efficiency calculations by BMP type and parameter, exploration of the relationship between design, climatic, and environmental parameters and their influence on efficiency, a summary of conclusions, and recommendations.

2 Methodology Used for Evaluating Efficiency

A variety of methods were explored in establishing the approach to be used to conduct the evaluations of efficiency and effluent quality contained in this report. As an integral part of conducting this data exploration and evaluation, a method for conducting the work was established prior to the work being conducted. A memorandum, “Developing Performance Measures- Task 3.1 Technical Memorandum”, (seen in Appendix 1-A) was prepared and peer reviewed by members of UWRRC describing existing methods used and a study plan for the analyses contained in this report. A discussion of data preparation and the statistical and graphical approaches used to evaluate efficiency and effluent quality are presented in this section.

2.1 Data Preparation

Before data could be analyzed, it often needed to be prepared. This preparation process involved understanding the details of how the water quality data was collected. The Database provides detailed information on the specifics of each monitoring study. Rules were established to convert data having a variety of characteristics into a comparable data set. For example, in some cases multiple inlets were present and combinations of grab and composite samples were collected.

2.1.1 Compositing Techniques, Sample Type, and Multiple Inlets

The water quality used in this exploration can be broken down into two basic types:

- Composite Water Quality Data (manual or automatic compositing)
    - Flow weighted composite event mean concentrations (EMCs)

- Discrete Water Quality Data
    - Field measurements
    - Grab Samples

In a few cases, grab samples were collected in conjunction with automatic samples. For example, two inflows are present at the Carver Ravine Detention/wetland facility. The first of these is from runoff from the watershed directly upstream, the second inflow is from flow pumped from an adjoining, but not connected watershed. Automatic sampling was conducted for the watershed draining to the facility and discrete samples were collected for the runoff pumped to the BMP. In order to determine the effective event mean concentration for the inflows to the BMP, the two inflows were numerically composited. EMCs for the grab-sampled flow were estimated assuming a rectangular pollutograph (i.e., the single grab sample data taken was used as the event mean concentration for the pumped flows).

If a BMP had multiple inflows, the EMCs were calculated as the sum-product of the individual EMCs and the volume of flow for each inflow for the event divided by the total flow volume (for all inflows) for the event or,

$$\text{Composite EMC} = \frac{\sum_{i=1}^{n} EMC_i \cdot V_i}{\sum_{i=1}^{n} V_i}$$

where,

i: inflow monitoring station
n: total number of inflows

2.1.2 Statistical Distribution of Water Quality Data

Urban stormwater runoff EMCs for many constituents have been shown to be well fit by a log-normally distribution (U.S. EPA, 1983 and Harremoes, 1988, Van Buren et al., 1996) and justified theoretically by Chow (1954). The assumption that a population is log-normally distributed implies that the standard deviation is proportional to the mean.

The assumption that BMP effluent event mean concentrations are also log-normally distributed has additionally been explored in the literature. Van Buren et al., 1996 have stated that the normal distribution may be a better estimate for pond effluent and/or for soluble constituents, this assertion is supported by work conducted by Watt et al. 1989.

The assumption that both influent and effluent EMCs are well fit by the log-normal distribution has been explored for the data set used in this report and the assumption appears to be a good approximation of the distribution of water quality data in most cases. A number of parameters were not assumed to fit a lognormal distribution namely: pH, dissolved oxygen, bacterial counts (e.g., fecal coliform), and turbidity due to the nature of the methods used to quantify these parameters.

For dissolved and particulate water quality constituents the assumption of log-normality of the Version 1 data set has been explored in three ways using samples of the data:

- A comparison between the non-parametric and parametric analyses of variance (p-values within 10%) has been conducted to assess differences found using the different methods;
- Results of the Pearson Chi-square test indicated that, where an appreciable number of data points are available, the normal approximation is a good estimate of the central tendency and the distribution of the logarithm of the event concentrations. In cases where a small number of data points are present, there is often very little confidence that either the transformed or non-transformed data is well represented by a normal distribution; and
- Graphical probability plots of influent and effluent were examined.

For purposes of this study, log-normality was assumed; in some specific cases normality may be a more appropriate assumption.

An example from the Database best demonstrates the consequences of assuming log-normality. The following example has been taken from the Tampa Office Pond data (1994-1995) for total suspended solids (TSS). Figure 2.1 shows the normal probability plot for the raw untransformed data. The straight line fit represents the normal distribution fit to the data and the dashed line represents the 95% confidence interval. A box and whisker plot superimposed on a vertical histogram with normal curve approximation is shown in Figure 2.2, further demonstrating the poor results from assuming that the raw data is normally distributed. Figures 2.3 and 2.4 show the same data log-transformed and demonstrate the better fit of the data after transformation. These results are typical for a large number of BMPs and parameters examined.

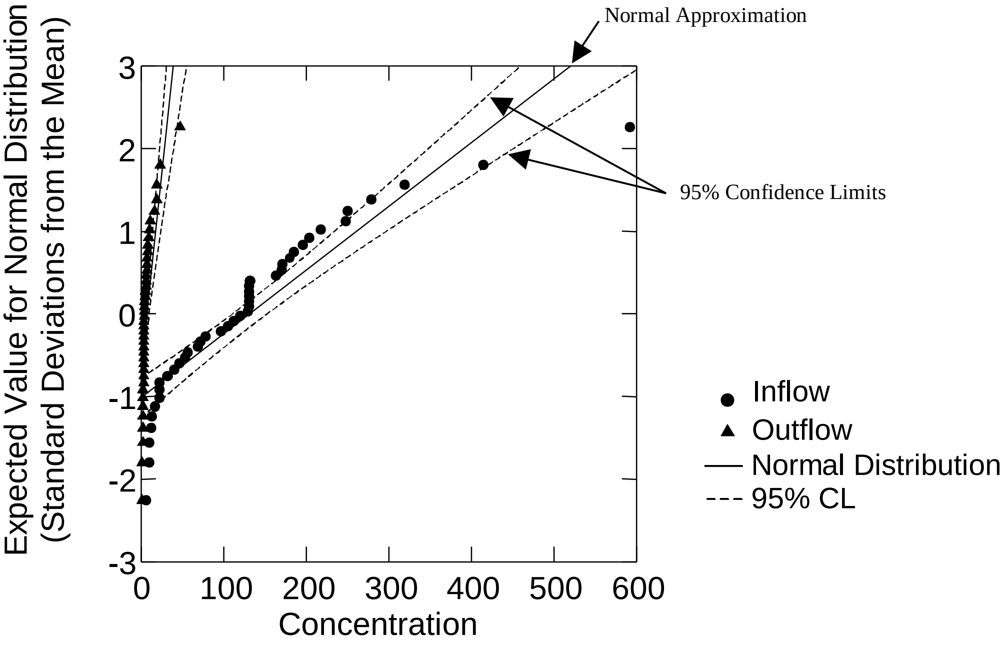


Figure 2.1 Normal Probability Plot for TSS Data for the Tampa Office Pond 1994-1995 Prior to Log-Transformation.

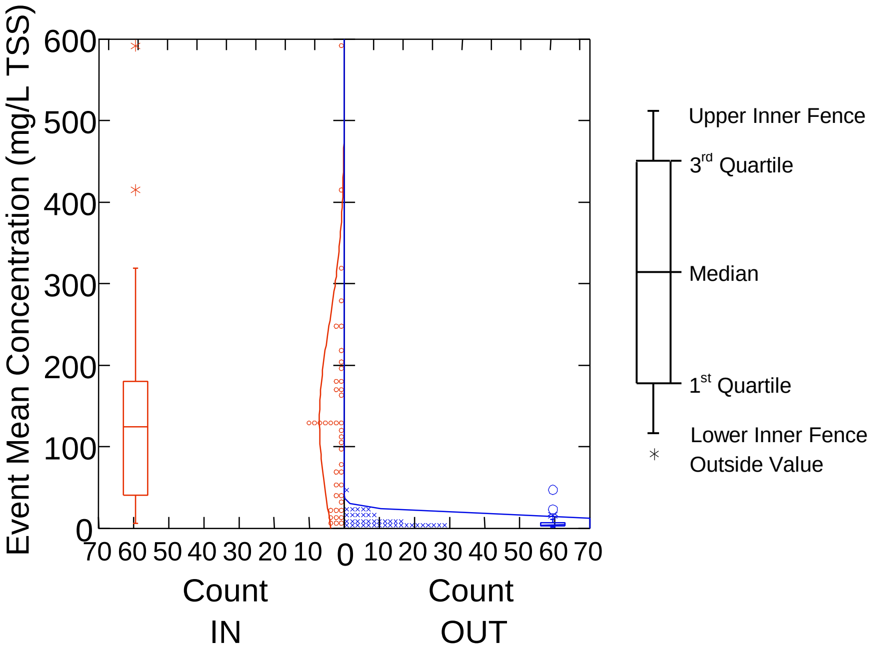


Figure 2.2 Box Plot and Histogram for TSS Data for the Tampa Office Pond 1994-1995 Prior to Log-Transformation. Normal curve provides only relative central tendency and variance and is not fit to the histogram.

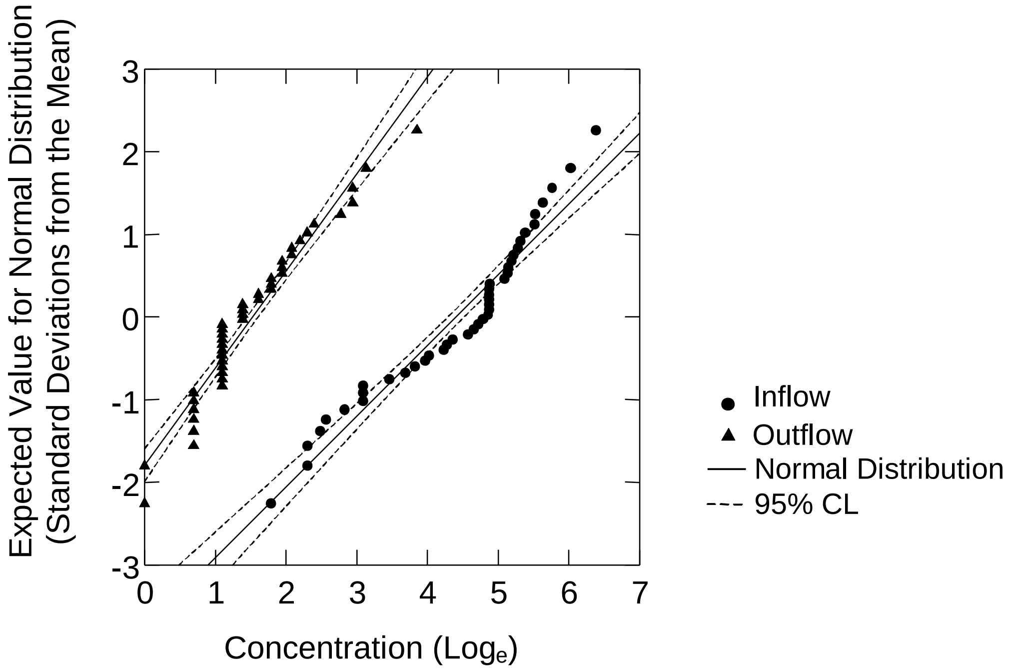


Figure 2.3 Normal Probability Plot for TSS Data for the Tampa Office Pond 1994-1995 After Log-Transformation.

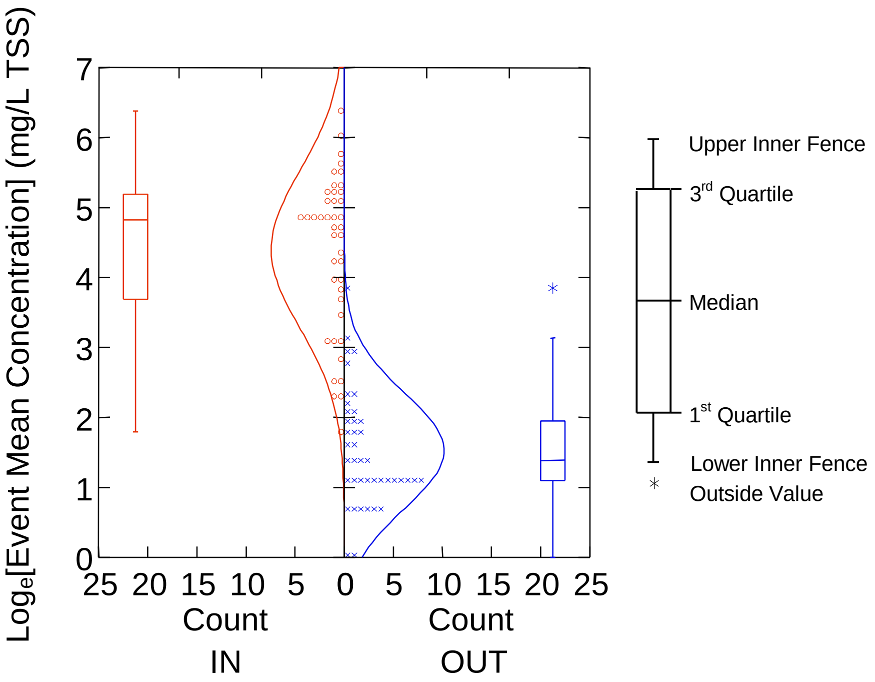


Figure 2.4 Box Plot and Histogram for TSS Data for the Tampa Office Pond 1994-1995 After Log-Transformation. Normal curve provides only relative central tendency and variance and is not fit to the histogram.

In addition, a subset of the water quality data was examined for the applicability of a generic power function transform for the data. In some cases the power function provided a better fit of data, however, the log-transform was used due to its simplicity and general acceptance.

2.2 Interpretation of Linear Influent/Effluent Plots

Plots showing event concentrations of influent and effluent are included in the analyses sheets presented in Appendices 2-B trough 2-F. These plots were compiled based on data collected for each storm. Water quality sample concentrations are identified on a linear scale with inflows and outflows being identified using different symbols. These graphs are provided to give an indication of the number of samples collected over the course of the study, which events had paired samples, and the relative difference between influent and effluent concentrations. The sample number indicates each period where samples were collected. This period typically coincides with a storm event; however, this is not always the case. Samples collected during a single dry period would be indicated with a separate sample number. More than one sample could have been collected at a single location during a period. This would be indicated by two of the same symbol at a single sample number. All samples are shown in chronological order. An example of the influent/effluent plot for the Tampa Office Pond (1994-1995) for TSS is presented in Figure 2.5

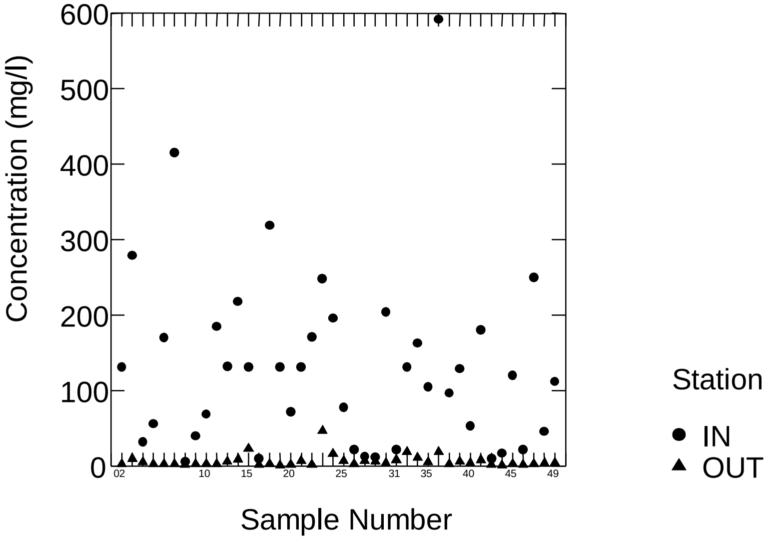


Figure 2.5 Linear Influent/Effluent Plot for the Tampa Office Pond (1994-1995) for TSS

2.3 Interpretation of Box and Whisker Plots

Box and whisker plots used in this report provide an evaluation tool for the distribution of inflow and outflow concentrations. The box and whisker plots used in this report have the following structure:

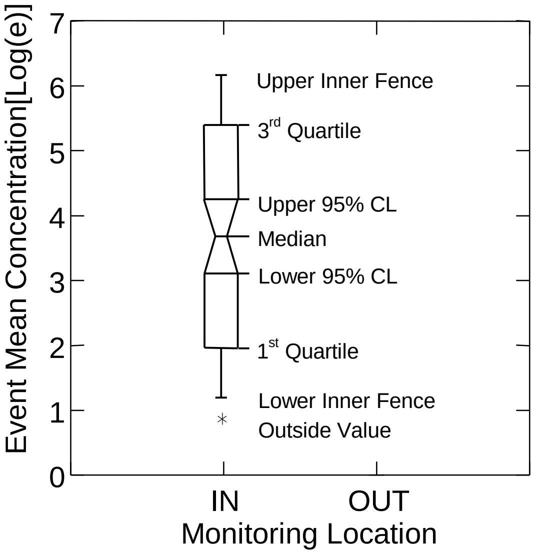


Figure 2.6 Annotation of Box and Whisker Plots

The median value gives an estimate of the central location of the distribution that is less sensitive than the mean to a single or small number of high or low observations. In addition, the median is a distribution-free statistic and therefore often gives a better estimate of the central location of the distribution when the data depart significantly from normality. Therefore, the box and whisker plots provide an additional tool, (i.e., in addition to comparisons of the log mean) which is helpful for assessing differences in influent and effluent quality particularly where normality may be a poor assumption.

The first and third quartiles delimit the range in which the central 50% of values lie (i.e., 25% of the values lie below the first quartile and 25% of the values lie above the third quartile). The whiskers on the box and whisker plots show the range of values that lies within the inner fences, which are defined by the following equations:

$$\text{Lower inner fence} = \text{value of the first quartile} - \left[1.5 \cdot \left(\text{median - value of the } 1^{\text{st}} \text{ quartile}\right)\right]$$

$$\text{Upper inner fence} = \text{value of the first quartile} + \left[1.5 \cdot \left(\text{median - value of the } 3^{\text{rd}} \text{ quartile}\right)\right]$$

The interquartile range is defined as the difference between the values at the limits of the middle 50% of the data, which is equal to the difference between the upper and lower hinges (i.e., the 1st and 3rd quartiles).

The confidence interval is shown by the location of the notches in the box plot and are based on the work of McGill et al. (1978) which recommend the following definition of the confidence interval (SPSS, 1999):

$$\text{Confidence Interval of the Median} = \text{Median} \pm \left[\frac{1.25 \cdot \text{IQR}}{1.35 \cdot \text{n}}\right]$$

IQR: interquartile range
n: number of samples

The upper and lower 95% confidence limits of the median allow the box and whisker plot to be used as a nonparametric, graphical analysis of variance. The extent to which the confidence intervals for the distributions of event concentrations at the inflow and outflow overlap give a good indication if the medians can be considered statistically different, (i.e., we can reject the null hypothesis that the inflow and outflow medians are the same). In most cases, the parametric analysis of variance (ANOVA), the non-parametric Kruskal-Wallis test, and the non-parametric Kolomogorov-Smirnov test will support the results of the notched box and whisker plot. Four primary behaviors are observed when comparing distributions of inflow and outflow event concentrations using box and whisker plots as shown in the following examples:

1. **Positive or negative differences where the confidence intervals do not overlap** (Figures 2.7 and 2.8) Here the null hypothesis stated above can be rejected indicating that the median EMCs are statistically not the same.

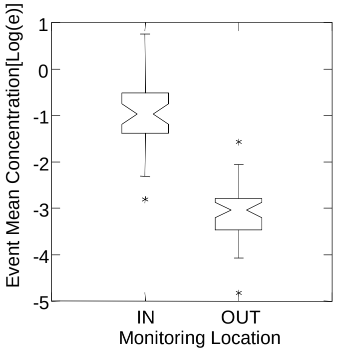


Figure 2.7 Statistically Significant Positive Efficiency as Indicated Through the Box and Whisker Plot

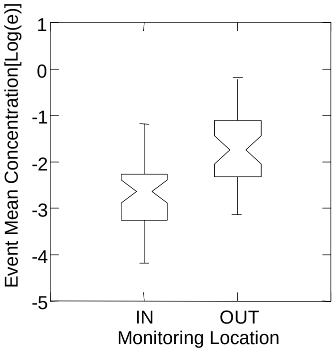


Figure 2.8 Statistically Significant Negative Efficiency as Indicated Through the Box and Whisker Plot

2. **Differences where the confidence intervals appreciably overlap** (Figure 2.9). In this case the confidence interval about the median for the outflow overlaps the confidence interval for the outflow. The graphical non-parametric analysis of variance (i.e., the notched box and whisker plot) indicates that the observed differences in the median are not statistically significant at the 95% confidence level.

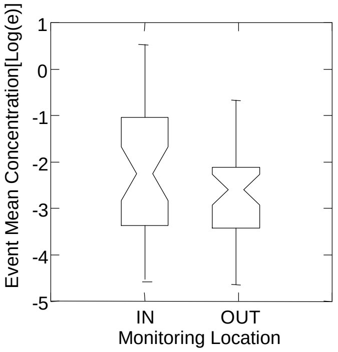


Figure 2.9 Statistically Ambiguous Difference in Median Event Concentration as Indicated Through the Box and Whisker Plot

3. **Positive or negative differences where the confidence intervals marginally overlap** (Figures 2.10 and 2.11). This case requires quantitative parametric and/or non-parametric analyses of variance to determine if the observed differences in event concentration are statistically significant.

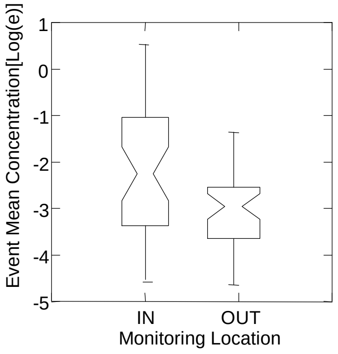


Figure 2.10 Marginally Statistically Significant Positive Efficiency as Indicated Through the Box and Whisker Plot

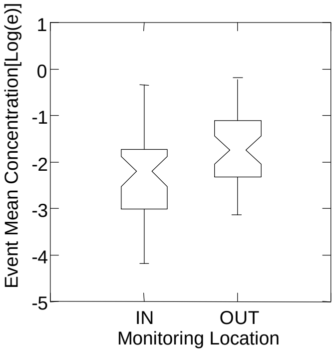


Figure 2.11 Marginally Statistically Significant Negative Efficiency as Indicated Through the Box and Whisker Plot

4. **Other Cases**. In some cases the 95% confidence limit is either in excess of the third quartile or less than the first quartile or both (see Figure 2.12). These cases correspond to a distribution of values that is strongly skewed and/or has a low number of samples. The examination of the probability plot may help shed light on the cause for the confidence limit to be outside of the interquartile range.

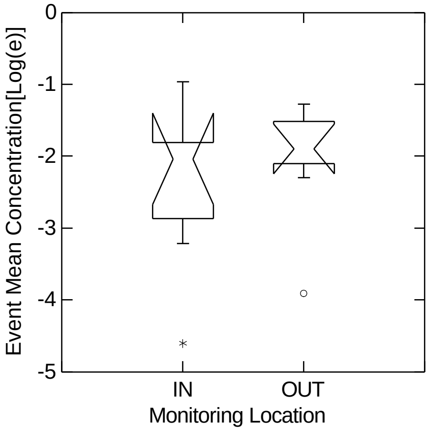


Figure 2.12 Example Box and Whisker Plot Demonstrating Quartiles that are Inside the Confidence Interval due to the Small Number of Events Monitored

2.4 Interpretation of Probability Plots

Probability plots were chosen for graphical analysis of the water quality concentration data due to the plot's ability to quickly and succinctly relay information about the following:

- How well data, or transformed data, at each monitoring station are represented by the normal distribution;
- The mean and standard deviation of the normal distribution and the value of any specific quantile. Slope of the normal approximation is an indication of the magnitude of the standard deviation (straight line), the x-intercept demonstrates the log mean concentration
- The relationship between two distributions across the range of quantiles;
- The presence of any significant outliers; and
- Width of 95% confidence interval of the normal approximation.

Two example probability plots are given below in order to explain the range of behaviors that may be encountered during the analysis of water quality data.

The results of overlaying normal probability plots for two data sets (typically EMCs from inflow and outflow from a BMP) exhibit five primary types of behavior that are described below.

The first example (Figure 2.13) demonstrates the behavior of two transformed data sets (one from the inflow and one from the outflow of a BMP) that have very similar standard deviations (slope of the normal probability plot) and a uniform difference (in the log-scale) across the range of quantiles. This indicates that there is a significant difference not only in the log mean EMCs, but a significant difference across any given quantile.

Figure 2.14 shows two distributions (inflow and outflow EMCs for TSS) with similar means and different standard deviations. The regression lines cross near the x-intercept (expected value at the mean). This behavior demonstrates negative removal at lower quantiles and positive removal at higher quantiles. This suggests that the BMP may have a minimum effluent concentration that can be achieved, particularly if the intersection point occurs at a low concentration.

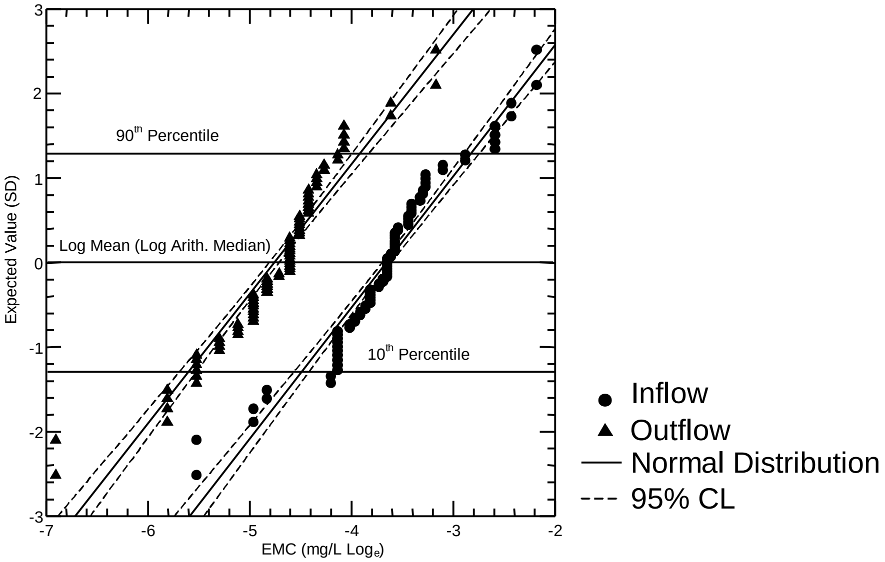


Figure 2.13 Example Normal Probability Plot for BMP Exhibiting Similar Standard Deviations and a Consistent Positive Difference in the Log Transformed Values Across the Range of Quantiles for the Tampa Office Pond (1994-1995) for TSS.

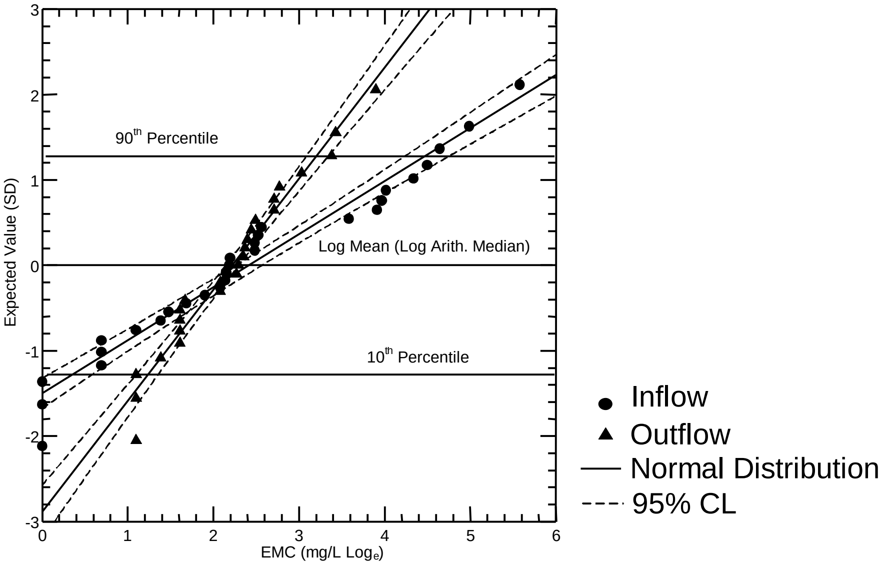


Figure 2.14 Example Normal Probability Plot for BMP Exhibiting Higher Standard Deviation at the Outflow than at the Inflow and a Positive Difference Between the Inflow and Outflow at High Quantiles and Negative Difference Between the Inflow and Outflow at Low Quantiles for the Tampa Office Pond (1993-1994) for TSS.

The other three behaviors that are observed are:

- That the difference in the means is not appreciable and the standard deviation of the distributions are similar (no effect from BMP on parameter)
- The means either have a positive or negative difference and the inflow and outflow distributions overlap at concentrations well below the mean. (Shows clear positive or negative removal at the mean but little difference in lower quantiles)
- The means either have a positive or negative difference and the inflow and outflow distributions overlap at concentrations well above the mean. (Shows clear positive or negative removal at the mean but little difference in higher quantiles)

3 Overview of Results of Efficiency and Effluent Quality by BMP Type and Parameter

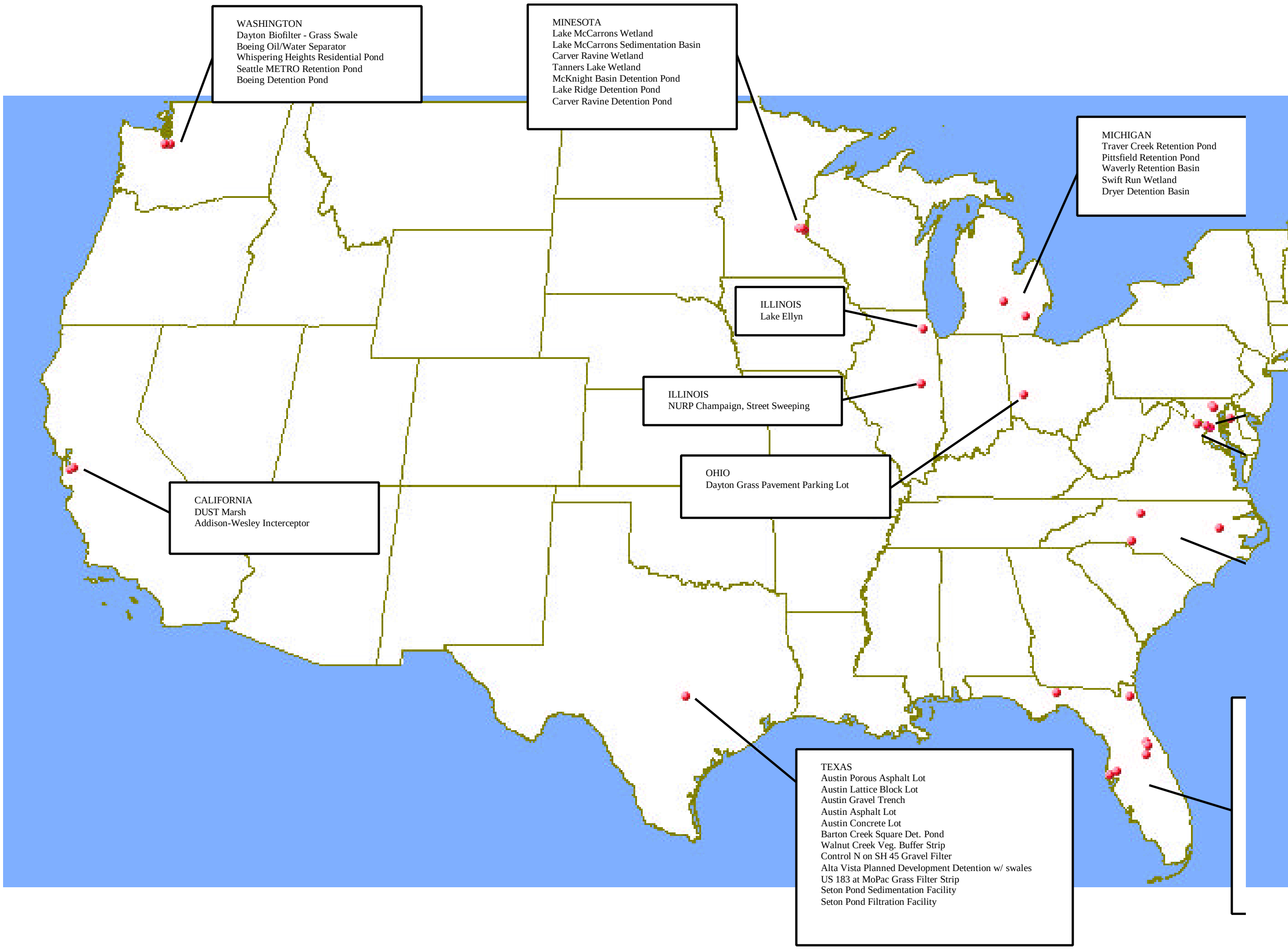
Two primary data appendices are included in Volume 2 of this document: Appendices 2-A and 2-B. Appendix 2-A is a compilation of box plots organized into sections addressing each BMP type explored and containing separate plots by water quality parameter. These plots allow for a quick overview of the range of influent and effluent concentrations across a number of structural BMPs of similar type. Appendix 2-B is a detailed analysis for each BMP and parameter organized by BMP type that gives an in-depth examination of the characteristics of the distribution of influent and effluent concentrations. A cut-sheet page describing the BMP in detail from reviewer's notes precedes each detailed analysis and, where available, a diagram of the BMP is included. The cut-sheet also summarizes other characteristics of the BMP including watershed information, parameters monitored, calculated removal efficiencies, and results of three types of analysis of variance.

For retention and detention ponds and wetlands enough data points were available to do further exploration of influent and effluent quality. Section 4 describes exploration that was conducted looking at the relationship between static and state variables and BMP efficiency.

4 Exploring Design Attributes (design, environmental, and climatic data)

4.1 Geographic Distribution of Sites

The sites contained in the database are not geographically diverse. A large number of studies originate from a small number of states with the largest number coming from Florida and Texas as shown in Figure 4.1. In this exploration, geographic differences in BMP performance could not be explored in detail due to the small number and poor distribution of studies.



WASHINGTON
Dayton Biofilter - Grass Swale
Boeing Oil/Water Separator
Whispering Heights Residential Pond
Seattle METRO Retention Pond
Boeing Detention Pond

MINESOTA
Lake McCarrons Wetland
Lake McCarrons Sedimentation Basin
Carver Ravine Wetland
Tanners Lake Wetland
McKnight Basin Detention Pond
Lake Ridge Detention Pond
Carver Ravine Detention Pond

MICHIGAN
Traver Creek Retention Pond
Pittsfield Retention Pond
Waverly Retention Basin
Swift Run Wetland
Dryer Detention Basin

ILLINOIS
Lake Ellyn

ILLINOIS
NURP Champaign, Street Sweeping

CALIFORNIA
DUST Marsh
Addison-Wesley Incterceptor

OHIO
Dayton Grass Pavement Parking Lot

TEXAS
Austin Porous Asphalt Lot
Austin Lattice Block Lot
Austin Gravel Trench
Austin Asphalt Lot
Austin Concrete Lot
Barton Creek Square Det. Pond
Walnut Creek Veg. Buffer Strip
Control N on SH 45 Gravel Filter
Alta Vista Planned Development Detention w/ swales
US 183 at MoPac Grass Filter Strip
Seton Pond Sedimentation Facility
Seton Pond Filtration Facility

Figure 4.1 Map of BMP Studies Currently Stored in the Database

4.2 Analysis of Precipitation Data from Studies Included in the Database

In addition to the analysis of water quality data, an analysis of monitored rainfall depths was conducted. The information resulting from this analysis sheds light on the extent of the monitoring conducted for a given BMP relative to the mean storm size for a specific location.

Few management practices provide optimal treatment under all flow conditions. Typically a design flood storm or runoff event and/or water quality storm or runoff event is used to estimate runoff volumes and pollutant loads, and to size BMPs and estimate their treatment efficiency. Use of a BMP during an event that is substantially different than its design storm can significantly influence its efficiency. Failure to design a BMP for indigenous rainfall characteristics often leads to poor performance; therefore, the relationship between observed storm flow volumes and the physical design of the BMP is highly relevant to any examination of the performance or effectiveness of BMPs.

Of the 71 BMPs contained in the Database, 36 provided rainfall data that met the criteria for entry. An analysis including descriptive statistics of the rainfall data collected in these 36 studies as well as a comparison of the characteristics of rainfall events monitored to average rainfall event statistics for nearby weather stations compiled by Driscoll et al., (1989) in *Analysis of Storm Event Characteristics for Selected Rainfall Gauges Throughout the United States*. The results of this comparison are provided in Section 4.2.1 below.

Note: The Driscoll et al. study and the analysis described above only included events greater than or equal to 0.1 inch in total depth, as smaller events were generally not considered to produce significant runoff.

4.2.1 Comparative Analysis of Rainfall Data from Studies Included in the Database

Each BMP has a cut sheet in Appendix 2-B that describes the watershed characteristics, summarizes flow and precipitation data, provides rainfall information from the nearest climate station monitored in Driscoll et al., and summarizes the water quality information that was analyzed for that specific BMP.

For the total data set, the number of significant rainfall events (>0.1 in) monitored during the various studies ranged from to 2 to 187 and averaged 36 events per study. These samples were collected over a period of from 16 days to 5 years with the average sampling period being about 15 months.

The mean monitored storm varied in depth between studies and ranged from 0.6 in to 0.8 in. About 75% of the studies had average monitored storm depths that were greater than the average depth of storms at the nearest climate station analyzed in the Driscoll study.

A bias toward larger events is indicated. This bias could result in efficiencies that might be different than those found in a more comprehensive monitoring program.

4.3 Design Parameters

A variety of factors complicated the extraction of comparable design information from BMP monitoring studies, specifically:

- The inclusion of design factors that did not directly translate into database fields (e.g., design storm drain times versus brim full and half brim full emptying times)
- Lack of supporting information (e.g., no scale maps or reported values for wetland surface area in many cases)

Although much of the desired design information was not obtained for input into the database, some data was consistent in many of the documents warranting examination of the relationship between design and efficiency. Parameters explored include:

- Water quality detention volume (detention basins) or permanent pool volume (retention basins)
- Ratio of mean monitored storm to permanent pool volume or water quality detention volume for wet and dry ponds
- Comprehensive climatic data from national weather service data and synoptic analysis of rainfall
- Rainfall totals for monitored storms
- Flow volumes for monitored storms at the inflow(s) and outflow(s)
- Average Depth (detention/retention ponds)
- Surface area of permanent pool or water quality detention (detention and retention basins)
- Watershed area
- Overall Percent imperviousness for watershed
- Land use information

The current version of the Database tables does not provide enough data points to examine a number of these parameters in detail for many of the sites.

Appendix 1-B presents tables for wetlands and wet and dry detention/retention facilities summarizing the efficiency of removal, mean effluent quality and Anova P-value for TSS, TN, TP, TPb, TCu, TZn, and TCd and selected static and state variables for each BMP.

Little correlation could be shown between any of the design parameters available for the BMPs in the initial data set and efficiency or effluent quality. This is a result of the small number of BMPs of each type. Appendix 1-C presents the results of analyses conducted to explore potential relationships between design and efficiency. Increased numbers of studies will improve the usefulness of the results obtained from this type of analysis.

4.4 Comparison of BMP Effluent Quality

As shown in the attached Task 3.1 memorandum (Appendix A-1), the quantification of efficiency of BMPs has often centered on examinations and comparisons of "percent removal" defined in a variety of ways. BMPs do not typically function with a uniform percent removal across a wide range of influent water quality concentrations. For example, a BMP that demonstrates a large percent removal under heavily polluted influent conditions may demonstrate poor percent removal where low influent concentrations exist. The decreased efficiency of BMPs receiving low concentration influent has been demonstrated and it has been shown that in some cases there is a minimum concentration achievable through implementation of BMPs for many constituents (Schueler, 1996 and Minton, 1998). Percent removal alone, even where the results are statistically significant, often does not provide a useful assessment of BMP performance.

Box and whisker plots showing the distribution of mean influent and effluent water quality by BMP type are provided in Appendix 1-D.

5 Summary of Conclusions

The quantity of data initially stored in the Database limits the number of BMP types that could be examined in detail; however, a number of conclusions were reached as a result of the exploration and evaluation of this data set.

- The standard set of statistical methods and data collection protocols established by this cooperative agreement and implemented here and in the Database software can significantly improve the transferability of data between studies.

- Much more data are needed for many BMP types.

- Removal percentages are not very useful for characterizing performance, unless looked at much more carefully (e.g., only at "dirty" sites for example). As a result, BMP performance requirements should not be specified in terms of percent removal.

- Some BMP types may have been mischaracterized as less effective because of cleaner influent. For example, BMPs that rely on settling as a primary removal mechanism cannot have high percent removals where suspended solids concentrations are low in the influent.

- Effluent quality may be a better way to characterize efficiency, although at an individual site, it is important to test whether the BMP had a statistically significant effect on water quality.

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

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