Development of Performance Measures

Task 3.1 – Technical Memorandum

Determining Urban Stormwater Best Management Practice (BMP) Removal Efficiencies

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Scope of Memorandum

This memorandum is intended for use in this cooperative research effort as an outline and description of the methodology for Task 3.0, Data Exploration and Evaluation. Although the memorandum describes, in detail, methods to be used for analysis of stormwater best management practices, the discussion included here is not inclusive of all of the issues relevant to the subject and is not intended as a "guidance manual" of analysis techniques. The application of the approach should be limited to the current scope of this project until the methods and issues described have been further explored and reviewed by the Team, ASCE(UWRRC), and EPA.

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1 Overview

The purpose of this cooperative research effort 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), specifically by assessing the relationship between measures of effectiveness and BMP design. 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. Almost all past BMP monitoring studies have provided very limited data that is useful for comparing BMP design and selection. This technical memorandum provides an overview of methods for evaluating the efficiency, performance, and effectiveness of best management practices (BMPs) through analysis of water quality, flow, and precipitation data for monitored storm events as well as BMP design attributes collected and stored in the National Stormwater (NSW) Best Management Practices Database. Furthermore, it provides a specific description of the methods that will be used to conduct the data exploration and evaluation, described under Tasks 3.2-3.4 of this project. These methods provide the basic techniques for analyzing data manually and a preliminary basis for integrated analysis tools to be built into the database in the future.

1.1 Definition of Terms

In order to better clarify the terminology used to describe the level of treatment achieved and how well a device, system, or practice meets its goals, definitions of some terms, often used loosely in the literature, are provided here. These terms help to better specify the scope of monitoring studies and related analyses.

- Best Management Practice (BMP) **-** A device, practice, or method for removing, reducing, retarding, or preventing targeted stormwater runoff constituents, pollutants, and contaminants from reaching receiving waters.
- BMP System **-** A BMP system includes the BMP and any related bypass or overflow. For example, the efficiency (see below) can be determined for a offline retention (Wet) Pond either by itself (as a BMP) or for the BMP system (BMP including bypass)
- Performance **-** measure of how well a BMP meets its goals for stormwater that the BMP is designed to treat.
- Effectiveness **-** measure of how well a BMP system meets its goals in relation to all stormwater flows
- Efficiency **-** measure of how well a BMP or BMP system removes pollutants.

The primary focus of the data exploration and evaluation will be to determine efficiency of BMPs and BMP systems and to elucidate relationships between design and efficiency. In addition, effectiveness and performance will be evaluated, acknowledging the limitations of existing information about the goals of specific BMP projects. Quantification of efficiency only evaluates a portion of the overall performance or effectiveness of a BMP or BMP system. Calculation of the efficiency, however, does help to determine additional measures of performance and effectiveness, for example the ability of a BMP to meet any regulatory goals based on percent removal. A list of typical goals and the current ability of the ASCE/EPA project to help evaluate them is shown in Table 1.1.

Table 1.1 Goals of BMP Projects and the Ability of the National Stormwater BMP Database to Provide Information Useful for Determining Performance and Effectiveness

Goals of BMP Projects		Ability to Evaluate Performance and Effectiveness
Category		
Hydraulics	• Improve flow characteristics upstream and/or downstream of BMP	-
Hydrology	• Flood mitigation, improve runoff characteristics (peak shaving)	✓
Water Quality (Efficiency)	• Reduce downstream pollutant loads and concentrations of pollutants	✓
	• Improve/minimize downstream temperature impact	✓
	• Achieves desired pollutant concentration in outflow	✓
	• Removal of litter and debris	-
Toxicity	• Reduce acute toxicity of runoff	✓[1]
	• Reduce chronic toxicity of runoff	✓[1]
Regulatory	• Compliance with NPDES permit	-
	• Meet local, state, or federal water quality criteria	✓[2]
Implementation Feasibility	• For non-structural BMPs, ability to function within management and oversight structure	-
Cost	• Capital, operation, and maintenance costs	✓[1]
Aesthetic	• Improve appearance of site	-
Maintenance	• Operate within maintenance, and repair schedule and requirements	✓[1]
	• Ability of system to be retrofit, modified or expanded	✓
Longevity	• Long term functionality	✓[1]
Resources	• Improve downstream aquatic environment/erosion control	
	• Improve wildlife habitat	-
	• Multiple use functionality	-
Safety, Risk and Liability	• Function without significant risk or liability	-
	• Ability to function with minimal environmental risk downstream	-
Public Perception	• Information is available to clarify public understanding of runoff quality, quantity and impacts on receiving waters	✓

✓ can be evaluated using the ASCE/EPA Database as information source
✓[1] will be able to be evaluated using the database as primary source of information after enough studies have been submitted
✓[2] can be evaluated using the database as the primary source of information combined with a secondary source of comparative data
\- can be evaluated only qualitatively through included comments by reviewer or author, or are unable to be evaluated at this time

The term event mean concentration (EMC) is used throughout this memorandum. The EMC is a statistical parameter used to represent the flow-proportional average concentration of a given parameter during a storm event. It is defined as the total constituent mass divided by the total runoff volume. It is often estimated via the collection of multiple flow volume triggered grab samples that are composited for analysis. When combined with flow measurement data, the EMC can be used to estimate the pollutant loading from a given storm.

1.3 BMPs Types and Implications for Calculation of Efficiency

The issues involved in selection of methods for quantifying efficiency, performance, and effectiveness are complex. It would be difficult, at best, to find one method that would cover the data analysis requirements for the widely varied collection of BMP types and designs found in the NSW Database. When analyzing efficiency, it is convenient to classify BMPs according to one of the following four distinct categories:

- BMPs with well-defined inlets and outlets whose primary treatment depends upon extended detention storage of stormwater, (e.g., wet and dry ponds, wetland basins, underground vaults)
- BMPs with well-defined inlets and outlets that do not depend upon significant storage of water, (e.g., sand filters, swales, buffers, structural “flow-through” systems)
- BMPs that do not have a well defined inlet and/or outlet (e.g., retention, infiltration, porous pavement)
- Widely distributed BMPs that use reference watersheds to evaluate effectiveness, (e.g., catch basin retrofits; education programs)

Any of the above can also include evaluations where the BMP’s efficiency was measured using before and after or paired watershed comparisons of water quality.

The difficulty in selection of measures of efficiency stems not only from the desire to compare a wide range of BMPs, but also from the large number of methods currently in use. There is much variation and disagreement in the literature about what measure of efficiency is best applied.

1.4 Relationship Between Monitoring Study Objective and Data Analysis

In developing a method for quantifying BMP performance of effectiveness, it is helpful to look at the objectives of previous studies seeking such a goal. BMP studies usually are conducted to obtain information regarding one or more of the following objectives:

- What degree of pollution control does the BMP provide under typical operating conditions?
- How does efficiency vary from pollutant to pollutant?
- How does efficiency vary with various input concentrations?
- How does efficiency vary with storm characteristics such as rainfall amount, rainfall density, antecedent weather conditions?
- How do design variables affect performance?
- How does efficiency vary with different operational and/or maintenance approaches?
- Does efficiency improve, decay, or remain the stable over time?
- How does the BMP's efficiency, performance, and effectiveness compare relative to other BMPs?
- Does the BMP reduce toxicity to acceptable levels?
- Does the BMP cause an improvement or protect in downstream biotic communities?
- Does the BMP have potential downstream negative impacts?

The monitoring efforts implemented most typically seek to answer a small subset of the above questions. This often leaves larger questions about the efficiency, performance and effectiveness of the BMP, and the relationship between design and efficiency, unanswered. The goal of this document is develop a recommended approach to utilize the National Stormwater BMP Database to evaluate BMP data that have been entered such that some of or all of the above questions about BMP efficiency can be assessed where sufficient data is available.

1.5 Physical Layout and Its Effect on Efficiency and Its Measure

The estimation of the efficiency of BMPs is often approached in different ways based on the goals of the researcher. A BMP can be evaluated by itself or as part of an overall BMP system. The efficiency of a BMP not including bypass or overflow may be dramatically different than the efficiency of an overall system. Bypasses and overflows can have significant effects on the ability of a BMP to remove constituents and appreciably reduce the efficiency of the system as a whole. Researchers who are interested in comparing the efficiency of an offline wet pond and an offline wetland may not be concerned with the effects of bypass on a receiving water. On the other hand, another researcher who is comparing offline wet ponds with online wet ponds would be very interested in the effects of the bypass. Often detailed information about the bypass of the BMP is not available for analysis. In some cases, comprehensive inflow and outflow measurements allow for the calculation of a mass balance that can be used to estimate bypass flow volumes. Estimations of efficiency of a BMP system can be based on these mass balance calculations coupled with sampling data.

The efficiency of a BMP system or a BMP can be directly effected by the way in which an operator chooses to manage the system. This is the case where parameters of a design can be adjusted, (e.g., adjustments to the height of an overflow/bypass weir or gate). These adjustments can vary the efficiency considerably. In order to analyze a BMP or BMP system thoroughly, all static and state variables of the system must be known.

1.6 Relevant Period of Impact

The period of analysis used in an efficiency calculation is important. The period used should take into account how the parameter of interest varies with time. This allows for observation of relevant changes in the efficiency of the BMP on the time scale in which these changes occur. For example, in a wetland it is often observed that during the growing season removal efficiency increases for nutrients. The opposite effect may be observed during the winter months or during any period where decaying litter and plant material may contribute significantly to export of nutrients and, potentially, other contaminants. Therefore, the efficiency calculations may need to be made based on data collected over a few months or seasonally. This variation of efficiency on a temporal scale is extremely important in understanding how BMPs function.

In addition to observing how factors, such as climate, affect efficiency as a function of time, it is important to relate the calculation period to the potential impact a given constituent would have on the receiving water. For example, it may not be useful to study the removal of a chlorinated organic for a short period of record when the negative impacts of such a contaminant are generally expressed over a long time scale. Likewise, some parameters (e.g., temperature, BOD, DO, pH, TSS and metals) may have a significant impact in the near term.

Toxicity plays a major role in evaluating what time period should be used to analyze efficiency. Specific constituents that are acutely toxic require a short-term analysis on an "intra-storm" basis. Where dilution is significant and/or a constituent is toxic on a chronic basis, long-term analysis that demonstrates removal of materials on a sum of loads or average EMC basis may be more appropriate. Many contaminants may have both acute and chronic effects in the aquatic environment. These contaminants should be evaluated over both periods of time. Similarly, hydraulic conditions merit both short and long term examination. Event peak flows are examples of short-term data, while seasonal variations of the hydrologic budget due to the weather patterns are examples of long-term data. Examples of water quality parameters and their relationship to the time scale over which they act are given in Table 1.2.

Table 1.2

Time Scale for Analysis	**Water Quality Parameter**
Short Term	BOD, DO
Long Term	Organics, Carcinogens
Both Short and Long Term	Metals, TSS, Nitrogen, Phosphorous, Temperature, pH, Pesticides

2 Example Study for Examination of Efficiency Calculation Methods

In order to discus and contrast the various methods that have been employed for estimating the efficiency of BMPs, an example data set was utilized. The examples taken from this data set are based upon data from *Three Design Alternatives for Stormwater Detention Ponds*, (Rushton, Miller, Hull and Cunningham, 1997). The study was conducted by the Southwest Florida Water Management District (SWFWMD). The single pond studied with different design attributes was located at the SWFWMD Service office in Tampa. The following quote from the executive summary of the report describes the site:

> *The drainage basin is 6.5 acres with about 30 percent of the watershed covered by roof tops and asphalt parking lots, 6 percent by a crushed limestone storage compound and the remaining 64 percent as a grassed storage area. The impervious surfaces discharge to ditches which provide some pre-treatment before stormwater enters the pond. During the first year of the study (1990), the pond was shallow and completely vegetated with a permanent pool less than one foot deep and an average wet season residence time of two days. In the second year (1993), the vegetated littoral zone covered 35 % of the pond area and the volume of the permanent pool was increased to include a five-day residence time by excavating the pond to five feet. For the final year (1994), the vegetated littoral zone was planted with desirable species, the depth of the pond was kept at five feet and the area of the permanent pool was enlarged for a calculated wet season residence time of 14 days.*

This example study was chosen due its comprehensive data set and its ability to demonstrate the effects of changes in efficiency based on design variations. The pond study also demonstrates the potential effects of average wet season residence time on the calculated performance of the BMP. All calculations included in this memorandum are based on the raw data provided in the report as stored in the National Stormwater Best Management Practices Database at this time. The values reported in the SWFWMD report are given in Table 2.1 for comparison. Two methods were used by SWFWMD to enumerate effectiveness, 1) the *Summation of Loads* and, 2) the *Efficiency Ratio*. Both of these methods are described in more detail in Section 3 of this memorandum.

Table 2.1

	TSS Percent Removal Reported by SWFWMD		
Method	**1990**	**1993-1994**	**1994-1995**
Efficiency Ratio (EMC)	61	69	95
Summation of Loads	71	67	94
Other Information			
Number of Rain Events (>0.05 in)	53	60	83
Percent Monitored	43	50	56
Average Depth of Monitored Storms	0.53 inch	0.57 inch	0.53 inch
Total Rainfall During Monitoring Period	28 inch	34 inch	44 inch

Differences between the values calculated for the examples given in this memo and the values reported in the SWFWMD report were checked thoroughly and it was determined that the cause for the difference in reported efficiencies is due to rounding of each flow weighted sample value in the SWFWMD report. All of the calculations in this memo were based on the digital data provided by SWFWMD, which were not rounded. SWFWMD also excluded some of the values in their final analysis of the BMP during the 1993-1994 water year due to a leaking water main and problems with the rain collector used on site. This change to the data set used for calculating performance had no net effect on the efficiency reported for TSS. The examples in this document use the entire data set.

3 Review of Commonly Used Efficiency Calculation Methods

A variety of pollutant removal methods have been utilized in BMP monitoring studies to evaluate efficiency. This section describes and gives examples of methods employed by different investigators. One of five methods are typically used by investigators for the calculation of BMP efficiency:

- Efficiency ratio
- Summation of loads
- Regression of loads
- Mean concentration
- Efficiency of individual storm loads
- Reference watersheds and before/after studies

Although these methods do present a summary of efficiency, they do not look at removal statistically, and thus, do not provide enough information to determine if the differences in inflow and outflow water quality measures are statistically significant. Previous studies comparing BMP efficiency for a number of BMPs statistically examined reported removal efficiencies that were based upon various efficiency calculation methods. The National Stormwater Best Management Practices Database allows for the consistent calculation of efficiencies for each of the BMPs based on event data. Calculating efficiency on this basis makes detailed statistical analysis possible. Section 4 of this memorandum describes and gives examples of the methodology that will be used in Tasks 3.2-3.4 of the project. This selected methodology, the Lognormal Statistical Efficiency (LSE) is an expansion of the efficiency ratio method (ER). The LSE method fully describes the statistical distribution of water quality upstream and downstream of BMPs and determines if differences in water quality are statistically significant.

3.1 Efficiency Ratio

Definition

The efficiency ratio is defined in terms of the average event mean concentration (EMC) of pollutants over some time period:

$$ER = 1 - \frac{\text{average outlet EMC}}{\text{average inlet EMC}} = \frac{\text{average inlet EMC - average outlet EMC}}{\text{average inlet EMC}}$$

EMCs can be either collected as flow weighted composite samples in the field or calculated from discrete measurements. The EMC for an individual event or set of field measurements, where discrete samples have been collected, is defined as:

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i}$$

where,

V: volume of flow during period i
C: average concentration associated with period i
n: total number of measurements taken during event

The arithmetic average EMC is defined as,

$$\text{average EMC} = \frac{\sum_{j=1}^{m} EMC_j}{m}$$

where,

m: number of events measured

In addition, the log mean EMC can be calculated using the logarithmic transformation of each EMC. This transformation allows for normalization of the data for statistical purposes.

$$\text{Mean of the Log EMCs} = \frac{\sum_{j=1}^{m} Log\left(EMC_j\right)}{m}$$

Estimates of the arithmetic summary statistics of the population (mean, median, standard deviation, and coefficient of variation) should be based on their theoretical relationships (Appendix A) with the mean and standard deviation of the transformed data. Computing the mean and standard deviation of log transforms of the sample EMC data and then converting them to an arithmetic estimate often obtains a better estimate of the mean of the population due to the more typical distributional characteristics of water quality data. This value will not match that produced by the simple arithmetic average of the data. Both provide an estimate of the population mean, but the approach utilizing the log-transformed data tends to provide a better estimator, as it has been shown in various investigations that pollutant, contaminant and constituent concentration levels have a log-normal distribution (NURP, 1983). As the sample size increases, the two values converge.

Assumptions

This method

- Weights EMCs from all storms equally regardless of relative magnitude of storm. For example a high concentration/high volume event has equal weight in the average EMC as a low concentration/low volume event. The logarithmic approach tends to minimize the difference between the EMC and mass balance calculations.

- Is most useful when loads are directly proportional to storm volume. For work conducted on nonpoint pollution (i.e., inflows), the EMC has been shown to not vary significantly with storm volume. This lends credence to using the average EMC value for the inflow but does not provide sufficient evidence that outflows are well represented by average EMC. Accuracy of this method will vary based on the BMP type.

- Minimizes the impacts of smaller/cleaner storm events on actual performance calculations. For example, in a storm by storm efficiency approach, a low removal value for such an event is weighted equally to a larger value.

- Allows for the use of data where portions of the inflow or outflow data are missing, based on the assumption that the inclusion of the missing data points would not significantly impact the calculated average EMC.

Comments

This method

- Is taken directly from non-point pollution studies and does a good job characterizing inflows to BMPs but fails to take into account some of the complexities of BMP design. For example, some BMPs may not have outflow EMCs that are normally distributed (e.g., a media filter that treats to a relatively constant level that is independent on inflow concentrations).

- Assumes that if all storms at the site had been monitored, the average inlet and outlet EMCs would be similar to those that were monitored.

Example

The example calculations given below are for the Tampa Office Pond using arithmetic average EMCs in the efficiency ratio method.

Period of Record	Average EMC In	Average EMC Out	Efficiency Ratio
1990	27.60	11.18	0.59
1993-1994	34.48	12.24	0.64
1994-1995	131.43	6.79	0.95

3.2 Summation of Loads

Definition

The summation of loads method defines the efficiency based on the ratio of the summation of all incoming loads to the summation of all outlet loads, or:

$$\text{SOL} = 1 - \frac{\text{sum of outlet loads}}{\text{sum of inlet loads}}$$

The sum of outlet loads are calculated as follows:

$$\text{sum of loads} = \sum_{j=1}^{m}\left(\sum_{i=1}^{n} C_i V_i\right) = \sum_{j=1}^{m} EMC_j \cdot V_j$$

Assumptions

- Removal of material is most relevant over entire period of analysis.
- Monitoring data accurately represents the actual entire total loads in and out of the BMP for a period long enough to overshadow any temporary storage or export of pollutants.
- Any significant storms that were not monitored had a ratio of inlet to outlet loads similar to the storms that were monitored.
- No materials were exported during dry periods, or if they were, the ratio of inlet to outlet loads during these periods is similar to the ratio of the loads during the monitored storms.

Comments

- A small number of large storms typically dominate efficiency.
- If toxics are a concern then this method does not account for day to day releases, unless dry weather loads in and out are also accounted for.
- Based on mass balance.

Example of Summation of Loads for TSS Using the Tampa Office Pond

Period of Record	**Sum of Loads In (kg)**	**Sum of Loads Out (kg)**	**SOL Efficiency**
1990	134.60	39.67	0.71
1993-1994	404.19	138.44	0.66
1994-1995	2060.51	130.20	0.94

3.3 Regression of Loads (ROL), Martin and Smoot (1986)

Definition

The regression of loads method defines the regression efficiency as the slope of a least squares linear regression of inlet loads and outlet loads of pollutants, with the intercept constrained to zero. The equation for the ROL efficiency is:

$$\text{Loads out} = b \bullet \text{Loads in} = b - \frac{\text{Loads out}}{\text{Loads in}}$$

The percent reduction in loads across the BMP is estimated as:

$$\text{Percent Removal} = 1 - b = 1 - \frac{\text{Loads out}}{\text{Loads in}}$$

Assumptions

- The assumptions for this method are identical to the assumptions for the *Summation of Loa*ds method.

Comments

- A few data points often control the slope of line due to clustering of loads about the mean storm size. Regressions are best used where data is equally populous through the range to be examined. This is readily observed in the examples that follow (See Figures 3.1 and 3.3).

- The process of constraining the intercept of the regression line to the origin is questionable and in some cases could significantly misrepresent the data. It may be more useful to apply the *Regression of Loads* method over some subset of the data without requiring that the intercept be constrained to the origin. The problem with this alternative approach is that a large number of data points are required in order to get a good fit of the data. Often (See Figure 3.1) a meaningful regression cannot be made using the data that was collected. This is well illustrated by the very low R^2 values in the table below. Forcing the line though the origin, in these cases, provides a regression line even where no useful trend is present.

- There is sufficient evidence that this first order polynomial (straight line) fit is not appropriate over a large range of loadings. Very small events are much more likely to demonstrate low efficiency where larger events may demonstrate better overall efficiency depending on the design of the BMP.

Example of ROL Efficiency Results for TSS in the Tampa Office Pond

Period of Record	**Slope of Regression Line**	**R^2**	**Percent Removal**
1990	0.21	0.06	0.79
1993-1994	0.18	-0.06	0.82
1994-1995	0.05	0.46	0.95

The regressions used to arrive at the above slopes are given in Figures 3.1-3.3.

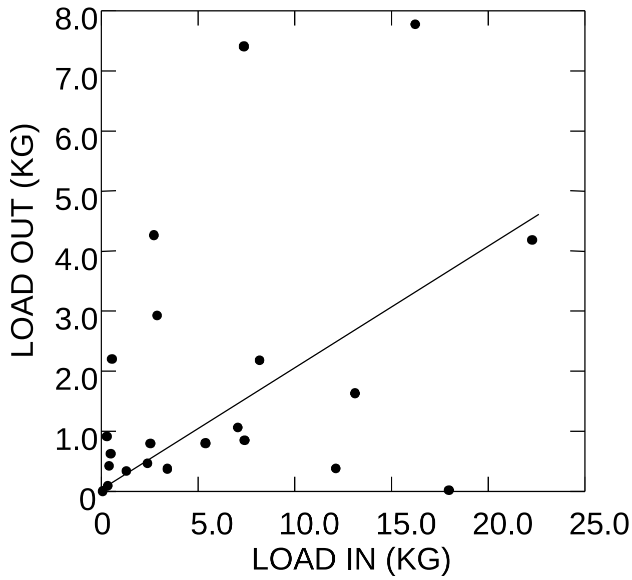


Figure 3.1 ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1990) (Slope = 0.2135, R^2 = 0.0563, Standard Error in Estimate = 2.176, one point is considered an outlier with a Studentized Residual of 3.304). All points were used for regression.

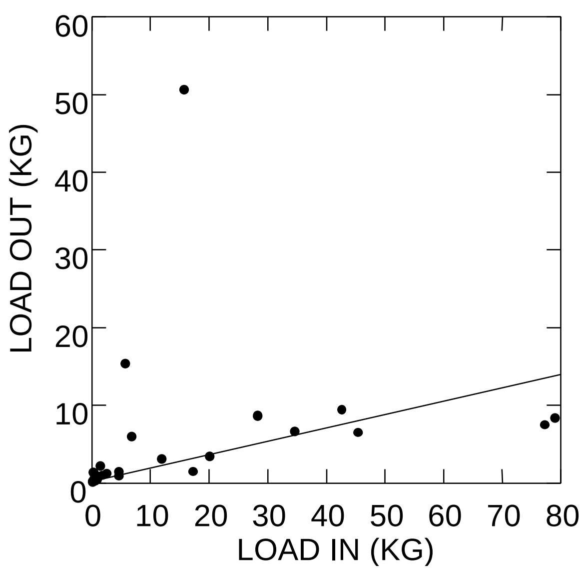


Figure 3.2 ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1993-1994) (Slope = 0.1801, R^2 = -0.0562, Standard Error in Estimate = 10.440, One point is considered an outlier with a Studentized Residual of 13.206 and one point has a high Leverage of 0.323). All points were used for regression.

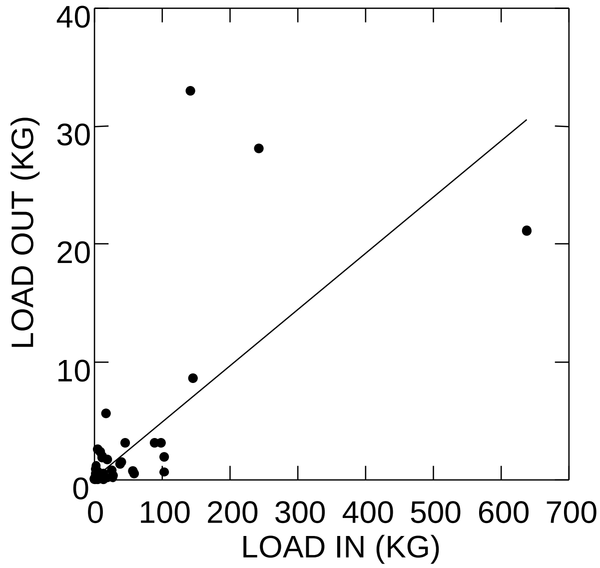


Figure 3.3 ROL Plot for use in Calculating Efficiency for TSS using the Tampa Office Pond (1994-1995) (Slope = 0.0492, R^2 = 0.4581, Standard Error in Estimate = 5.260, three points are considered outliers (Studentized Residuals of 3.724, 8.074, and –4.505, The point to the far right on the graph has large Leverage (0.724) and Influence, Cook Distance = 36.144). All points were used for regression.

3.4 Mean Concentration

Definition

The mean concentration method defines the efficiency as unity minus the ratio of the average outlet to average inlet concentrations. The equation using this method is, thus:

$$MC = 1 - \frac{\text{average outlet concentration}}{\text{average inlet concentration}}$$

This method does not require that concentrations be flow weighted. This method might have some value for evaluating grab samples where no flow weighted data is available or where the period of record does not include the storm volume.

Assumptions

- The flows from which the samples were taken are indicative of the overall event.

Comments

- This method may be useful for calculating BMP's effectiveness in reducing acute toxicity immediately downstream of the BMP. This is due to the fact that acute toxicity is measured as a threshold concentration value of a specific constituent in the effluent at or near the point of discharge. If more than one sample per event is analyzed, this method would result in more information on potential toxicity reduction.

- Weights individual samples equally. Biases could occur due to variations in sampling protocols or sporadic sampling (i.e., collectively many samples close in time and others less frequently. The sample collection program specifics are not accounted for in the method and estimated efficiencies are often not comparable between studies.

- This method does not account for storage capacity. Typically BMP's will have an equal or lesser volume of outflow than of inflow, on a mass basis this affects removal, since volume (or flow) is used with concentration to determine mass for a storm event,

$$1 - \frac{C_{out} V_{out}}{C_{in} V_{in}} \geq 1 - \frac{\text{average outlet concentration}}{\text{average inlet concentration}}$$

where:

C_{in}: Concentration In
C_{out}: Concentration Out
V_{in}: Volume In
V_{out}: Volume Out

In this respect, it is often more conservative (i.e., lower removal efficiency stated) to use concentration rather than mass-based removal.

3.5 Efficiency of Individual Storm Loads

Definition

The Efficiency of Individual Storm Loads (ISL) method calculates a BMP's efficiency for each storm event based on the loads in and the loads out. The mean value of these individual efficiencies can be taken as the overall efficiency of the BMP. The efficiency of the BMP for a single storm is given by:

$$\text{Storm Efficiency} = 1 - \frac{Load_{out}}{Load_{in}}$$

The average efficiency for all monitored storms is thus:

$$\text{Average Efficiency} = \frac{\sum_{j=1}^{m} \text{Storm Efficiency}_j}{m}$$

where,

m: number of storms

Assumptions

- Storm size or other storm factors do not play central roles in the computation of average efficiency of a BMP.
- Storage and later release of constituents from one storm to the next is negligible.
- The selection of storms monitored does not significantly skew the performance calculation.

Comments

- The weight of all storms is equal. Large storms do not dominate the efficiency in this scenario. The efficiency is viewed as an average performance regardless of storm size.
- Some data points are not able to be used due to the fact that there is not a corresponding measurement at either the inflow or the outflow for a particular storm, and thus an efficiency cannot always be calculated on a storm by storm basis. This is not true for the ER method, however it is a limitation of the Summation of Load Method.
- Storm by storm analysis neglects the fact that the outflow being measured may have a limited relationship to inflow in BMPs that have a permanent pool. For example, if a permanent pool is sized to store a volume equal to the average storm, about 60 to 70 percent of storms would be less than this volume [from studies conducted using SYNOP (EPA, 1989)].

Example of Efficiency of Individual Storm Loads for TSS in the Tampa Office Pond

Period of Record	Efficiency
1990	0.29
1993-1994	-0.02
1994-1995	0.89

3.6 Reference Watershed Methods

Discussion

Many BMPs do not allow for comparison between inlet and outlet water quality parameters. In addition it is often difficult or costly, where there are many BMPs being installed in a watershed (e.g., retrofit of all catch basins), to monitor a large number of specific locations. Often a reference watershed is used to evaluate the effectiveness of a given BMP or multiple BMPs of the same type. The database allows for a watershed and all associated data to be identified for use as a reference watershed. One of the primary reasons for using a reference watershed is that there is no clearly defined inlet or outlet point at which to monitor water quality. Such is the case with many non-structural BMPs, porous pavements, and infiltration practices.

The difficulty in determining the effectiveness of a BMPs using reference watersheds stems from the large number of variables typically involved. When setting up a BMP monitoring study, it is advantageous to keep the watershed characteristics of the reference watershed and the test watershed as similar as possible. Unfortunately, finding two watersheds that are similar is often quite difficult and the usefulness of the data can be compromised as a result. In order to attempt to determine the effectiveness of a BMP based on a reference watershed, an accurate accounting of the variations between the watersheds, operational, and environmental conditions is needed. The database explicitly stores some of the key parameters required for normalization of watershed and environmental conditions.

The most obvious parameter used to normalize watershed characteristics is area. If the ratio of land uses and activities within each watershed is identical in both watersheds then the watershed area can be scaled linearly. Additionally, the loads found at each downstream monitoring station, for each event, can be scaled linearly with area as well. Difficulty arises when land use in the reference watershed is not found in the same ratio. In this case, either the effects of land use must be ignored or a portion of the load found for each event must be allocated to a land use and then scaled linearly as a function of the area covered by that land use. In many cases, the differences in land use can be ignored, (e.g., between parking lots with relatively small, but different unpaved areas). The effect of the total impervious area is relevant and provided in the database in all cases and can be used to normalize the water quality data collected. The ratio of the total impervious areas can be used to scale event loads. Scaling the loads based on impervious areas would be best used where it is determined that the majority of pollutants are from runoff from the impervious areas (e.g., parking lots), or the contaminant of interest primarily results from deposition on impervious surfaces, (e.g., TSS in a highly urban area). Methods that attempt to determine BMP performance from poorly matched watersheds yield poor results at best. As the characteristics of the two watersheds diverge, the effect of the BMP is masked by the large number of variables in the system; the noise in the data becomes greater than the signal.

The analysis of BMPs utilizing reference watersheds also requires incorporation of operational details of the system, (e.g., frequency of street sweeping, type of device used, device setup). The database asks users to provide the frequency, extent, and other operational parameters for nonstructural BMPs. If the BMP is an alteration of the frequency of a certain practice, the system can be viewed in two ways, (1) as a control/test system, or (2) as a series of data aimed at quantifying the continuous effect of increasing or decreasing BMP frequency. In the first case the BMP can be analyzed in a manner similar to other BMPs with reference watersheds. In the second case, the loads realized at the monitoring stations need to be correlated with the frequency using some model for the effectiveness of the practice per occurrence.

3.7 Summary and Comparison of Methods from the Examples

The table below shows the results of the various methods shown above for calculation of efficiency for the Tampa Office Pond. It can be seen that the four methods demonstrated (mean concentration method was not applicable to data available from the Tampa Office Pond study) vary widely in their estimates of percent removal depending on the assumptions of each method as discussed above.

	Method			
Design	Efficiency Ratio (ER)	Summation of Loads (SOL)	Regression of Loads (ROL)	Efficiency of Individual Storms
1990	0.59	0.71	0.79	0.29
1993-1994	0.64	0.66	0.82	-0.02
1994-1995	0.95	0.94	0.95	0.89

4 Proposed Methods for Calculation of Efficiency

This section describes methods that will be used in Task 3.2 of the project to quantify efficiency of each BMP currently stored in the database. In order assess efficiency, water quality data needs to be analyzed in a consistent manner. Background information on data preparation is provided in Section 4.1, procedures and techniques that will be used for graphical exploration of the data are demonstrated in Section 4.2, the proposed primary method for quantification of efficiency (the Lognormal Statistical Efficiency, LSE) is outlined in Section 4.3, and Section 4.4 describes an alternative method (the Relative Outflow Efficiency) for quantification of efficiency where outflow EMCs do not vary with respect to inflow concentrations.

4.1 Data Preparation

There are a number of types of water quality data stored in the database due to the varying methods used conduct monitoring studies. In order to analyze the data, some degree of preparation of the data is required.

The water quality data stored in the database can be broken down into two principal types.

1. Event Mean Concentration Data
    - Discrete (manual or automatic) Sample Flow Weighted Composite EMCs
    - Discrete Sample Time Weighted Composite EMCs
    - Discrete Sample Composite EMCs Without Flow or Time Weighting

2. Discrete Water Sample Data
    - Grab Samples

The approach described and demonstrated in Sections 4.2 and 4.3 is based on EMC monitoring data. The use of grab samples for the calculation of removal efficiencies requires additional preparation of water quality sampling data. On a study by study basis, grab sampling programs will be examined. Numerical methods will be used to approximate EMCs for certain constituents (based on flow and/or time weighting), where this is possible. If EMCs cannot be calculated for a particular study, then estimations of efficiency will be based on the grab samples themselves (i.e., a statistical analysis of concentration data will be conducted to the extent possible). For some constituents and field parameters, a discrete sample approach is required. In calculating the ability for a BMP to improve field parameters such as temperature, a “grab” sample approach will need to be utilized even where EMCs were collected in a flow or time weighted manner.

In many of the BMPs currently stored in the database, the number of inflows does not necessarily equal the number of outflows. Although many BMPs have one inflow and one outflow, many do not, and in some cases, the layout of the BMP system is quite complicated. Best management practice designs containing multiple, inflows, outflows, bypasses, and BMPs in series and/or parallel are common and all analyses of BMPs and BMP systems should take these important design details into account.

For cases where more than one inlet and outlet are present, the concentration data will be composited based on flow weighting   This will be conducted by calculating a single EMC based on the total mass flowing into or away from the BMP and the associated total flow.

In some cases the flow into or out of a BMP is not directly measured, but can be calculated from the flows that are recorded. In these cases, mass balance equations will be used and checked against work conducted by the original author. In addition, total flow volumes can be estimated from runoff coefficients and the available rainfall data, where available.

4.2 Exploratory Data Assessment

An initial exploratory data analysis will be conducted to provide a common starting point for quantification of efficiency, effectiveness and performance.   Three initial sets of graphs will be produced for each BMP and constituent monitored as shown below:

1. A normal probability plot showing the log transform of both inflow and out flow EMCs for all storms for the BMP. If the log transformed data deviates significantly from normality, other transformations will be explored to determine if a better transformation exists. Examples for TSS for the three designs examined in Tampa Office Pond Study are shown in Figures 4.1-4.3

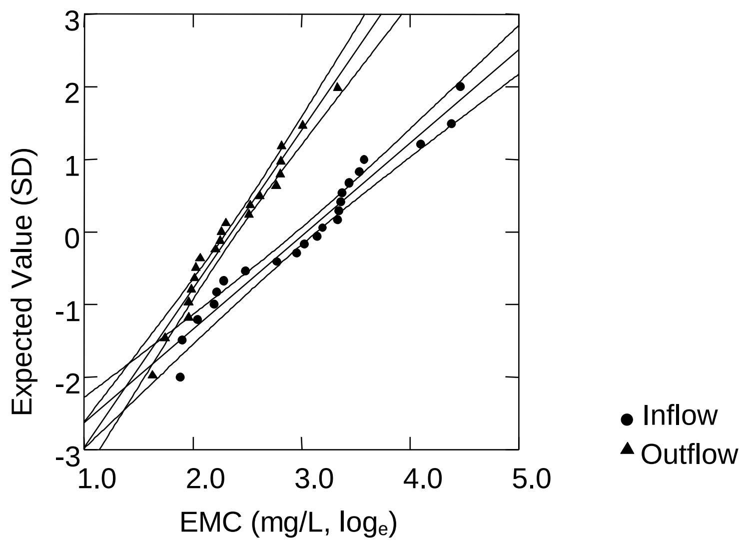


Figure 4.1 Normal Probability Plot for Log Transformed Inflow and Outflow Data for TSS for the Tampa Office Pond (1990), (0.95 confidence interval on the regression lines)

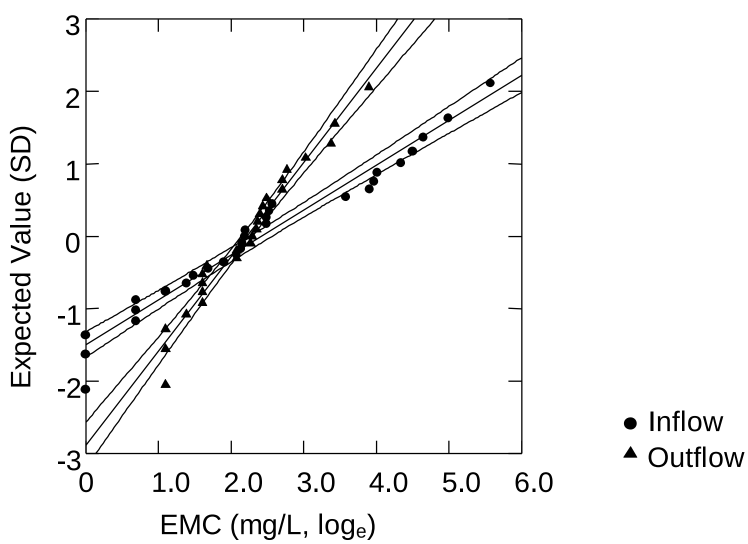


Figure 4.2 Normal Probability Plot for Log Transformed Inflow and Outflow Data for TSS for the Tampa Office Pond (1993-1994) , (0.95 confidence interval on the regression lines)

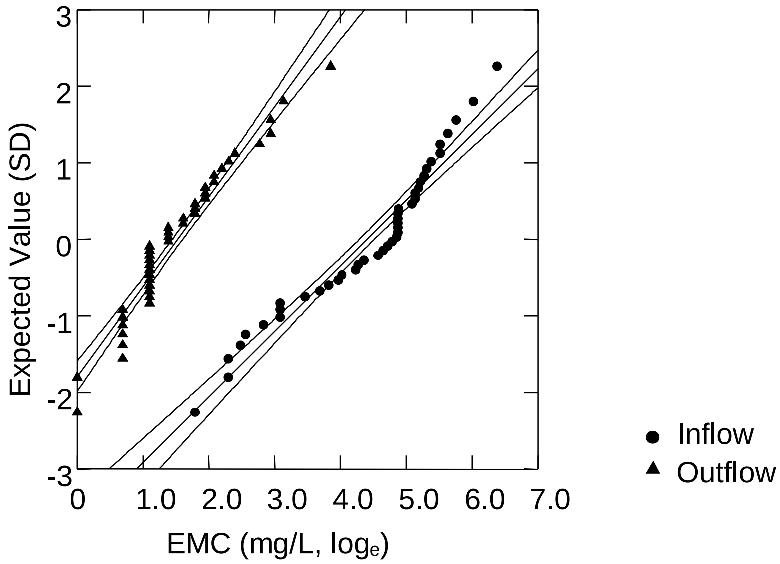


Figure 4.3 Normal Probability Plot for Log Transformed Inflow and Outflow Data for TSS for the Tampa Office Pond (1994-1995), (0.95 confidence interval on the regression lines)

2. A notched grouped box plot will be generated showing both inflow and outflow on the same plot. One plot will be generated based on transformed EMCs or grab sample concentrations and one will be generated based on transformed loads. Each box plot will include the standard deviation and selected percentiles and/or confidence intervals. Examples for TSS for the three designs examined in Tampa Office Pond Study are shown in Figure 4.4.

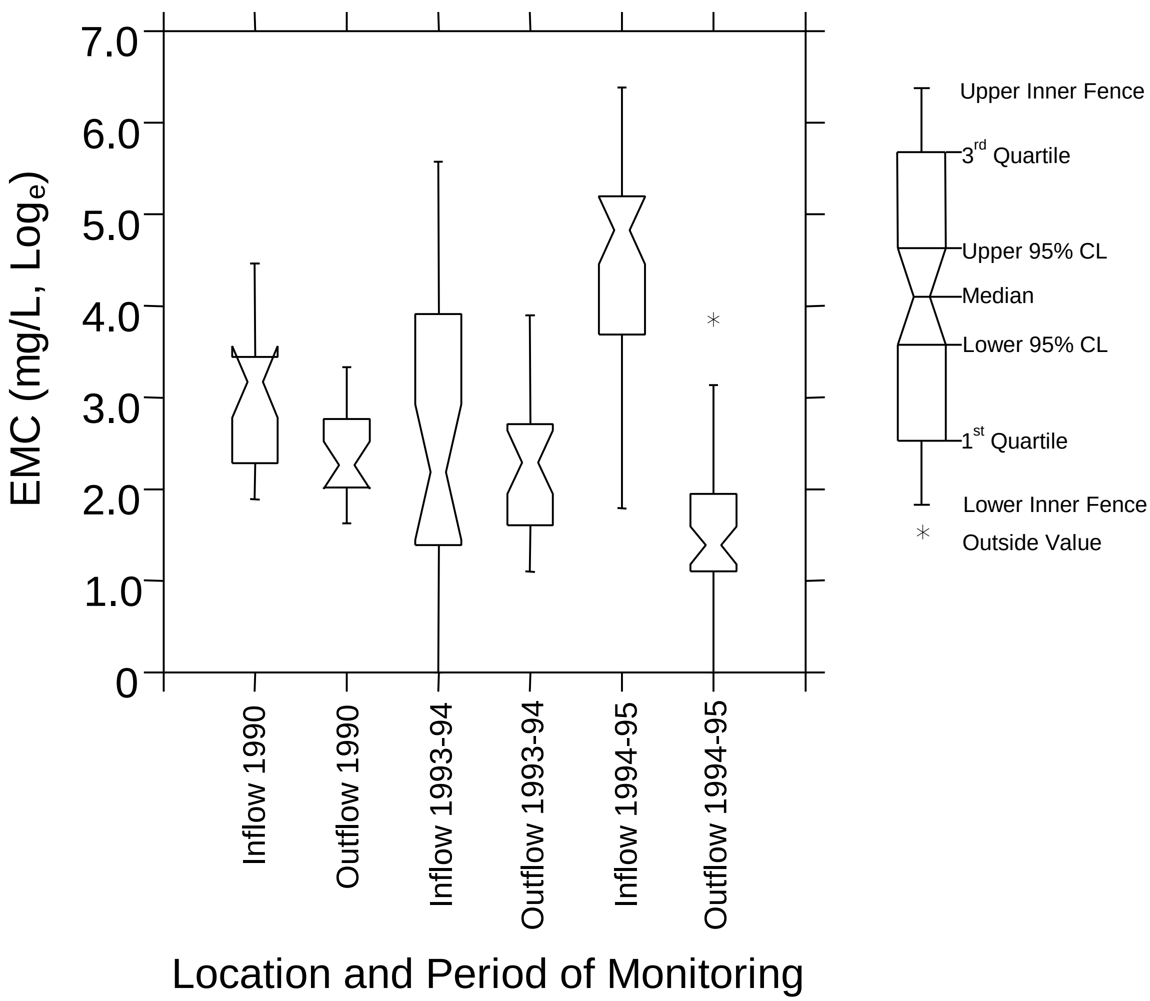
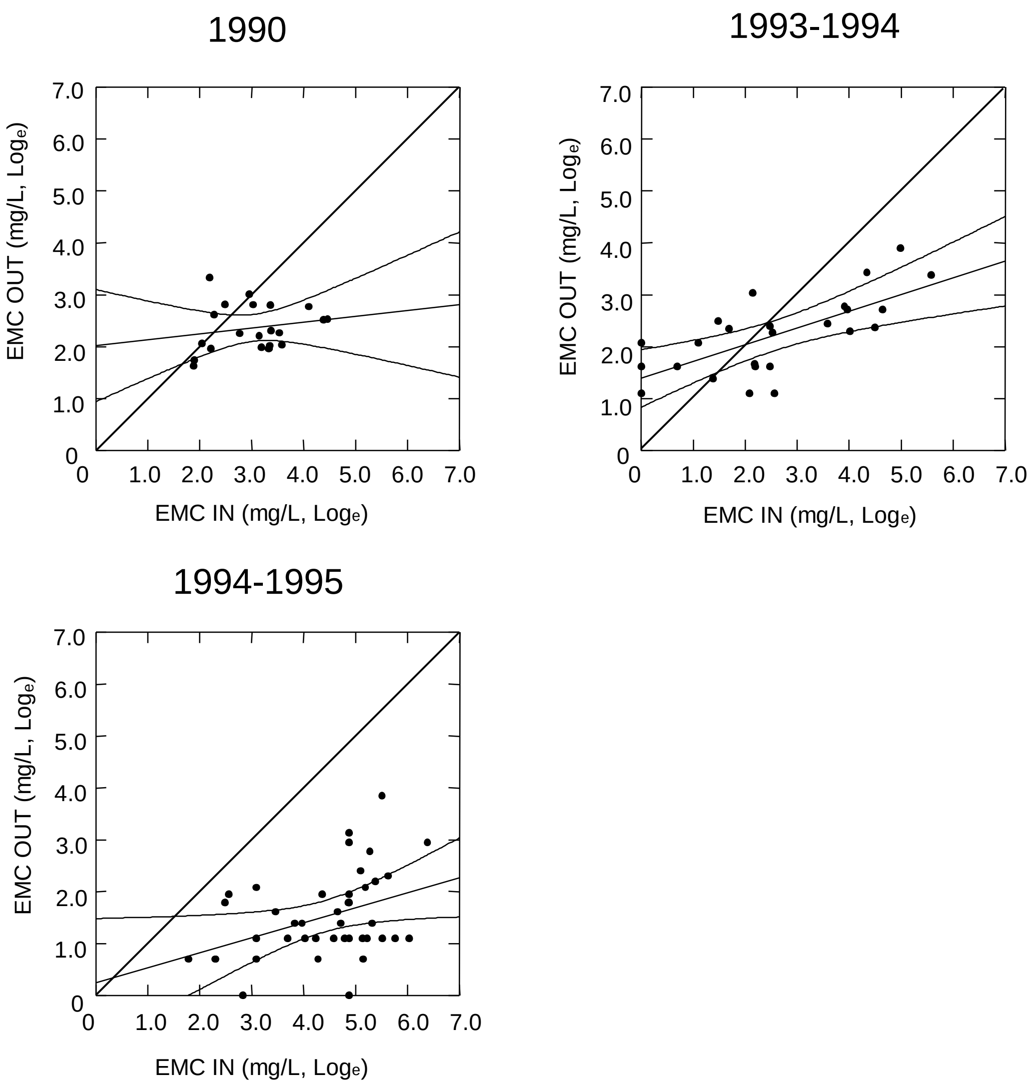


Figure 4.4 Notched Box Plot for Log Transformed Inflow and Outflow Data for TSS for the Tampa Office Pond (Boxes are narrow at the median and are full width at the lower and upper 95% confidence interval. The limits of the box show the range within which the central 50% of the values lie (also called the lower and upper hinge). The whiskers represent the upper and lower inner fences defined as: hinge ± (1.5 * (median- hinge)). Outside values are labed as an asterix and are defined as being between the inner and outer fence.

3. A scatter plot will be generated showing EMC out as a function of EMC in. This plot will allow for the visual inspection of the degree of "pairing" of EMCs at the inflow and outflow. The scatter plot will be produced with transformed data on both axes. If appropriate, a best-fit line will be plotted.



Figures 4.5-4.7 Scatter Plot for Log Transformed Inflow and Outflow Data for TSS for the Tampa Office Pond (0.95 confidence interval on the regression lines).

After an analysis of the graphical output for each of the above methods, decisions will be made about the best way to further analyze the data on a case by case basis. The paired t-test will be used and other paired and non-paired non-parametric tests will be explored as appropriate.

4.3 Data Analysis: Lognormal Statistical Efficiency

The graphical methods shown in Section 4.2 allow for the data to be explored. These methods help determine if a statistical approach to the data is appropriate and if any transformations of the data would improve interpretation. After data for a particular BMP are deemed appropriate for further analysis (i.e., there are enough data points available for a particular study and constituent to lend statistical significance to further analysis) the water quality data will be analyzed as described in this section.

The lognormal statistical efficiency (LSE) defines efficiency, not as a single value, but as a summary of the statistical characteristics of the inflow and outflow. An example of a full analysis using this method is shown in Table 4.1.

The test of statistical significance of the results takes as its hypothesis that the inflow and outflow values are derived from the same population. This null hypothesis allows the efficiency of the BMP to be evaluated by the probability that the BMP has no statistically relevant effect on the distribution of EMCs downstream of the BMP compared to upstream values. This hypothesis is best evaluated using the results of the one-way analysis of variance (ANOVA) test. The effect of the BMP will be considered significant if the probability (P-value) that the resulting F-ratio from the ANOVA could have been generated by chance is less than a chosen significance level (to be chosen after results are examined, typically 0.05). The overall efficiency will be summarized by reporting: the P-value, the percent difference between the arithmetic estimate of the mean log transformed EMCs at the outflow and the inflow along with the related confidence limit of the means, and the percent difference between specific percentile ranges (most likely the 10^{th} and 90^{th}). Note that using only the difference in the mean is identical to the Efficiency Ratio method described in Section 3.1, using the log transform of the data. Additional tests of the statistical relevance of the differences in population characteristics at the inflow and outflow will also be examined depending on the usefulness of parametric methods.

If the assumptions of the parametric ANOVA cannot be met or if the proportion of non-detects in the data set exceeds 15%, a Kruskal-Wallis nonparametric ANOVA (analogous to the parametric one-way analysis of variance) will be used to examine the hypothesis regarding significant differences in constituent concentrations at the inflow and the outflow. The nonparametric ANOVA evaluates the ranks of the observed concentrations at each location. Non-detects will be treated as tied values and are assigned an average rank. The two-sample Kolmogorov-Smirnov test will also be explored. In general, nonparametric methods are less powerful than their parametric counterparts, for distributions that are approximately log normal, reducing the likelihood that a “true” significant difference between treatments will be detected.

Example of the Lognormal Statistical Efficiency for TSS in the Tampa Office Pond

All supporting graphs for the NSE method are shown in Section 4.2 of the memorandum. Table 4.1 given below shows what typical results will be presented to define efficiency of each BMP in the database.

Table 4.1 Summary of Preliminary Analysis of Tampa Office Pond Using LSE Method

BMP Name	Constituent	Location	Mean (Log EMC), [Upper CL, Lower CL]	SD	Estimate of Arithmetic Mean EMC Based on Appendix A		10th Percentile EMC[1]		90th Percentile EMC[1]		Analysis of Variance (ANOVA)
					Value	Diff., [%]	Value	Diff. [%]	Value	Diff. [%]	
Tampa Office Pond 1990	TSS	Inflow	3.046 [3.382, 2.711]	0.757	28.009	16.282 [58.1]	7.82	0.72 [9.2]	57.15	40.45 [70.8]	N: 43 Multiple R: 0.488 Squared Multiple R: 0.239 Sum of Squares: 5.028 Mean-Square: 5.028 F-ratio: 12.850 **P-value: 0.001** Durbin-Watson D Statistic: 1.976 First Order Auto Correlation : -1.034
		Outflow	2.362 [2.566, 2.159]	0.447	11.727		7.10		16.7		
Tampa Office Pond 1993-1994	TSS	Inflow	2.413 [3.012, 1.814]	1.575	38.602	26.386 [68.4]	1.74	-1.26 [-72.4]	108.91	90.24 [82.9]	N: 54 Multiple R: 0.077 Squared Multiple R: 0.006 Sum of Squares: .500 Mean-Square: 0.500 F-ratio: 0.314 **P-value: 0.578** Durbin-Watson D Statistic: 0.712 First Order Auto Correlation : 0.629
		Outflow	2.220 [2.530, 1.909]	0.752	12.216		3.00		18.67		
Tampa Office Pond 1994-1995	TSS	Inflow	4.401 [4.753, 4.050]	1.128	154.037	147.591 [95.8]	12.69	10.69 [15.8]	248.60	231.75 [93.2]	N: 84 Multiple R: 0.828 Squared Multiple R: 0.685 Sum of Squares: 173.832 Mean-Square: 173.832 F-ratio: 178.207 **P-value: 0.000** Durbin-Watson D Statistic: 1.820 First Order Auto Correlation : 0.088
		Outflow	1.524 [1.781, 1.268]	0.824	6.446		2.00		16.85		

1. Calculated based on the difference between the EXP (10th percentile of the Log transformed data) for the inflow minus the outflow.

In looking at the results of the ANOVA test the criteria for the P-value (<0.05) is met in two of the three cases (1990 and 1994-199 inherent to the ANOVA test, the null hypothesis has been rejected, (i.e., there is less than a 5% chance that the two data sets were t population). In addition the two non-parametric tests (i.e., the Kruskal-Wallis test and the Two Sample Kolmolgorov-Smirnov tes ANOVA test (the probability for both the 1990 and 1994-1995 data are below 0.05). When looking at the 1993-1994 data (the P- the criteria for all three tests), it is apparent that even though the percent difference in the estimates of the mean values is quite larg information is not statistically relevant and therefore should be identified such. Although the analysis of the difference in the mea relevant, the statistically insignificant differences provide the best estimate of the efficiency of the BMP, though there is little conf records should be flagged to prevent misinterpretation of any resulting “percent removal” values. The 1990 and 1994-1995 results significant approximation of the efficiency of the BMP (for TSS), where the 1993-1994 data fail to do so.

4.4 Relative Outflow Concentration

In addition to exploring the LSE, the relative outflow concentration will be examined as an alternative method for quantification of effectiveness where outflow EMCs do not vary significantly with respect to inflow concentrations. The relative outflow concentration examines the relationship between outflow EMCs for a number of separate BMPs, and explores the parameters that affect outflow water quality. The logarithmic transform of the EMC data will be used to statistically characterize the outflow. Descriptive statistics, identical to those methods used in Section 4.2, can be utilized to examine the relationship between outflow concentrations at a number of different BMPs of the same type. In this method, influent EMCs are viewed as one of the design parameters, along with environmental, and design factors. This focuses attention on the actual water quality levels the BMP is theoretically designed to provide and explicitly assumes that there may not be a functional, or at least an overriding, relationship between influent and effluent EMCs. Both multiple regression analysis and population testing can be used to determine the effects of each design parameter, including influent EMCs (see Section 11)

Due to the fact that the method relies on data from multiple BMPs of the same type, the data and studies used to establish the baseline information must be numerous enough to establish a reliable nationwide trend. The inflow concentration may not be the primary factor affecting the performance of a BMP. In some specific cases it is expected that outflow concentrations are independent of or only partially dependent on inflow concentrations (i.e., outflow EMCs often do not parallel inflow EMCs). Therefore, there should be less emphasis on the difference between inflow and outflow EMCs and measures, such as percent removal, when judging BMP effectiveness. In addition, the type of constituent and its associated removal mechanism are important when considering if influent EMCs have an effect on effluent EMCs.

5 Analysis of Rainfall Events

Analysis of rainfall data can often shed light on the factors that contribute to the performance of a given BMP. In order for the impact of non-structural BMPs and BMPs that lack an upstream gauging station to be properly evaluated, the rainfall for a particular event must be available for analysis. In most cases, it is sufficient to quantify the relationship between total flow at some downstream monitoring station and total rainfall depth in the BMP's tributary watershed. This can help quantify any effects the BMP may have on reducing the quantity of water that reaches the downstream monitoring location. This information is essential for comparing porous pavements, minimization of directly connected impervious areas, and many non-structural BMPs. In all cases where reference watersheds and/or temporal variation of BMP design are employed, rainfall is one of the key normalization parameters.

Analysis of storm rainfall data can also be very useful for quantifying the effects of bypass of the overall performance of a BMP. In some cases monitoring of bypass and overflows has not been conducted. In these cases, rainfall data provides the only potential means for determining the performance of the overall BMP system, where one is evaluating not only the effect on water quality of flow that pass through a BMP, but also how much the BMP can "treat". In some cases a theoretical hydrograph (which would introduce error) would be required in order to use the data stored in the database to approximate bypass or overflow for a particular event.

6 Number of Storms and Number of Samples

The number of storms used for any of the above analyses in Sections 3 and 4 directly impact the statistical relevance of the calculated performance, as evidenced in the ANOVA and confidence interval of the mean log-transformed value at a particular monitoring station. An analysis of the number of storms monitored in comparison to the number required to obtain statistically relevant results will be conducted.

7 Characteristics of Storms Monitored

In addition to confirming that the number of storms monitored is sufficient to yield statistically useful results, the types of storms monitored have a major impact on extrapolating the results obtained to determine the overall long-term performance. The relationship between storm size and storm frequency in most locations ensures that smaller storms are more prevalent in most stormwater flow records. This often presents a particular challenge. It must be ensured that the methods inherent to the data collection effort do not unduly skew the results of the performance analysis or that this bias is taken into account or at least recognized. For many of the methods presented in Section 3 and 4, this requires restraint in extrapolation of results to areas of the record that are less populated by data. For example, the presence of a small number of large storms can dominate a summation of loads calculation.

8 Toxicity Determinations

The concentrations of both inflow and outflow EMCs can be utilized to evaluate the potential toxicity reduction of BMPs. Although instantaneous grab samples provide a more accurate picture of toxicity at any given time, the EMC comparison will provide a measure of the average concentration during an event versus criterion values. In this effort we will utilize both EMC data and grab sample data (separately) to assess a BMP's potential to reduce toxicity, comparing the frequency and magnitude of the number of both EMCs and grab samples that exceed EPA published values.

9 Net Export of Contaminants (Negative Removal Efficiencies)

In some cases, the performance of a given BMP is masked by the introduction of contaminants from within the BMP. This may be caused by significant levels of sorbed or particulate contaminants in the soil matrix, decaying matter within the BMP that exports significant quantities of nutrients, or sources such as ground water, rainwater, or airborne contaminants. If negative removal efficiencies are regularly observed during data analysis, for a contaminant, the causes for such a net export will be sought. Often net export of contaminants is observed where concentrations of the contaminant in the inflow to the BMP are quite low. When concentrations are very low, a slight shift in the quantity of contaminants could greatly affect the calculated efficiency.

10 Information Stored in the Database

For each BMP type, and indeed each BMP, there exists an intimate and complex relationship between the environmental and design parameters and the mechanism for removal. An analysis of the relationship between environmental, design, and operational parameters requires an examination of factors that are most likely to observably influence the performance of particular type of BMP. We will explore both individual design attributes and carefully selected "groups" of design attributes to look for potential factors that affect performance. In order to define what information is available through the database, a list of each BMP type along with related design, environmental, and watershed parameters are shown in Table 10. A list of the types and number of BMPs that will be part of the initial data set contained in the database is shown in Table 10.1.

Table 10.1 Parameters to Report with Water Quality Data for Various BMPs

Parameter Type	Parameter	Ret. (Wet) Pond	Extended Detention (Dry) Basin	Wetland Pond Basin	Grass Swale/ Wetland Channel	Media Filter	Oil & Sand Trap/ Hydrodyn. Device	Infilt. Basins and Trenches
Tributary Watershed	Area, average slope, average runoff coeff., length, soil types, veg. types	•	•	•	•	•	•	•
	Imperv. % and % hyd. connected	•	•	•	•	•	•	•
	Details about gutter, sewer, swale, ditches, parking, roads in watershed	•	•	•	•	•	•	•
	Land use types (res., com. ind. open)	•	•	•	•	•	•	•
General Hydrology	Date and times for monitored storms	•	•	•	•	•	•	•
	Runoff volumes for monitored storms Peak 1-hr intensity	•	•	•	•	•	•	•
	Design storm/flood recurrence intervals and magnitude	•	•	•	•	•	•	•
	Peak flow rate, depth, and Manning's roughness coeff. for the 2-year storm				•			
	Depth to seasonal high groundwater/impermeable layer		•		•			•
	Saturated hydraulic conductivity, infiltration rate, soil group				•			•
	Average annual values for number of storms, precipitation, snowfall, min./max. temp.	•	•	•	•	•	•	•
Water	Pollutant and constituent EMCs, and alkalinity, hardness and pH by event	•	•	•	•	•	•	•
	Water temperature	•	•	•	•	•	•	•
	Sediment settling velocity dist.	•	•	•	•	•	•	•
	Facility on- or off-line?	•	•	•	•	•	•	•
	Bypassed flows during events	•	•	•	•	•	•	•
General Facility	Facility Location (Lat./Long.), address, city, state, country, age of BMP, etc.	•	•	•	•	•	•	•
	Type and frequency of maintenance	•	•	•	•	•	•	•
	Types and location of instruments	•	•	•	•	•	•	•
	Inlet and outlet details, and number	•	•	•	•	•	•	•
Wet Pool	Media or granular material depth, type, storage volume, and porosity					•		•
	Volume, surface area, length of permanent pool	•		•		•	•	
	Littoral zone surface area	•						
Detention Volume	Solar radiation, days of sunshine, wind speed, pan evaporation	•	•	•	•			•
	Detention (or surcharge) and flood control volumes	•	•	•		•	•	•
	Basin's surface area and length	•	•	•		•	•	•
	Brimful and half-brimful empty time	•	•	•		•	•	•
Pre-Treatment	Bottom stage/infil. surface area, type			•	•			•
	Forebay volume, surface area	•	•	•		•	•	•
Wetland Plant	Relationship to other BMPs upstream	•	•	•	•	•	•	•
	Wetland/swale type, surface area, and length, side slope, bottom width			•	•			
	Percent of wetland surface between 0-12", 12"-24", and 24"-48"			•	•			
	Plant species and age of facility	•	•	•	•			

Based on Urbonas (1994,1995) and NSW database tables

11 Parameter Evaluation

This section discusses the selection process for parameters used to evaluate the relationship between, design and environmental conditions, and efficiency. Two methods are presented. The first of these methods is multiple regression analysis. The second is BMP group testing.

11.1 Selection of Parameters and Scalability

Parameters that are selected for evaluation must be present or consistently and reliably derivable from the data in the majority of BMP reports. Parameters that relate to sizing of a BMP that are selected as indicative of performance must be scalable. This scalability allows the results obtained from one set of BMPs to be compared with results from another set. As was mentioned in the Section 3, the correlation of the results from two different locations having varied conditions cannot be compared if all significant variables that are related to sizing are not scaled appropriately. Where conditions are significantly dissimilar or a small number of data points are available, scaling can introduce significant errors in analysis.

Parameters that can be calculated from a combination of database fields will be utilized for evaluating the relationship between static and state variables and efficiency. Parameters that correlate well with efficiency should be directly linked to the removal mechanism for that particular BMP type.

For example, in all BMPs that utilize settling as a primary removal mechanism, storm detention time is a key factor. The average detention time for a BMP during a given event is dependent on the design of the BMP and flow conditions during the event. For the general case, average detention time for an event can be calculated based on the average storage volume of the BMP and flows in and out, neglecting other losses; each of these may vary with time as shown in Equations 11.1-11.4.

The volume in the BMP, $V(t)$, at time t is given by:

$$V(t) = V_o + \int_{t_0}^{t} \left[Q_{in}(t) - Q_{out}(t)\right] \cdot dt \qquad \text{Equation 11.1}$$

where,

t:	time
V_0:	permanent pool storage volume of BMP
Q_{in}:	volume flow rate into BMP
Q_{out}:	volume flow rate out of BMP

In most cases, detention time is outflow dominated and thus can be approximated using the average volume flow rate at the outflow and the average total volume in the BMP.

The average volume flow rate, $\overline{Q_{out}(t)}$, on $[t_0, t]$ is given by:

$$\overline{Q_{out}(t)} = \frac{1}{(t - t_0)} \int_{t_0}^{t} Q_{out}(t) \cdot dt \qquad \text{Equation 11.2}$$

The average value of the total volume in the BMP, $\overline{V(t)}$, on $[t_0, t]$ is:

$$\overline{V(t)} = \frac{1}{t - t_0}\int_{t_0}^{t} V(t)\cdot dt$$ Equation 11.3

Finally, an average detention time, $\overline{t_{\det}}$, for the BMP on [t_0, t], can be found from Equation 11.4:

$$\overline{t_{\det}} = \frac{\overline{V(t)}}{\overline{Q_{out}(t)}}$$ Equation 11.4

For locations that do not have a significant change in detention volume with time during events (e.g., ponds with a large permanent pool and little surcharge detention volume) the volume of the pond can be assumed to be constant ($V(t) = V_0$, or $Q_{in}(t) = Q_{out}(t)$) and the storm average detention time can be approximated as:

$$\overline{t_{\det}} = \frac{V_0}{\left(V_{out} / t \right)}$$ Equation 11.5

If "intra-storm" flow rate data is not available, (the database does not currently support "raw" flow data, although it can be stored in generic attached data tables) and the storage volume in the BMP changes significantly over the course of an event, either an approximate average storage volume would need to be selected based on more detailed information about the system, or some theoretical hydrograph would need to be used based on rainfall and runoff characteristics, BMP design, and design of the outflow structure.

In addition to calculating the detention time for each storm event, an average detention time can be calculated for the BMP based on the historic average wet season rainfall rate for the area (Rushton et al, 1997). This method is applicable to BMPs that have effluent flows that continue for periods well in excess of the duration of the storm event and locations that have fairly steady rainfall rates over some specified wet season. Although the actual storm detention time calculated using this alternative method is not based on data from the monitoring period, it does provide a uniform means of comparing BMP design over a wide variety of locations based on average rainfall characteristics.

It is expected that detention time will be one of the primary parameters of interest for detention based BMPs. In addition to calculating the detention time for each storm event that was monitored, it will be useful to calculate a mean detention time, and a detention time for the mean storm based on the synoptic rainfall data stored in the database. Each of these factors will be assessed to determine if there is a correlation between these factors and the efficiency of removal.

In addition to examining design parameters that are directly stored in the database (e.g., surcharge detention volume), and standard calculated parameters (e.g., detention time), additional ratios composed of more than one factor will be examined. These "treatment factors" allow for examination of other possibly important ratios between design parameters. For example, a "treatment volume factor", which can be defined for BMPs that use storage as the primary treatment process, is shown in Equation 11.6.

$$\frac{f(design\ volume)}{f(runoff\ volume)}$$ Equation 11.6

For BMPs that are "flow-through" in nature, a "treatment flow factor" (Equation 11.7), will be examined.

$$\frac{f\left(treatment\ flow\ rate\right)}{f\left(runoff\ flow\ rate\right)}$$ Equation 11.7

These two “factors” are examples taken from a larger set of combinations of parameters that will be examined. The methods outlined in Sections 11.2 and 11.3 will be used for determining the usefulness of the parameters and factors described in this section.

11.2 Multiple Linear Regression

Multiple regression analysis systematically allows for examination of any relationships between the outcome of the performance measurements discussed in Section 3 of the memorandum and some design parameter or “factor” for a type of BMP.

For example, for dry detention ponds, the relationship between the design parameters length, depth, and draw down rate could be evaluated against the efficiency of the BMP for removing TSS.

Multiple linear regression can be used to see if there is a linear relationship between the parameters or “factors” of interest and efficiency. Multiple linear regression attempts to define a continuous linear relationship between the set of parameters and the resulting efficiency of the BMP. The method first assumes that each of the variables of interest are independent. In the example we can assume, for the sake of analysis, that length and depth meet this criteria. Multiple linear regression also assumes that a linear correlation exists between each independent variable and the dependent variable. It is always advisable to plot the dependent variable as a function of each independent variable in order to determine if there may be some transformation of the independent data that may allow for a linear relationship.

After linear regression is conducted, the correlation coefficient gives a measure of the goodness of fit for the regression line. In addition the F statistic can be used to determine if the results occurred by chance and the t-statistics can be used to determine the relative usefulness of each variable in the regression equation.

11.3 BMP Group Test Methods

Group testing methods use a “cutoff” value for a design or environmental parameter and report the effects of exclusion of BMPs based on this “cutoff”. Most likely, this would be done with a set of factors; a BMP to make the “cutoff” might have to meet 4 of 6 “good” design factors. This approach does not require that a continuous relationship between some parameter and performance exists. This method can therefore be applied to yes/no factors, (e.g., forebay volume >10% of the total volume of a wet pond; length to width ratio of 3:1, etc.) or factors that have a small set of discrete values. In addition, the group testing method follows the design process, where often a required value is specified in order to meet a certain performance goal. The group testing method will probably be a more successful approach, compared to multiple regression, due to the small number of data points available for any given BMP type.

APPENDIX A

Table A.1

T=EXP(U)	S=M * CV
M = EXP(U + 0.5 * W^2)	W = SQRT(LN(1 + CV^2)
M = T * SQRT(1 + CV^2)	U = LN(M / EXP(0.5 * WP)
CV = SQRT(EXP(W^2) – 1)	U = LN(M/SQRT(1 + CV^2)

	Arithmetic	Logarithmic (ln)
Mean	M	U
Standard Deviation	S	W
Coefficient of Variation	CV	
Median	T	

Table A.1 presents transformations between logarithmic transformed population statistics and estimates of arithmetic population statistics.