THESIS

AN EVALUATION OF HYDRAULIC RETENTION TIME ON BMP WATER QUALITY PERFORMANCE

Submitted by

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ABSTRACT

AN EVALUATION OF HYDRAULIC RETENTION TIME ON

BMP WATER QUALITY PERFORMANCE

Urban stormwater contains elevated concentrations of pollutants that are carried to receiving waters as runoff travels over roads, rooftops, and other hard surfaces. Structural best management practices (BMPs) are used to mitigate the negative impacts of urbanization by improving the water quality of stormwater runoff. Volume-based BMPs attenuate the peak flow of runoff and increase the hydraulic retention time (HRT) of runoff allowing pollutants to be removed through settling, adsorption, and other physiochemical processes. When BMPs provide longer HRTs for runoff events, the capacity for pollutant removal is increased because there is greater opportunity for pollutants to settle out of the water column and more time for plant and biological uptake. However, increasing the HRT that a BMP provides requires more storage volume, costs more to construct, and takes away land that could be developed for other uses. There is a tradeoff between the size of a BMP, the cost to build a BMP, and the capacity for pollutant removal.

Two regional BMPs that serve the downtown area of Fort Collins, CO, were investigated in an effort to relate the HRT of a BMP to its water quality performance.

The Udall Natural Area (Udall WP) is a wet extended detention basin that provided storm HRTs of over 80 hours. Contrastingly, the Howes St. BMP has an unregulated outlet and provided storm HRTs less than 20 hours. Stormwater quality data was collected from 2009-2011 at the inlet and outlet of each facility. The pollutant removal at each BMP was quantified for various runoff constituents including heavy metals, total suspended solids (TSS), bacteria, and nutrients. The Udall WP consistently had cleaner TSS effluent than the Howes St. BMP had and also removed significant amounts of heavy metals. The cleaner effluent at the Udall WP can be attributed to the longer HRT that the BMP provided. If the Howes St. BMP were modified to have a water quality outlet, it is believed that the BMP could enhance water quality more consistently and that it would actually be more cost-effective than the Udall WP. Furthermore, the degree of pollutant removal from the undersized and unregulated outlet at the Howes St. BMP was enough to warrant the suggestion that the Udall WP was constructed larger than necessary for significant pollutant removal.

To further develop the relationship between HRT and water quality enhancement, additional stormwater studies for wet ponds and extended detention basins were investigated from the International BMP Database. A lognormal approximation was used to estimate the average HRT provided by a BMP based on the volume of runoff recorded at the BMP inlet during a storm event. The computed storm HRTs were matched with effluent water quality results for TSS, total recoverable zinc, total recoverable copper, and total phosphorous. Results were binned into HRT groups and a statistical analysis was conducted to determine whether longer HRTs enhanced the water quality at the BMP outlet. The analysis did not focus on water quality enhancement from inlet to outlet, but was aimed at determining whether additional treatment occurred from longer HRTs at the outlet. The results indicated that additional pollutant removal was not achieved in wet ponds when HRTs longer than 12 hours were provided. The only exception was total phosphorous, which was statistically lower in concentration when extremely long HRTs were provided. For dry extended detention basins, better pollutant removal was achieved when longer HRTs were provided, and longer HRTs (greater than 60 hours) may be required if total phosphorous or heavy metal reduction is desired. The findings could be used to refine BMP design criteria for the optimal HRT that will provide significant enhancements in water quality.

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LIST OF KEY TERMS

Alk	Alkalinity
BMP(s)	Best Management Practices (structural stormwater facilities)
BMP Database	International Stormwater BMP Database
^{o}C	Degrees Celsius
C*	Irreducible Minimum Concentration
Ca	Calcium
CCC	Colorado Climate Center
CI	Confidence Interval
City	City of Fort Collins
Cl^{-}	Chloride
COD	Chemical Oxygen Demand
CSU	Colorado State University
CWA	Clean Water Act
DO	Dissolved Oxygen
D Cd	Dissolved Cadmium
D Cr	Dissolved Chromium
D Cu	Dissolved Copper
D Pb	Dissolved Lead

D Zn	Dissolved Zinc
E. coli	*Escherichia coli*
EDB	Extended Detention Basin (dry)
EMC	Event Mean Concentration
FTCFWS	Fort Collins Flood Warning System
Hardness	Total Hardness
HRT	Hydraulic Retention Time
IQR	Inner Quartile Range
K	Potassium
MDL	Method Detection Limit
Mg	Magnesium
MS4	Municipal Separate Storm Sewer System
Na	Sodium
NH_3	Ammonia
NOAA	National Oceanic and Atmospheric Administration
NO_2	Nitrite
NO_3	Nitrate
NPDES	National Pollutant Discharge Elimination System
NURP	National Urban Runoff Program
PCL	Fort Collins Pollution Control Lab
PI	Prediction Interval
Q_{peak}	Peak Effluent Flowrate
QPF	Quantitative Prediction Forecast

ROS	Regression on Order Statistics
SC	Specific Conductivity
SO_4^{2-}	Sulfate
SWMM	U.S. EPA Stormwater Management Model v5.0
TKN	Total Klendenjal Nitrogen
TN	Total Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphorus
TR Cd	Total Recoverable Cadmium
TR Cr	Total Recoverable Chromium
TR Cu	Total Recoverable Copper
TR Pb	Total Recoverable Lead
TR Zn	Total Recoverable Zinc
TSS	Total Suspended Solids
Udall WP	Udall Natural Area Wet Pond
UDFCD	Urban Drainage and Flood Control District
U.S. EPA	United States Environmental Protection Agency
WP	Wet Pond
WQCV	Water Quality Capture Volume

1.0 INTRODUCTION

Stormwater runoff is generated when precipitation from rain and snowmelt events flows over land or impervious surfaces and does not percolate into the ground. As the runoff flows over the area within a watershed, it accumulates debris, chemicals, sediment and/or other pollutants that adversely affect water quality. Pollutants are eventually deposited into lakes, streams, rivers, and other types of receiving waters where poor water quality can have a detrimental effect on plants, animals, and entire ecosystems. When a watershed is developed into an urban area, the pollutant loading may increase, and the hydrologic pattern of runoff is altered.

Urbanization changes the hydrologic regime of a watershed and changes the chemical composition of stormwater runoff. The pervious area of a watershed is reduced which diminishes the amount of infiltration that can take place during a storm and ultimately causes a larger volume of runoff to reach receiving waters. Simultaneously, the peak flow of the runoff is increased. The result of both hydrologic changes is an increase in pollutant conveyance capacity and an increase in erosive potential from stormwater runoff. Changing the land use also introduces increased amounts of pollutants and different pollutants to the watershed that may not have been present prior to development.

Previously conducted stormwater sampling studies have been successful in quantifying the typical pollutants that are present in stormwater runoff. In 1983, the U.S.

Environmental Protection Agency (U.S. EPA) conducted a series of stormwater studies termed the National Urban Runoff Program (NURP) to determine which pollutants were prevalent in stormwater. Heavy metals were commonly found in stormwater runoff in concentrations exceeding ambient freshwater criteria and bacteria concentrations were found to be present at high levels. Oxygen demanding substances were found at approximately the same order of magnitude as secondary wastewater treatment plant discharges and levels of total suspended solids were frequently encountered at higher concentrations than secondary wastewater treatment plant discharges. Finally, elevated nutrient loads existed in stormwater (U.S. EPA 1983). All of these pollutants have detrimental effects on aquatic life and vegetation in receiving waters.

In 1972, Congress passed the Clean Water Act which defined municipal and industrial stormwater runoff discharges as a "point source" and required communities to develop unique management plans to mitigate the effects of stormwater pollution. Over the past several decades, Best Management Practices (BMPs) have been implemented to minimize the detrimental impacts of urbanization and to improve water quality. BMPs can include street sweeping operations, construction and post-construction practices, public education and involvement, and water quality facilities and maintenance. Structural BMPs are facilities used to reduce runoff and/or remove pollutants from runoff through physiochemical and biological processes. Within the context of this thesis, the term "BMP" will refer to structural BMPs.

Volume-based BMPs detain stormwater runoff in order to attenuate the peak flow of runoff and to remove pollutants from runoff. Typical examples of volume-based BMPs include dry extended detention basins (EDBs), wet retention ponds (WPs), and wetlands. These BMPs are constructed with outlets that slowly release runoff over an extended drainage time. When BMPs provide longer HRTs for runoff events, the capacity for pollutant removal is increased because there is greater opportunity for pollutants to settle out of the water column and more time for plant and biological uptake. Increasing the HRT requires an increase in the size of the BMP because more storage capacity must be provided to detain a given volume of runoff if it is released at a lower discharge rate. Thus, a trade-off exists between the size of a BMP, where larger structures have incrementally higher construction and maintenance costs, and the potential for water quality enhancement. Previous studies have recommended that an optimal storage volume exists when somewhere between the 70^{th} and 90^{th} percentile event is captured (WEF and ASCE 1998). This analysis was based on simulated storage of stormwater runoff using long-term rainfall records and the theoretical pollutant removal associated with variously sized BMPs.

A two-part investigation was conducted to develop the relationship between the HRT and water quality enhancement based on actual water quality results from stormwater sampling studies. First, a new stormwater sampling study was performed for two BMPs in Fort Collins, CO. One facility, called the Udall Natural Area (Udall WP), was built as a series of two wet ponds. Stored runoff was released from the facility through two outlets in series, which made the average HRT at the Udall WP very long and created favorable pollutant removal conditions. Contrastingly, the Howes St. BMP did not have a water quality outlet structure, and did not provide HRTs of the same duration. Samples were collected at the inlet and outlet of each BMP to establish the extent of water quality enhancement at each facility. A comparison of effluent quality results between the Udall WP and Howes St. BMP was performed to establish the extent of pollutant removal at each facility and to determine the impact of a longer HRT.

Then, additional stormwater sampling results from the International BMP Database were used to further develop the relationship between the HRT that a BMP provides and the effluent water quality. Individual storm average HRTs were calculated and matched to the corresponding effluent water quality results for EDBs and WPs. A comprehensive statistical analysis was performed to determine if the results indicated an optimal HRT that should be provided for the removal of TSS, total recoverable zinc, total recoverable copper, and total phosphorous. The findings could be used to refine BMP design criteria for the optimal HRT that will provide significant enhancements in water quality.

Section 2 of this thesis presents the results of a literature review for urban stormwater characteristics, management strategies, BMP performance analysis, and methods of statistical analysis. Section 3 details the stormwater sampling program that was performed in Fort Collins, CO. It includes site descriptions and other background information, the methods used to obtain stormwater samples, presents the stormwater sampling results, and highlights major conclusions from the study. Section 4 presents the BMP hydraulic retention time analysis that was performed using additional stormwater studies from the International BMP Database. It lists the methods used to calculate the storm average hydraulic retention time, displays the results of the investigation, and summarizes the findings of the investigation.

2.0 LITERATURE REVIEW

2.1 Urban Stormwater Characteristics

Urbanization changes the hydrology, land use, pollutant load, and potentially the type of pollutants found in stormwater runoff. Currently, accurate models do not exist for predicting the quality of stormwater, which necessitates the direct measurement of runoff pollutants. An accurate portrayal of stormwater quality will include measurements of heavy metals, bacteria, nutrients, suspended solids, and oxygen demanding substances. Additional parameters are also important to quantify because they affect the toxicity and speciation of pollutants.

2.1.1 Effects of Urbanization

Urbanization changes the hydrology of a watershed by increasing the amount of impervious area, which reduces the amount of infiltration that takes place in a watershed, and corresponds to an increased volume of stormwater runoff. Increased runoff volume has the ability to convey a higher pollutant load from the watershed compared to predevelopment conditions. Additionally, the intensity, or "flashiness" of runoff will increase (Goonetilleke and Thomas 2003). A rise in stormwater runoff velocity and volume leads to enhanced erosion, dislodgement, entrainment, and solubility of pollutants present on the catchment surface (Simpson and Stone 1988). Urbanization increases the capacity for pollutant load conveyance from stormwater runoff, but additional detriments occur as new pollutant sources are introduced.

Urbanization alters the land use of a watershed and introduces pollutant sources that were not present prior to development. The primary pollutant sources in an urban catchment have been identified as street surfaces, industrial processes, construction and demolition activities, corrosion of materials, vegetation input, litter, spills, and erosion (Goonetilleke and Thomas 2003, Pitt 1979, Pitt et al. 1995). The land use for a watershed determines the type and amount of pollutants likely to be encountered. Sartor et al. (1974) conducted an extensive study of street pollution buildup and identified different loading rates for pollutant accumulation between residential, commercial, and industrial land uses. Pitt et al. (1995) suggested that industrial and commercial areas were the most significant pollutant source areas, especially when vehicle service areas or parking storage areas were present.

2.1.2 Accumulation and Transport of Pollutants

The amount of pollutants on a catchment fluctuates over time. Formulations of a build-up/wash-off model have been used to estimate the amount of pollutants present on a catchment and to predict the expected pollutant load from stormwater. Build-up is the accumulation of pollutants on surfaces resulting from dry and wet deposition during periods between runoff-producing rainfall events. It is dependent on several factors including climate, land use, impervious fraction, street cleaning method and frequency, and antecedent dry period (Goonetilleke and Thomas 2003, Sartor et al. 1974). Pollutant build-up models are usually exponential in form implying an increase of pollutant load toward an asymptotic level during antecedent dry periods (Sartor et al. 1974, Charbeneau and Barrett 1998). Wash-off is the process by which accumulated pollutants are removed from catchment surfaces by rainfall and runoff and incorporated in stormwater flow. Complicating the wash-off model is a phenomenon of urban runoff termed the "first flush" which represents the higher levels of initial concentrations of constituents that are washed off from a catchment at the beginning of a rainfall event (Lee et al. 2004, Lee et al. 2002).

Despite promising studies regarding the build-up and wash-off of pollutants, it is generally inappropriate to use mathematical models to determine expected pollutant loads. It is insufficient to use antecedent dry period alone as a parameter for the accumulation of pollutants and wash-off models generally overlook the influence of rainfall intensity, total runoff volume, and runoff rate (Charbeneau and Barrett 1998, Goonetilleke and Thomas 2003). Stormwater runoff sampling provides the most accurate portrayal of pollutant levels within a catchment.

2.1.3 Stormwater Pollutants

Identifying common pollutants in urban runoff and the detrimental impacts of these pollutants is the first step towards effective management of stormwater. The NURP study was a stormwater research project conducted between 1979 and 1983 by the U.S. EPA. Stormwater quality sampling results from 28 cities throughout the United States were compiled and analyzed in an effort to quantify the prevalence of certain pollutant types found in urban runoff (U.S. EPA 1983). Results from the NURP study and other stormwater studies since then have demonstrated that the most prevalent pollutants in urban stormwater are heavy metals, bacteria, oxygen demanding substances, suspended solids, and nutrients.

Heavy metals, which can be toxic to plants and wildlife, were commonly found in stormwater runoff in concentrations exceeding ambient freshwater criteria for freshwater aquatic life (U.S. EPA 1983). Heavy metal pollutants arrive on street surfaces from corrosion and wear of vehicle components but can also originate from building materials, industrial activities, and from atmospheric deposition (Goonetilleke and Thomas 2003, Sansalone and Buchberger 1997, Pitt et al. 1995). Quantifying the dissolved metal fraction in addition to the total metal concentration is important because the dissolved portion is more readily available to fish and microorganisms. U.S. EPA (1983) identified copper, lead, and zinc as the most prevalent metals in stormwater runoff. Other common heavy metals that can occur in stormwater include cadmium, chromium, nickel, silver, selenium, arsenic, iron, and mercury (Geosyntec and WWE 2009).

Bacteria concentrations were found to be present at high levels during and immediately following storm events in most rivers and streams as a result of stormwater runoff (U.S. EPA 1983). Gannon and Busse (1989) have established that urban stormwater runoff can elevate bacterial concentrations in a stream, but correlations between specific urban activities and bacterial increases have not been specified. Extreme variability of bacterial concentrations exists in urban runoff and it is common for bacterial levels to be one or two orders of magnitude higher than instream primary contact recreational standards (Clary et al. 2008). *Escherichia coli* (E. coli) is often measured as an indicator of bacterial concentration (Geosyntec and WWE 2009).

Oxygen demanding substances have been found to be present in stormwater runoff at approximately the same order of magnitude as secondary wastewater treatment plant discharges (U.S. EPA 1983). The common impact of organic matter is the reduction in dissolved oxygen in water due to microbial oxidation. A substantial load of oxygen demanding substances can lead to anaerobic conditions resulting in fish kills, foul odors, discoloration, and slime growth (Goonetilleke and Thomas 2003). Direct measurement of dissolved oxygen in stormwater runoff is possible during storm events using electronic sensors. Laboratory tests for the carbon oxygen demand and total organic carbon will indicate the overall presence of oxygen demanding substances (Geosyntec and WWE 2009).

Levels of total suspended solids (TSS) are frequently encountered in stormwater at higher concentrations than secondary wastewater treatment plant discharges (U.S. EPA 1983). Elevated levels of total suspended solids coincide with the presence of other toxic pollutants that will adsorb to the suspended particles. The presence of fine solids in receiving waters can alter the capacity for photosynthesis, change streambed characteristics through deposition, and affect existing wildlife through biological uptake of associated toxic materials (Goonetilleke and Thomas 2003).

Elevated nutrient loads exist in stormwater that can stimulate aquatic plantlife growth and reduce the aesthetic appeal of a receiving water body. Visual impacts may include color and turbidity, but other impacts including dissolved oxygen depletion and objectionable odor can occur. The primary sources of nutrients include lawn fertilizer, sewer overflows, animal waste, vegetation debris, industrial activities, vehicle exhausts, power generation and atmospheric dry and wet deposition (Goonetilleke and Thomas

2003). At a minimum, measurements of total phosphorous and total nitrogen are required to characterize the nutrient loading in stormwater runoff (Geosyntec and WWE 2009). It is often useful to measure other forms of nitrogen and phosphorous that are commonly found in runoff including orthophosphate, nitrate, nitrite, ammonia, and total Klendenjal nitrogen.

2.1.4 Other Runoff Parameters

In addition to pollutants encountered in runoff, other parameters are useful to quantify when characterizing stormwater quality. Alkalinity, pH, total hardness, temperature, and conductivity affect the speciation of metals and nutrients. Knowing the quantity of each of these parameters will indicate whether toxic ionic forms of pollutants are likely to exist. Furthermore, fish species have differing ranges of pH, dissolved oxygen, and temperature that are tolerable.

It is also beneficial to characterize ions that are present in stormwater runoff. An overall indication of the level of ionic activity is known when the specific conductivity is measured. Chloride, which is linearly related to specific conductivity at a given site, is arguably the most important ion to quantify. Increased chloride levels can result from the application of deicing products. Direct harm to aquatic organisms and declines in wetland biodiversity have been observed (Wenck Associates 2006). Other predominant aqueous ions encountered in typical stormwater pH ranges include magnesium, sodium, potassium, calcium, and sulfate. Measuring these parameters allows greater refinement when chemical models are used to determine metal speciation (Geosyntec and WWE 2009).

2.2 Management for Stormwater Quality

In order to mitigate the negative effects that urbanization has on stormwater quality, several types of BMPs have been implemented. The objective of BMPs is either to store and treat runoff through various processes, or to reduce the overall volume of runoff. Sizing a BMP correctly is critical for pollutant removal, although the methodology is based primarily on theoretical removal rates and rainfall records. Water quality enhancement will differ among BMPs, and there are limitations to the achievable effluent concentration.

2.2.1 Background

In 1972, Congress passed the Clean Water Act (CWA), which established the National Pollutant Discharge Elimination System (NPDES) program (U.S. EPA 2009). The CWA defined municipal and industrial stormwater runoff discharges as a "point source" and the NPDES program controls water pollution by regulating point sources that discharge pollutants into waters of the United States. Any discharge from a large or medium municipal separate storm sewer system (MS4) was required to develop a unique management plan to mitigate the effects of stormwater pollution. MS4 permits always require plans for minimum control measures including public education and outreach, illicit discharge detection and elimination, construction site runoff control, post-construction runoff control, and pollution prevention (U.S. EPA 2009).

Various categories of BMPs have been implemented to mitigate the damage that urban stormwater runoff can cause on receiving waters. Nonstructural BMPs include pollution prevention, source control, and other "Good Housekeeping" measures. Street sweeping and public education programs are two examples of nonstructural BMPs. Structural BMPs are facilities used to reduce runoff and/or remove constituents from runoff by passively treating urban stormwater before it enters a receiving water. The Urban Drainage and Flood Control District (UDFCD) recommends a Four Step Process for receiving water protection that focuses on reducing runoff volumes, treating stormwater runoff, stabilizing drainageways, and implementing long-term source controls (UDFCD 2010). The Four Step Process shown in Figure 1 pertains to management of smaller, frequently occurring events, as opposed to larger storms for which drainage and flood control infrastructure are sized.

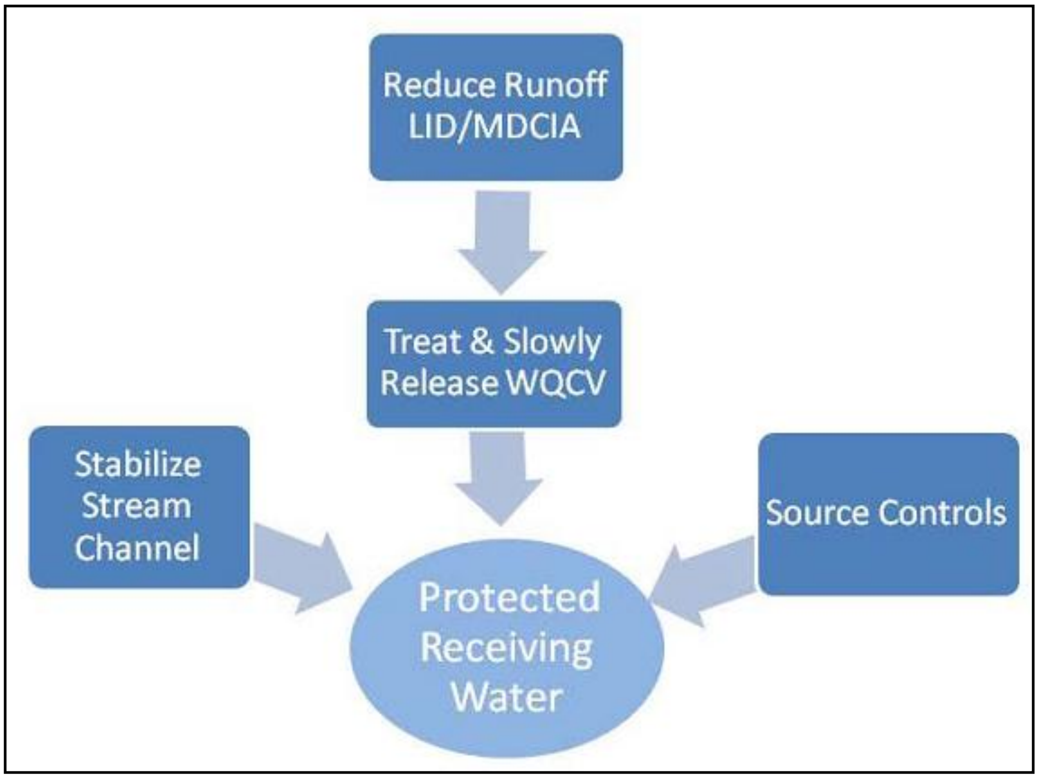


Figure 1. The Four Step Process for Stormwater Quality Management (UDFCD 2010)

Low impact development (LID) is a design philosophy that seeks to mimic the pre-development hydrologic regime through planning techniques and stormwater facilities. It involves land-planning goals like the protection of natural amenities, minimization of the overall impact of a development, and minimization of directly connected impervious area (UDFCD 2010). A major goal of LID is the reduction of stormwater volume that occurs from increasing the impervious area in a development. Typical LID stormwater features include permeable pavement, green roofs, grass buffers, swales, and bioretention areas (rain gardens). Volume-based structural BMPs treat stormwater runoff by storing it temporarily over an extended period of time. They may have the potential to achieve overall runoff volume reduction, but water quality enhancement is typically achieved through other processes. Stormwater wetlands, EDBs, and WPs are all examples of volume-based water quality BMPs.

2.2.2 Pollutant Removal Processes in Structural BMPs

Physiochemical processes and hydraulic controls promote water quality enhancement in structural BMPs. The main hydraulic controls associated with BMPs include flow attenuation, infiltration, and evapotranspiration. Dominant pollutant removal processes include adsorption, sedimentation, filtration, straining, and biological uptake.

Soluble sized pollutants such as dissolved nutrients, dissolved metals, bacteria, and very fine clays are readily removed by adsorption. This mechanism involves soluble pollutants becoming bound to other pollutants on the surface by chemical or physical forces. Clean, exposed soil on the bottom of a BMP can be an excellent location for pollutant removal through adsorption (Comings et al. 2000). More importantly, pollutants will adsorb to solids within the water column and then settle out through sedimentation.

The primary pollutant removal mechanism for volume-based stormwater BMPs is sedimentation. Significant loads of suspended pollutants such as metals, nutrients, sediments, and organics, can be removed by sedimentation. Extending the detention time of stormwater runoff allows smaller particles to agglomerate into larger ones, and a portion of the dissolved and liquid state pollutants will adsorb to suspended particles. Eventually, a larger proportion of pollutants will be removed through sedimentation. Stahre and Urbonas (1990) have estimated that smaller particles, such as fine silts and clays, can account for approximately 80% of the metals in stormwater attached or adsorbed along with other contaminants. These particles require significant time to settle out of suspension.

Filtration is a primary removal process for BMPs that promote infiltration. Larger pollutants are removed from water as it passes through a medium, usually sand, and dissolved constituents can be adsorbed onto the soil. Site-specific soil characteristics, such as permeability, cation exchange potential, and depth to groundwater or bedrock limit the number of sites where this mechanism can be used effectively (UDFCD 2010). Straining, which can be defined as coarse filtration, is a primary pollutant removal mechanism in some BMPs and usually a recommended component for others. Particulates and debris are physically removed as water flows through a device or vegetated area. Trash racks are recommended as pretreatment strainers in storage BMPs, and vegetation within various BMP types removes particulates.

Biological uptake involves the ingestion of minerals and dissolved nutrients by plants and microbes. Mallin et al. (1998) studied wet detention ponds and documented the importance of biological uptake by isolating the role of plants in constituent removal during winter months. Kantrowitz and Woodham (1995) documented increased efficiency in pollutant removal from the presence of plants. However, there is a limited amount of metals and other toxic materials that can be removed due to degradation of plant health. Moreover, the uptake process does not provide permanent removal, but represents temporary storage as a stage in the cycling and recycling of chemicals between biotic and abiotic compartments of the wetland system (Helfield and Diamond 1997). As plants die and decay, they re-release nutrients into the water column and can transform a BMP into a source of pollution. Biological conversion happens when microorganisms and bacteria break down organic contaminants into less harmful compounds. They can also assist in degradation of pollutants by catalyzing volatilization, hydrolysis, and photolysis (Huber et al. 2006).

Table 1 displays primary, secondary, and incidental processes common in stormwater BMPs (UDFCD 2010).

Table 1: Primary, Secondary, and Incidental Treatment Processes of Select BMPs (UDFCD 2010)

	Hydrologic Processes			Treatment Processes				
	Peak	Volume		Physical			Chemical	Biological
UDFCD BMP	Flow Attenuation	Infiltration	Evapo-transpiration	Sedimentation	Filtration	Straining	Adsorption/ Absorption	Biological Uptake
Grass Swale	I	S	I	S	S	P	S	S
Grass Buffer	I	S	I	S	S	P	S	S
Constructed Wetland Channel	I	N/A	P	P	S	P	S	P
Green Roof	P	S	P	N/A	P	N/A	I	P
Permeable Pavement Systems	P	P	N/A	S	P	N/A	N/A	N/A
Bioretention	P	P	S	P	P	S	S[1]	P
Extended Detention Basin	P	I	I	P	N/A	S	S	I
Sand Filter	P	P	I	P	P	N/A	S[1]	N/A
Constructed Wetland Pond	P	I	P	P	S	S	P	P
Retention Pond	P	I	P	P	N/A	N/A	P	S
Underground BMPs	Variable	N/A	N/A	Variable	Variable	Variable	Variable	N/A

Notes:
P = Primary; S = Secondary, I = Incidental; N/A = Not Applicable
[1] Depending on media

Maintenance is essential to ensure that pollutant removal mechanisms will continue to function in BMPs. Sediment accumulations can become too large and affect performance by reducing the storage volume of the BMP. Removal of debris collected at trash racks and removal of vegetation is often necessary. Wetland biota and sediments subjected to continuous contaminant loadings will eventually reach saturation. When pollutant influx and outflux are the same for a system, the assimilative capacity has been reached (Helfield and Diamond 1997). Replacing or harvesting plants and/or dredging soils may be necessary if greater performance is desired.

2.2.3 Sizing Volume-Based BMPs

Structural BMPs like EDBs and WPs must be designed to capture an appropriate amount of stormwater runoff in order to achieve pollutant removal. A BMP that is too small will be ineffective at storing water for sedimentation and have less potential for physiochemical interaction between pollutants. On the contrary, larger facilities cost more to construct and take away land that could be developed for other beneficial uses. Additionally, larger storms are less frequent and influence the overall pollutant load to a lesser degree than smaller, more frequent storms. This relationship implies that a theoretical BMP size exists whereby the maximum potential for pollutant removal can be achieved at a practical scale.

BMPs have been designed to detain runoff from storms between the 70th and 90th percentile event (WEF and ASCE 1998). This design standard was determined using simulated detention basins of various sizes that stored and released runoff. Long-term hourly precipitation records for various climates were used to estimate runoff. The amount of annual runoff captured was compared to the unit basin storage volume in an effort to determine the "knee of the curve" for capture efficiency. The "knee" was defined as the "maximized" or most cost-effective point on the curve because rapidly diminishing returns in the number of runoff events captured annually begin to occur past this point (Urbonas and Guo 1989). A pattern of diminishing returns was demonstrated in numerous hydrologic regions throughout the U.S. (Roesner et al. 1991). An example of the "maximized" storage point for Denver, CO, is shown in Figure 2 (Urbonas et al. 1989). A similar pattern of diminishing return was found in other hydrologic regimes, although the maximized storage volume was different as demonstrated in Figure 3 (Roesner et al. 1991).

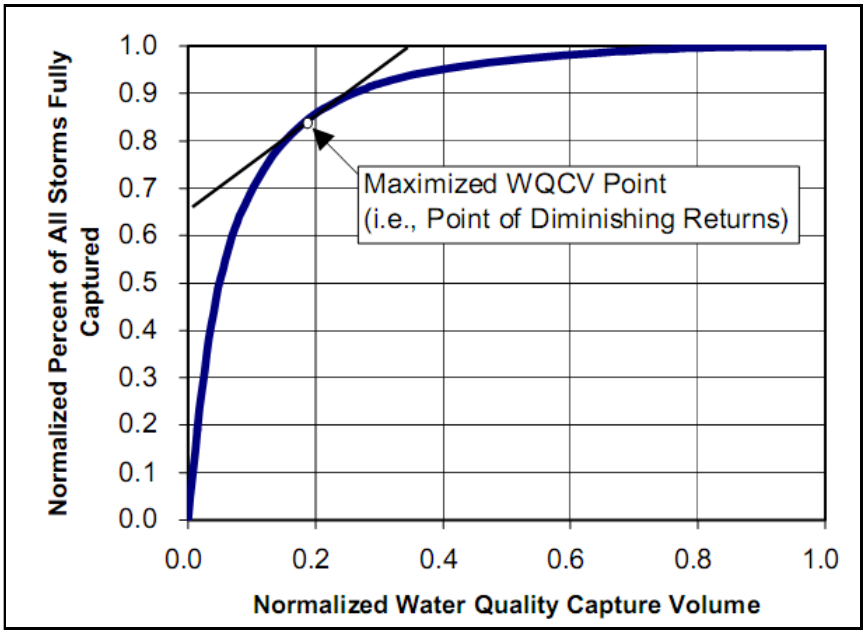


Figure 2. "Maximized" Storage Point-Denver Example (Urbonas et al. 1989)

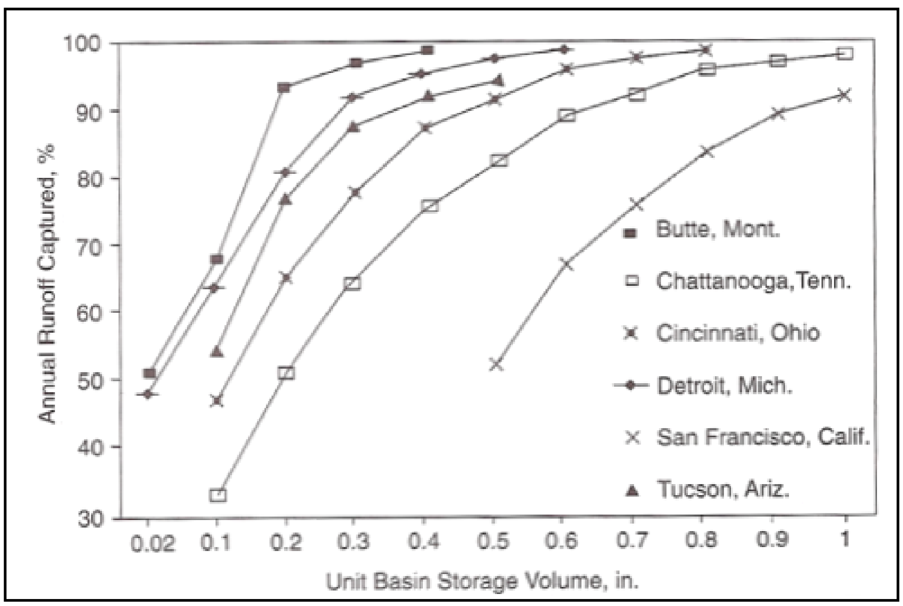


Figure 3. Runoff Capture Rates vs. Unit Storage Volume at Six Study Sites (Roesner et al. 1991)

Finding the "maximized" storage volume can be accomplished using the impervious area of a catchment and the average depth of a runoff-producing storm for the region (WEF and ASCE 1998). For a given basin, the runoff coefficient is determined by dividing the runoff volume at a catchment's outlet by the total storm volume that falls over the catchment. A relationship between the impervious area of a catchment and the runoff coefficient was developed by Urbonas et al. (1989) using 60 urban watersheds from the NURP study (U.S. EPA 1983). The best-fit line shown in Figure 4 is applicable for small storms and has broad applicability in the U.S.

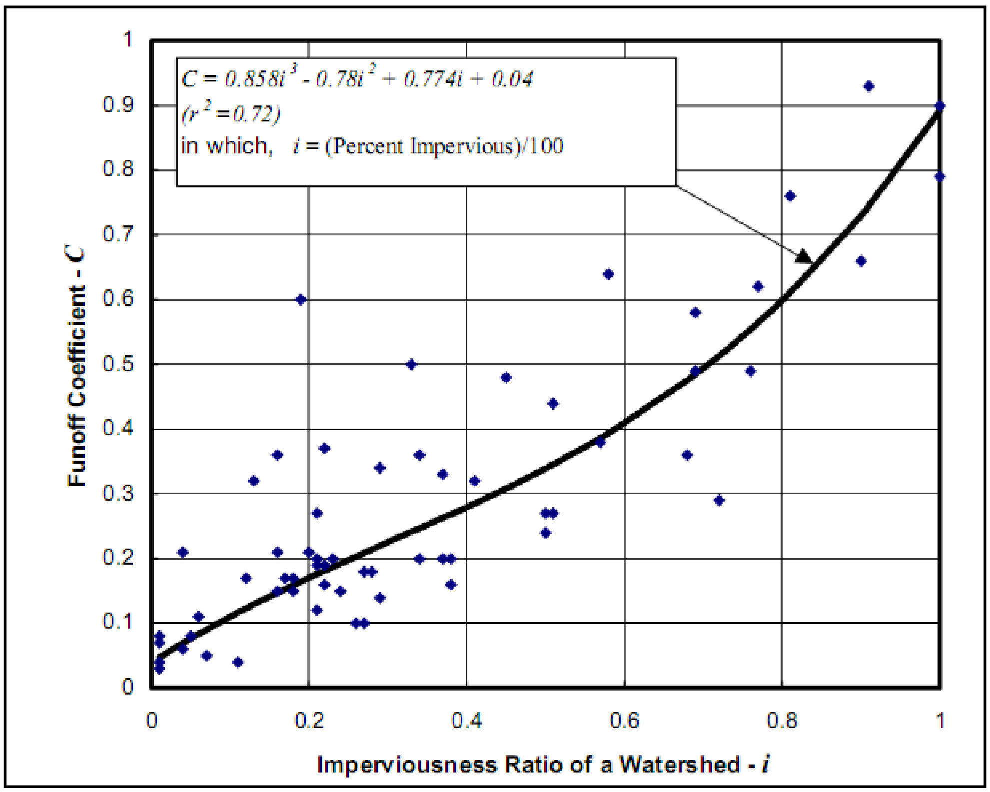


Figure 4. Runoff Coefficient Related to Catchment Imperviousness, NURP Storm Results (Urbonas et al. 1989)

BMPs designed for the "maximized" storage volume should theoretically achieve an ideal compromise between pollutant removal, efficiency, and facility cost. Larger storms will still receive some treatment but at a lesser efficiency, and the first flush of pollutants during a large event will still be captured. Theoretical water quality modeling was used to determine the sensitivity of adjusting the "maximized" storage size to pollutant removal. Additional removal of TSS was negligible (2% increase annually) if a BMP was doubled in size from the "maximized" storage size (Urbonas et al. 1989). This finding prompted the UDFCD to recommend that BMP storage facilities be designed to detain the 80th percentile event (UDFCD 2010).

The Water Quality Capture Volume (WQCV) represents the depth of rainfall that must be detained by a BMP in order to control runoff up to the 80th percentile storm (UDFCD 2010). It varies depending on the type of BMP and the desired drawdown time. Impervious area is directly related to the amount of runoff that a site is capable of producing, and thus is directly related to the associated WQCV needed to treat the runoff. Grizzard et al. (1986) demonstrated that detention basins emptying in 24 hours from the average runoff-producing storm were effective stormwater quality enhancement facilities. This equates to a 40-hour brimful drawdown time. Retention ponds and constructed wetlands have reduced drain times (12 hours and 24 hours, respectively) because the hydraulic residence time of the effluent is essentially increased due to the mixing of the inflow with the permanent pool (UDFCD 2010).

An empirical equation to calculate the WQCV has been developed for specific use in the Colorado Front Range and is shown in Equation 1 and Figure 5. Figure 5 displays the required WQCV based on different impervious percentages of a watershed and BMP drawdown times.

$$WQCV = a(0.91I^3 - 1.19I^2 + 0.78I)$$

Equation 1

Where: WQCV = Water quality capture volume (watershed inches)

a= Coefficient corresponding to BMP drain time

I = Imperviousness of watershed (%)

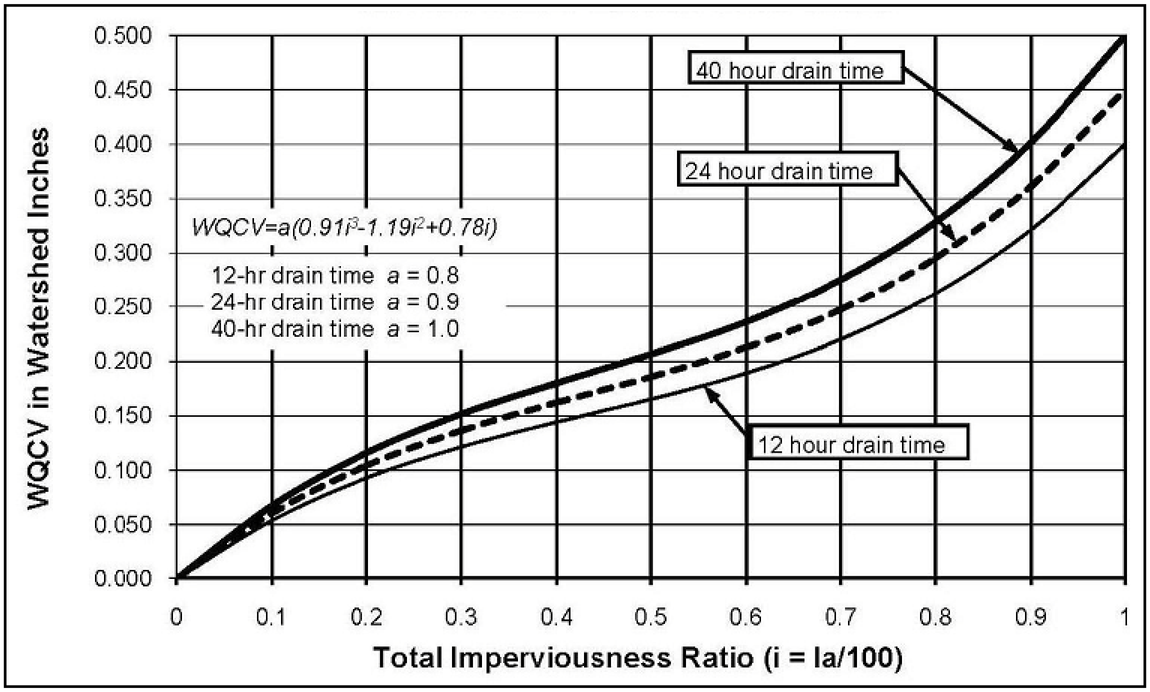


Figure 5: WQCV Based on BMP Drawdown Time (UDFCD 2010)

To find the required storage volume that a BMP should provide, the WQCV is multiplied by the contributing area as shown in Equation 2. It is typical to design a BMP to hold 120% of the required volume to account for future sedimentation accumulation and the associated loss of storage volume (UDFCD 2010).

$$V = \left(\frac{WQCV}{12}\right) A$$

Equation 2

Where: V = Required storage volume (acre-ft)

A = Contributing area of the drainage basin (acres)

WQCV = Water quality capture volume (in)

Other hydrologic regions can adapt the WQCV equation if a conversion is made to account for the mean precipitation depth of a runoff-producing storm. Equation 3 shows the conversion factor needed to find the WQCV for any region of the United States, and Figure 6 displays the mean runoff producing storm depths (Driscoll et al. 1989). Note that the denominator of Equation 3 is 0.43 inches, which corresponds to the mean storm depth for the Colorado Front Range, as shown in Figure 6.

$$WQCV_{other} = d_6 \left(\frac{WQCV}{0.43} \right)$$

Equation 3

Where: $WQCV_{other}$ = WQCV outside of the Denver region (in)

WQCV = WQCV calculates using Equation 1

d_6 = Depth of average runoff producing storm from Figure 6

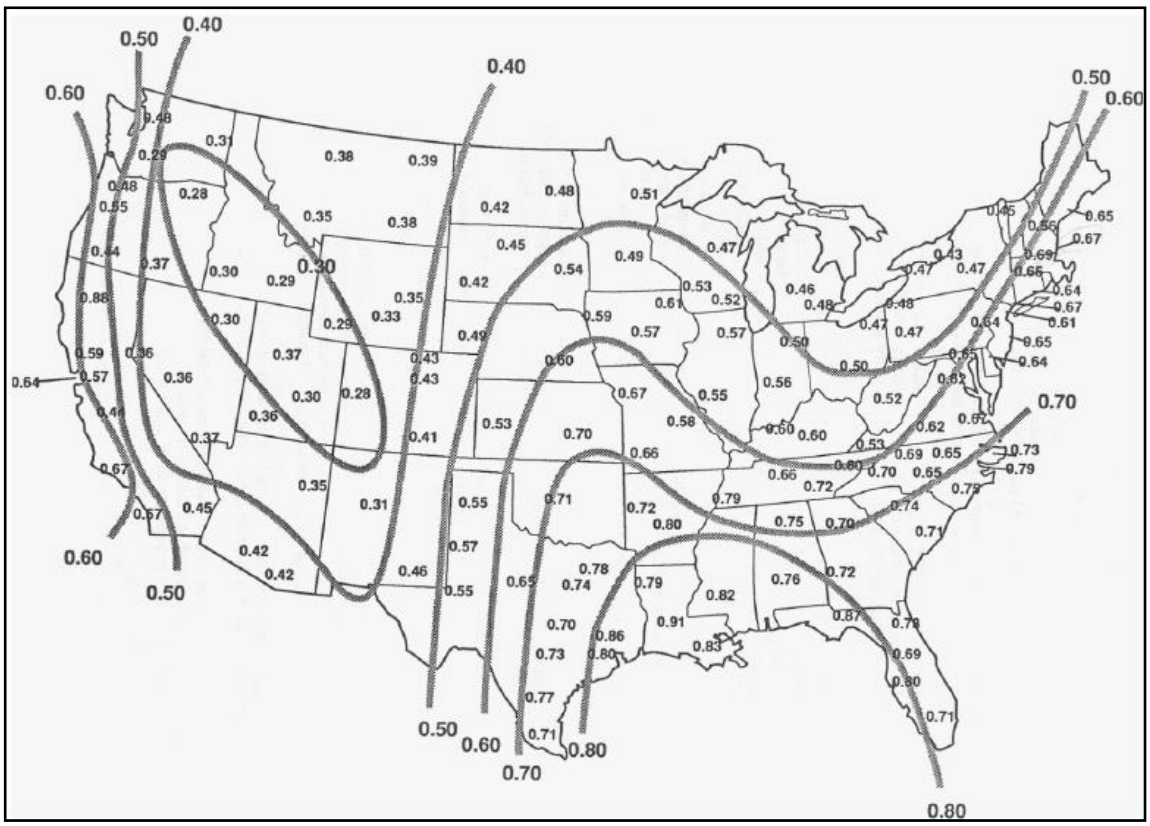


Figure 6. Depth of Average Runoff Producing Storm - Inches (Driscoll et al. 1989)

2.2.4 Design Criteria for Volume-Based BMPs

Volume-based BMPs have historically been used to control larger storm events by detaining a flood control volume. For water quality enhancement, a smaller outlet is used which extends the emptying time in order to facilitate pollutant removal. Mutual design considerations among volume-based BMPs include the use of trash racks to prevent outlets from clogging, the use of a forebay with easy maintenance access to remove gross solids, and the use of energy dissipaters to prevent sediment resuspension. Major differences include the design drawdown time, whether a permanent pool is established, and the extent of vegetation for pollutant removal through filtration and biological uptake.

An EDB is a sedimentation basin designed to detain stormwater for many hours after storm runoff ends. A 40-hour drain time for the WQCV is recommended to remove a significant portion of TSS from incoming runoff (UDFCD 2010). Longer drain times are required in EDBs because there is not a significant pool of stored water. Conditions occur when the pond fills and empties that are non-ideal for particle settling and there is no permanent pool of runoff to remove pollutants under quiescent conditions (Stanley 1996, Stahre and Urbonas 1990, Grizzard et al. 1986). Soluble pollutant removal can be enhanced by providing a small wetland marsh or "micropool" at the outlet to promote biological uptake. Trickle channels can be included to transport water from the forebay to the outlet and it is recommended that an initial surcharge volume be provided above the micropool for frequently occurring runoff. The initial surcharge volume will minimize standing water in the EDB to help control the mosquito population and prevent excessive sedimentation in upper parts of the basin. Figure 7 shows a typical stormwater EDB layout (UDFCD 2010).

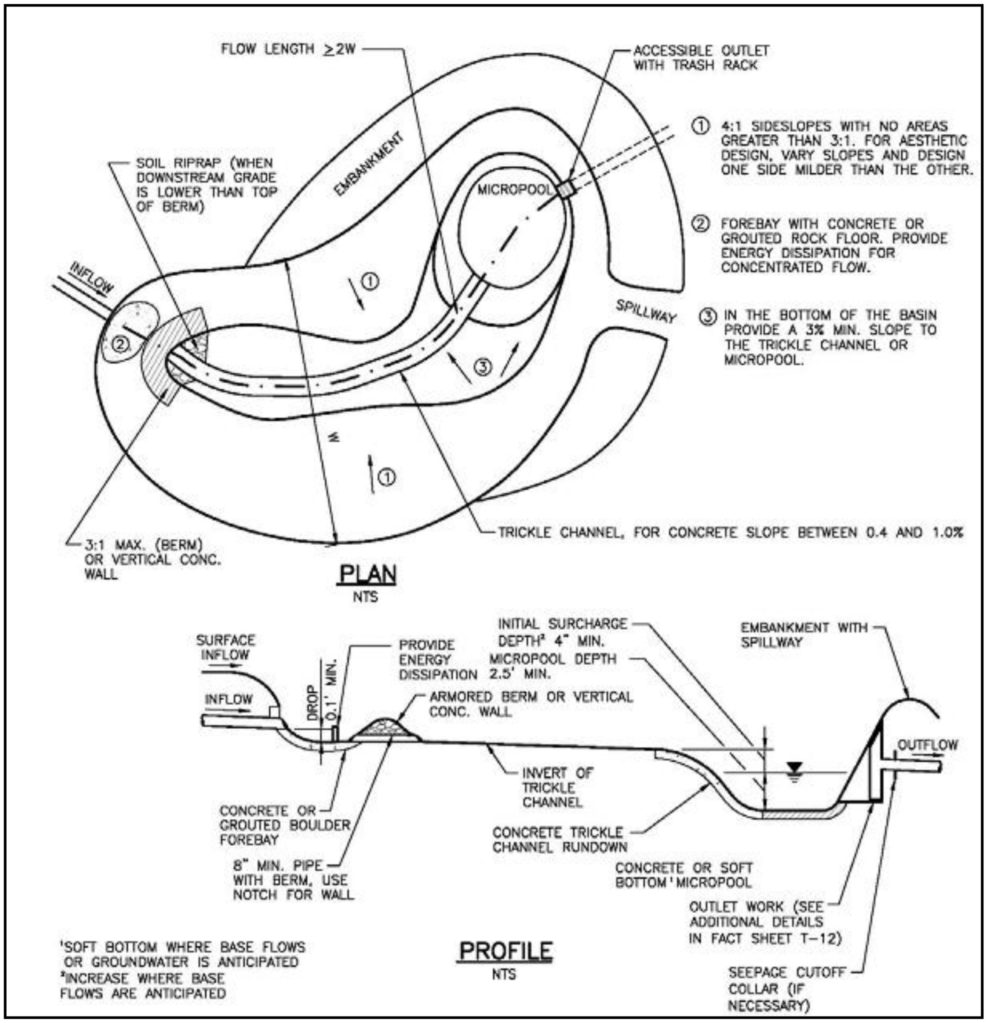


Figure 7. Typical EDB Layout (UDFCD 2010)

A retention pond, or WP, is a sedimentation facility that has a permanent pool of water that mixes, in part or total, with stormwater during runoff events. A temporary detention volume is included above the permanent pool level to capture the additional volume of runoff encountered from a storm event. WPs offer improved aesthetics and have the potential for multiple-uses compared to dry stormwater storage facilities.

Sediment deposits are submerged under a permanent pool of water where the public does not see them. Communities may desire open areas and view the facility as an amenity. In addition, an aquatic habitat is created for waterfowl. Recommended drain times for WPs varies from 12 hours to 48 hours, but the UDFCD recommends a 12-hour brimful drawdown time (U.S. EPA 2008, UDFCD 2010). A shorter drain time is needed because the permanent pool of water facilitates pollutant removal and is not usually displaced during a single event (Driscoll et al. 1989, Strecker et al. 2001). Figure 8 shows a typical layout of a WP (UDFCD 2010).

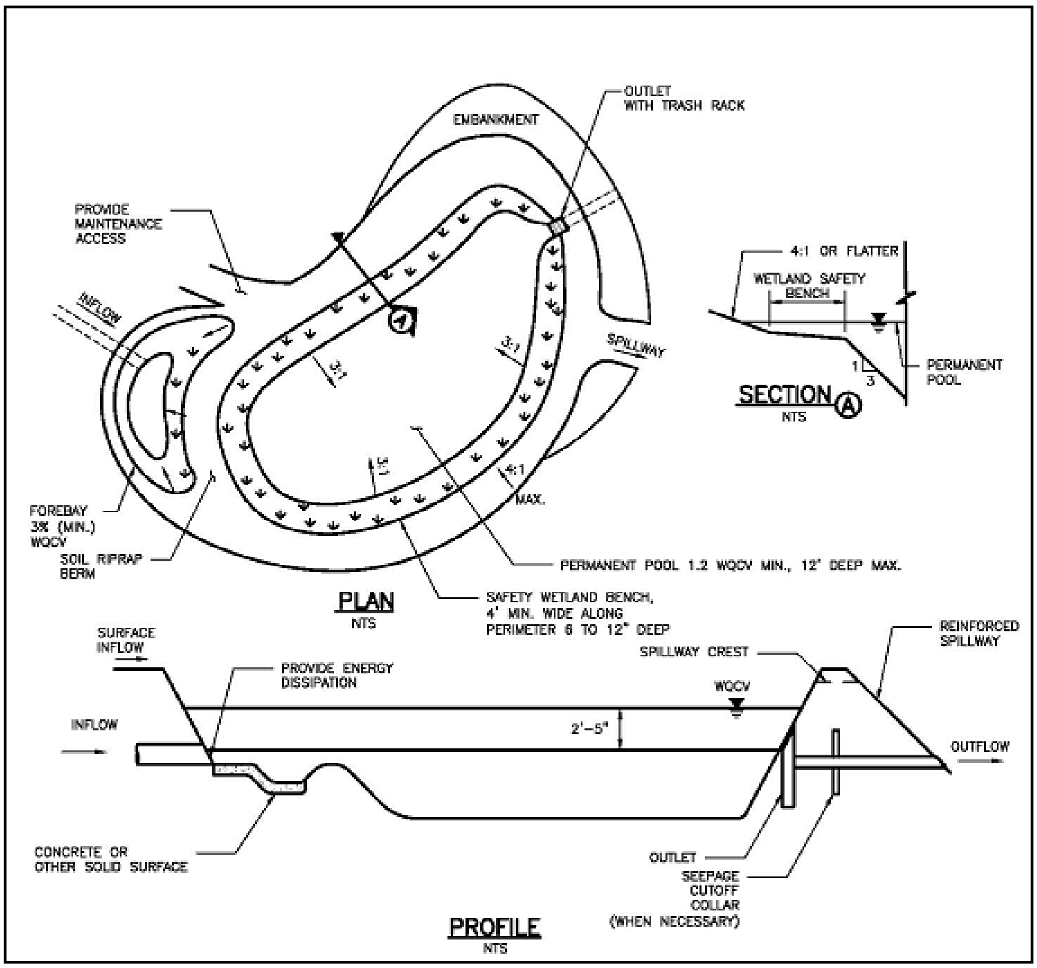


Figure 8: Typical WP Layout (UDFCD 2010)

A constructed wetland is a shallow retention pond that requires a perennial base flow to permit the growth of rushes, willows, cattails, and reeds to slow down runoff and allow time for sedimentation, filtering, and biological uptake (UDFCD 2010). Distinctions between WPs and wetlands can be difficult since WPs often have substantial amounts of vegetated zones. In general, if over 50% of the surface of the BMP is covered in vegetation, it is considered a wetland. A constructed wetland basin is different from a "natural" wetland in that it is designed to enhance stormwater quality, but it can still provide wildlife habitat, erosion protection, and be an aesthetic amenity to the community. Typically, wetlands are designed to capture the WQCV, but additional flood control storage can be added. The permanent water surface should not exceed 2 feet, and the site should have a near-zero longitudinal slope. The recommended drain time for a constructed wetland is 24 hours (UDFCD 2010). Longer drain times may kill aquatic plants in the wetland if they are submerged for too long (Knight 1992). Effective wetland design should display "complex microtopography" by including zones of both very shallow (less than 6 inches) and moderately shallow (less than 18 inches) water, using underwater earth berms to create the zones. This design will provide a longer flow path through the wetland to encourage settling, and it provides two depth zones to encourage plant diversity (U.S. EPA 2008). Figure 9 depicts a typical wetland layout.

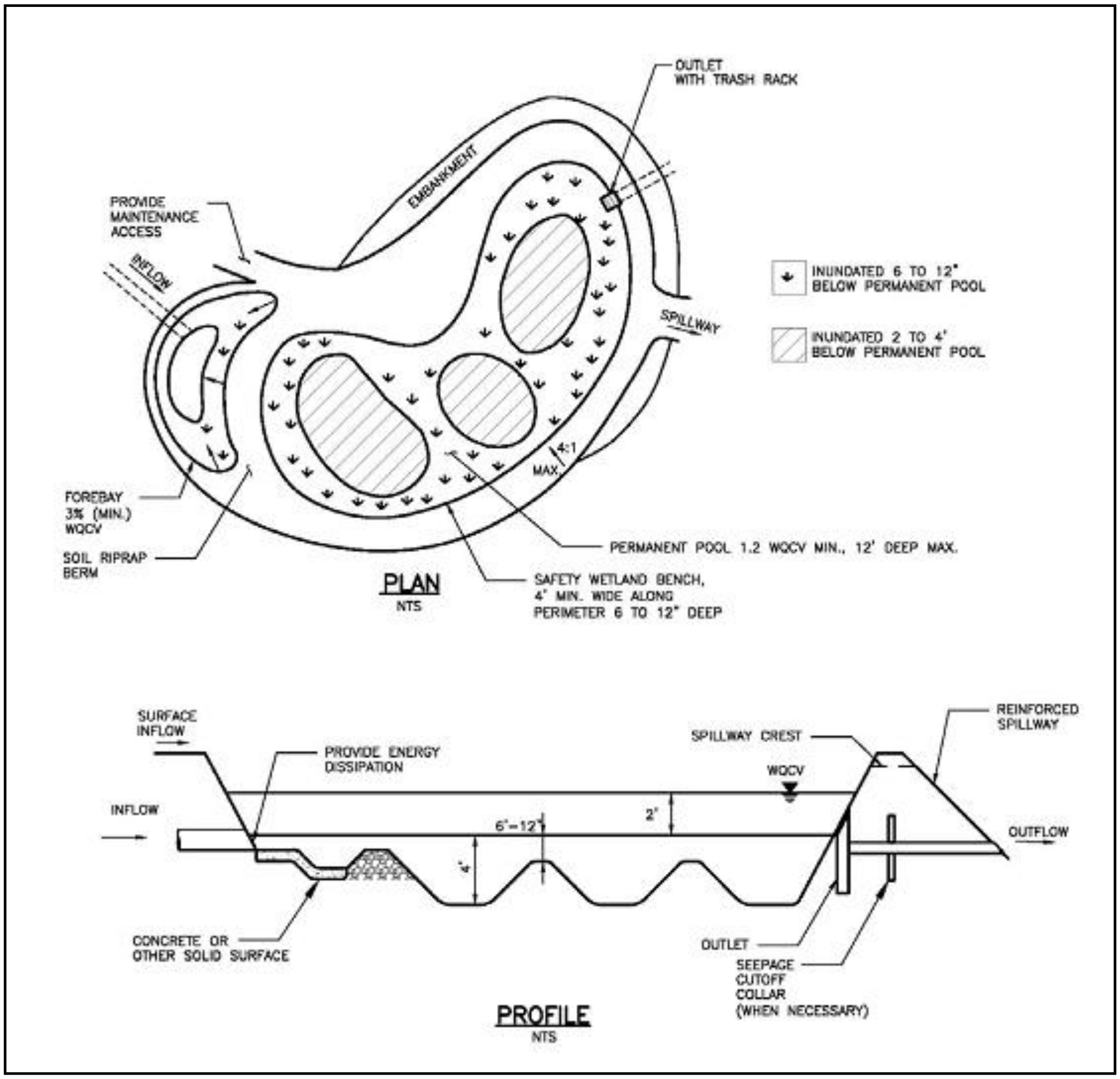


Figure 9: Typical Constructed Wetland Layout (UDFCD 2010)

2.2.5 Expected performance of BMPs

Quantifying the performance of stormwater BMPs is difficult for numerous reasons. Stormwater sampling data is difficult to acquire, each site has specific watershed conditions that affect influent pollutant concentrations, results have been reported in different ways, and theoretical minimum concentrations for pollutants may limit the potential for water quality enhancement. Historically, a BMP's performance was typically reported as a percent removal for each pollutant studied (Geosyntec and

WWE 2009). Unfortunately, the percent removal, which is sometimes called the efficiency ratio, is heavily dominated by incoming concentrations of pollutants and is not a good measure of performance (WWE and Geosyntec 2007). The performance of a BMP is better evaluated when the effluent concentration is examined.

Table 2 shows the median effluent event mean concentration (EMC) for numerous BMPs included in the International BMP Database (Roesner and Olson 2009, Geosyntec and WWE 2008). Median EMC values provide a reference point for comparison among BMPs of a certain type, but individual performance among BMPs varies widely.

In general, WPs and wetlands provide superior pollutant removal than EDBs. Better removal rates can be attributed to the permanent pool of water, which facilities pollutant removal, and the increased vegetation, which provides more opportunity for biological uptake (UDFCD 2010, Walker 2002). White (1998) proposed that the ancillary benefits of wetlands make them beneficial over WPs based on a net-present-value analysis. Admittedly, site conditions may necessitate the installation of a dry EDB, especially if there is a low groundwater table and no baseflow present in the drainage area.

Without proper maintenance, any BMP can become a source of pollution instead of a sink. Periodic removal of accumulated pollutants can be accomplished by dredging the bottom of a BMP and removal of plants is necessary when they have reached their assimilative capacity (UDFCD 2010, Helfield and Diamond 1997). Even with proper maintenance and adherence to design specifications, there are theoretical limits to the amount of pollutants that can be removed from runoff.

Table 2. BMP Median Effluent Event Mean Concentration

BMP	Total Suspended Solids	Total Phosphorus	Total Nitrogen	Total Kjeldahl Nitrogen	Total Zinc	Dissolved Zinc	Total Copper	Dissolved Copper	Total Lead	Dissolved Lead
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)	(ug/L)
Extended Detention Basin (EDB)	31.04	0.19	2.72	1.89	60.20	25.84	12.10	7.37	15.77	2.06
Retention Pond (WP)	13.37	0.12	1.43	1.09	29.35	32.86	6.36	4.73	5.32	2.48
Constructed Wetland Basin	17.77	0.14	1.15	1.05	30.71	17.90	4.23	7.36	3.26	0.87
Constructed Wetland Channel	37.25	0.37	1.91	1.35	30.71	17.90	4.23	7.36	8.75	0.87
Sand Filter Basin	10.25	0.13	0.80	1.44	34.56	25.85	9.56	8.25	1.37	1.03
Concrete Grid Pavers/Porous Pavement	26.40	0.15	1.19	1.38	30.70	15.40	11.90	18.00	12.20	1.02
Porous Landscape Detention/Raingarden	9.19	0.16	0.98	1.26	34.69	16.84	7.38	7.14	2.05	1.16

It has been suggested that minimum irreducible concentrations exist for pollutants in BMPs. Nutrients and turbidity can be created due to biological production from microbes, wetland plants, and algae. These internal processes can reintroduce pollutants back into the water column. In other cases, the minimum concentration may reflect the limitations of a particular removal pathway. Pollutants removed using sedimentation tend towards an asymptotic value regardless of the amount of detention time provided (Schueler 1996).

Kadlec and Knight (1996) proposed a two parameter model (referred to as the kC* equation) to describe the reduction of pollutants assuming steady and plug flow conditions. Equation 4 shows the basic formulation of the kC* model.

$$\frac{dC}{dx} = \frac{-k}{q}(C - C^*)$$

Equation 4

Where: C = Concentration of the quantity concerned (mg/L)

x = Fraction of the distance through the BMP (m)

k = Areal rate constant (m/yr)

q = Hydraulic loading rate (m/yr)

C* =background concentration, minimum concentration (mg/L)

The areal rate, k, governs the quantitative performance of the pond and the background concentration, C*, limits the potential for pollutant removal. Solution of the equation gives an exponential decrease in concentration along the length of the BMP, which would be reflected by an exponential decrease in the quantity of sediment collected. The expression for concentration at any point in the pond can be evaluated using Equation 5 (Walker 2002).

$$\frac{C - C^*}{C_i - C^*} = e^{-kx/q}$$

Equation 5

Where: C_i = Concentration at the inlet (mg/L)

C = Concentration of the quantity concerned (mg/L)

C* =background concentration, minimum concentration (mg/L)

x = Fraction of the distance through the BMP (m)

k = Areal rate constant (m/yr)

q = Hydraulic loading rate (m/yr)

The kC* model can be used to estimate the performance of a BMP relative to the minimum pollutant concentration achievable. Wong (1997) has proposed a method for sizing a CW using a formulation of model where C* is equal to a regulatory standard.

2.3 BMP Performance Analysis

Several methods have been used and reported as a measure of BMP performance for stormwater studies. Historically, performance was often characterized by relating influent water quality to effluent water quality using average pollutant concentrations. More recently, performance measures have been favored that utilize all of the data points collected without assuming an underlying distribution in the dataset. This section presents the ways BMP performance has been measured in the past and the recommended method to asses BMP performance.

2.3.1 Event Mean Concentration

The Event Mean Concentration (EMC) is a statistical parameter used to represent the flow-proportioned average concentration of a given water quality constituent throughout the course of a storm event. When combined with flow measurement data, the EMC can be used to estimate the pollutant loading for a given storm. Since the parameter does not capture the changes in concentration that occur throughout a storm, it is best suited for estimating the effects of stormwater runoff on receiving waters and for calculating annual loads of pollutants (Charbeneau and Barrett 1998). EMC data collection of individual BMP studies is the primary focus of the International Stormwater BMP Database (Geosyntec and WWE 2009). The EMC for a storm event is calculated using Equation 6.

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

Equation 6

Where: EMC = Event mean concentration
V: Volume of flow during period i
C: Average concentration associated with period i
n: total number of measurements taken during an event

Automated samplers can be set to collect samples at equal volume intervals if flow monitoring equipment is installed. Equal amounts of each aliquot sample can be combined for an overall flow-weighted composite that is the EMC of an event. Due to the stochastic nature of stormwater events, it can be difficult to collect an entire event with aliquot samples, especially if the total volume of the event greatly exceeds the programmed sampling interval. Practically, there is often a portion of the storm hydrograph that is not represented by the samples composited into an EMC. The California Department of Transportation (2003) recommends that 80% of the total observed hydrograph be captured for a representative EMC while the Federal Highway Administration (2001) recommends at least 60% of the storm be captured in aliquot samples for a representative EMC to be calculated.

2.3.2 Efficiency Ratio and Percent Removal

Several removal efficiency models have been used to calculate the performance of a BMP. These models are not generally considered true representatives of BMP performance if used as the sole measure of effectiveness. The relevance of the methods are greatly enhanced when a statistical difference between influent and effluent concentrations is established first.

Commonly, the efficiency ratio (ER) has been calculated to represent the removal of pollutants from a BMP (Geosyntec and WWE 2009). Using this method, the average EMC at the outlet of a BMP is compared to the average EMC at the inlet. The ER is the decimal equivalent of the percent removal of pollutants from inlet to outlet of a BMP. Equation 7 calculates the efficiency ratio of a BMP assuming multiple storm EMCs have been collected.

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

Equation 7

A major advantage of this method is the allowance of non-paired data from individual events to be included in average EMC computation. The inclusion of non-paired data implicitly assumes that the addition of missing data points would not significantly alter the calculated EMC value at either the inlet or the outlet (Geosyntec and WWE 2009).

Despite the popularity of this method, there are several shortcomings associated with its use. All EMCs are weighed the same regardless of the relative magnitude of individual events which causes this method to be highly sensitive to outliers. In addition, with small data sets, a statistical difference between the inflow and outflow may be impossible to establish and reporting the percent removal as an indicator of performance would be misleading (WWE and Geosyntec 2007).

Percent removal is primarily a function of influent quality. High values for removal efficiency may be more indicative of “dirty” water entering a BMP than the actual treatment being provided by the BMP. Direct comparison can be difficult because two BMPs providing the same effluent concentration could differ highly in calculated efficiency depending on the quality of incoming water. Furthermore, the method does not address the concept of irreducible minimum concentrations and provides no information regarding the actual levels of contaminants exiting the system (WWE and Geosyntec 2007). For these reasons, the ER is not recommended as a standalone assessment of BMP performance.

2.3.3 Relative Efficiency

A number ways exist to convert the ER, or percent removal, provided by a BMP to a relative measure of efficiency. The following methods all involve choosing a base concentration level to relate to influent and effluent concentrations, rather than computing removal based solely on the change of concentration from influent to effluent. Equation 8 presents the generalized relative efficiency formula (Geosyntec and WWE 2009):

$$Relative\ Efficiency = \frac{C_{in} - C_{out}}{C_{in} - C_{limit}}$$

Equation 8

Where: Relative Efficiency = Normalized efficiency to baseline value

C_{in} = Average EMC of influent

C_{out} = Average EMC of effluent

C_{limit} = Water quality standard, irreducible minimum concentration (C*), or average effluent EMC of a BMP for comparison

Changing C_{limit} will change the type of relative efficiency that is calculated, but the application of the formula is identical for each case.

<u>Relative Efficiency to WQ Standards</u>

The relative efficiency of a BMP to water quality standards is calculated when C_{limit} is set to a regulatory concentration for a constituent of interest. This method is useful in establishing an estimate of how well a BMP is treating runoff compared to the regulated goal. In fact, some BMPs may have relative removal efficiencies greater than 1.0

indicating that effluent concentrations are lower than regulatory limits (Geosyntec and WWE 2009).

Relative Efficiency to Irreducible Minimum Concentration, C*

As treatment occurs and pollutants in stormwater become less concentrated, they become increasingly hard to remove. There appears to be a practical limit to the effluent quality that any BMP can be observed to achieve for the stormwater it treats. This limit is dictated by the chemical and physical nature of the pollutant of concern, the treatment mechanisms and processes within the BMP, and the sensitivity of laboratory analysis techniques to measure the pollutant (Geosyntec and WWE 2009). The term “irreducible concentration” (C*) has been used in stormwater literature to represent the lowest effluent concentration for a given parameter that can be achieved by a specific type of stormwater management practice (Schueler 1996). In some cases, it may be possible to estimate the irreducible minimum concentration that a BMP might be able to achieve. Table 3 presents some C* values suggested by Schueler (1996). This model for efficiency is useful for estimating how much of a pollutant is being removed relative to the theoretical threshold of practical removal seen in other similar BMPs.

Table 3. C* Values for Various Constituents (Schueler 1996)

Contaminant	Irreducible Concentration
TSS	20 to 40 mg/L
Total Phosphorous	0.15 to 0.2 mg/L
Total Nitrogen	1.9 mg/L
Nitrate-Nitrogen	0.7 mg/L
TKN	1.2 mg/L

Average Effluent EMC of a BMP for Comparison

Another way to calculate removal efficiencies for two or more BMPs is to use the lowest effluent EMC as C_{limit}. Measuring BMP performance relative to other existing BMPs may be useful if retrofitting opportunities are possible, especially if the two BMPs being compared have similar watershed characteristics (Urbonas 2003).

2.3.4 Effluent Probability Method

The most useful approach to quantify BMP performance is termed the effluent probability method. Hypothesis testing is used to determine whether influent and effluent concentrations are statistically different from one another. Then, the influent and effluent concentrations are independently ranked according to the number of observations in each set and compared via probability plots. A normal probability plot generated from the log-transform data of both influent and effluent EMCs is examined to determine the effectiveness of BMP treatment (Geosyntec and WWE 2009, Van Buren et al. 1997).

Helsel and Hirsch (2002) recommend using the Cunnane formula to estimate the plotting position of the cumulative distribution function. Equation 9 calculates the exceedance probability of a data point based on the Cunnane plotting position.

$$Exceedance = 1 - \left(\frac{i - 0.4}{N + 0.2}\right)$$

Equation 9

Where: Exceedance = Probability of exceedence based on ranked data (%)

i = Rank of individual data point

N = Total number of data points

The plots efficiently show the central tendency of the data (median), along with the possible distribution type and variance. The assumption of a lognormal distribution for constituent EMC values can be verified if observations form a straight line when plotted. A steeper line of points indicates a wider variance in observed values. When multiple observation sets are plotted next to one another, an estimation of whether the datasets contain similar variances can be made. In addition, if plots do not overlap then there is better evidence that water quality treatment is occurring.

The effluent probability method focuses on the quality of effluent that is leaving the BMP instead of the removal of pollutants. Paired data showing the actual removal of pollutants during individual storms is lost as a consequence of ranking each dataset independently. Thus, interpretation of the probability plots should be made carefully since the implied relationship between influent and effluent may have never been achieved during any single event. Another limitation of the method can occur if a relatively constant effluent concentration is regularly achieved. BMPs that reduce concentrations to constant levels may appear to be functioning less effectively on an effluent probability plot. Sand filters, for instance, have been shown to provide treatment of TSS to a constant level regardless of influent concentration levels, and this result can be difficult to interpret on a probability plot (CASQA 2003).

2.4 Methods of Statistical Analysis

The aim of comparative data analysis is to determine whether the descriptive statistics of two data sets are significantly different (Geosyntec and WWE 2009). Choosing appropriate tests and descriptive statistics are of the utmost importance because the characteristics of the data set must be similar to the inherent assumptions of the tests. Stormwater sampling results exhibit common characteristics of environmental data that require attention when conducting analysis. Helsel and Hirsch (2002) list several characteristics of environmental data that are consistent with stormwater sampling results including:

- a lower bound of zero (no negative concentration can exist for an EMC);
- the presence of outliers, usually on the high side;
- positive skewness;
- non-normal distribution of data;
- data reported at or below some threshold, or method detection limit (MDL);
- seasonal patterns;
- autocorrelation - consecutive observations tend to be strongly correlated with each other; and
- dependence on other uncontrolled variables.

2.4.1 Hypothesis Testing for Differences in Central Tendency

Statistical testing involves the comparison between two groups of data and often requires summary values to be computed from the data. Hypothesis tests for statistical differences between two groups are available in two categories: parametric tests and nonparametric tests. Parametric tests assume an underlying distribution of the data, usually that the data is from a normal distribution. A student t-test, for example, compares two groups using the mean, standard deviation, and sample size, all of which are parameters needed to describe a normal distribution. Stormwater quality data does not follow a normal distribution, which means that parametric summary statistics like the mean and variance do not represent the data accurately. Transforming the data to an assumed distribution can validate the use of parametric statistics. Nonparametric tests, on the other hand, do not assume an underlying distribution of the data, which can be advantageous over parametric methods. The median is the nonparametric equivalent to the mean as a measure of central tendency. It is the central value of the distribution when the data is ranked according to magnitude and is more robust in the presence of outliers (Helsel and Hirsch 1993).

Previous studies have been successful in determining that a lognormal distribution is well representative of certain stormwater runoff constituents including TSS, heavy metals, nutrients, and organic contaminants (U.S. EPA 1983, Van Buren et al. 1997, Maestre et al. 2005). It is common practice to perform a log-transformation of constituent data prior to analysis and use a statistical t-test to decipher whether treatment is occurring within a BMP (Comings et al. 2000, Hunt et al. 2006). One stipulation when using a T-test for hypothesis testing is that the sample size of each group should be greater than 25 or 30 in order to detect a difference in means (Helsel and Hirsch 2002). Van Buren et al. (1997) also suggested that pond *effluent* EMCs tended to follow a normal distribution instead of a lognormal distribution for TSS, heavy metals, nutrients (except total phosphorous), and organic contaminants. Thus, influent and effluent water quality data do not always follow the same distribution, and choosing a parametric statistical test that accurately represents the data is difficult.

Non-parametric statistical tests are ideally suited for stormwater sampling analysis, especially when limited data points are available. They are capable of detecting changes in central tendency without being as heavily influenced by outliers, can account for reported MDL results by assigning tied ranks, and require less total data points to be accurate (Helsel 2002). Two common tests include the Rank-Sum test and the Sign test.

The Rank-Sum test (also called Wilcoxon rank-sum test or Mann-Whitney test and equivalent to the Kruskal-Wallis test for two groups) is similar to the non-paired student t-test and is used to determine whether two groups come from the same population. Joint ranks are computed using both groups and the sum of ranks for the group with the smaller sample size is used as the test statistic. A decision-rule is established to decide whether one group tends to have lower values than the other (Helsel and Hirsch 2002). The test does not account for differences in variance.

The Sign test (also called Wilcoxon Signed Rank Test and equivalent to the Friedman test for comparison of two groups) is the nonparametric equivalent to a paired T-test. For data pairs (x_i,y_i) i=1,…n, the Sign Test determines whether x is generally larger than y without regard to whether the differences are additive. A plus, minus, or zero value is assigned to each data pair (x_i,y_i) based on whether x is larger, smaller, or equal to y. A comparison of all plus values relative to minus values reveals whether one set tends to be larger than the other is. It is appropriate when comparing 20 or fewer pairs of samples (Helsel and Hirsch 2002).

2.4.2 Graphical Methods

Graphical methods of analysis are very useful aids to formal statistical tests and should always be done as part of exploratory data analysis (Gilbert 1987, Helsel and Hirsch 1992). Scatterplots displaying the entire dataset should be produced as an initial step to help verify the conclusions of later statistical comparisons. Standard boxplots are another graphical method of analysis that can be used as an independent statistical test or as a visual representation of the dataset. Ranked datasets are summarized by the median, upper and lower quartiles, and an assumed confidence interval that are plotted as a notched-box. Two medians are significantly different at the 95% significance level if their intervals do not overlap; interval endpoints are the extremes of the notches. When the sample size is small, notches may extend beyond the end of the box (MATLAB program file, Geosyntec and WWE 2008). A standard boxplot is shown in Figure 10.

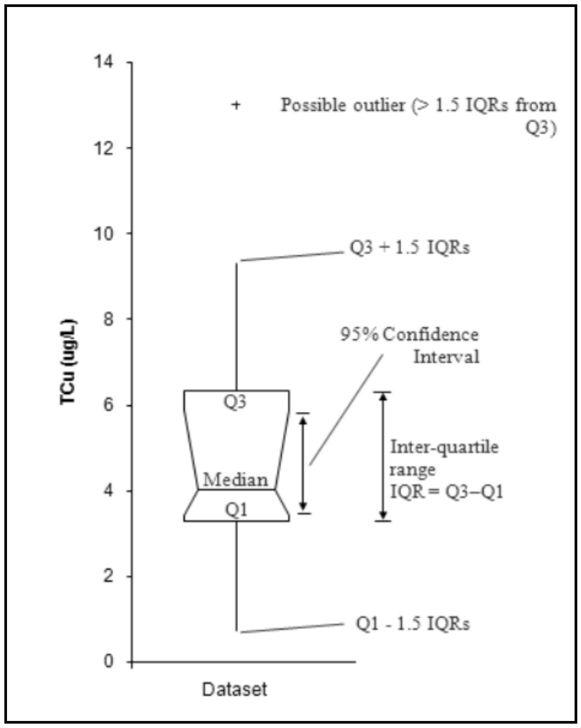


Figure 10. Standard Boxplot with Definitions (Geosyntec and WWE 2009)

McGill et al. (1978) recommends calculating the 95% confidence interval using the inner quartile range (IQR) and number of observations according to Equation 10.

$$CI = M \pm 1.7\left(\frac{1.25 * IQR}{1.35\sqrt{n}}\right)$$

Equation 10

Where: CI = 95% confidence interval about the median

M = Median (Q_2) of dataset

IQR = Upper quartile – lower quartile (Q_3 - Q_1)

n = Number of samples

2.4.3 Nonparametric Confidence Intervals and Prediction Intervals

Another useful method of analysis is to calculate a meaningful interval to describe the central tendency of data. A confidence interval indicates the reliability of an estimate to a certain degree of confidence. A prediction interval is used to determine the expected value of a single new observation based on the values that have already been observed to a certain degree of confidence.

A two-sided nonparametric confidence interval based on the median of the data can be calculated according to Equation 11 and Equation 12 (Gilbert 1987). The equations are valid for sample size n>20 only because a standard normal approximation is utilized (Helsel and Hirsch 2002).

$$C_L = p(n+1) - Z_{1-\alpha/2}[np(1-p)]^{1/2}$$

Equation 11

$$C_U = p(n+1) + Z_{1-\alpha/2}[np(1-p)]^{1/2}$$

Equation 12

Where: C_L = Corresponding quantile to lower value of confidence interval

C_U = Corresponding quantile to upper value of confidence interval

p = Percentile = 0.5 for the median value

n = Sample size

$Z_{1-\alpha/2}$ = Corresponding statistical z-value for a specified degree of confidence equal to $1-\alpha$ (1.96 for 95% confidence level and 1.64 for 90% confidence level)

The values of L and U will seldom be integers that correspond directly to the ranking of an observed value. Thus, linear interpolation is required between the closest order statistics to find the corresponding value from the dataset that matches the computed quantile.

When n<20, a table of the binomial distribution critical values must be used. Nonparametric intervals cannot always exactly produce the desired confidence level when sample sizes are small. This is because they are discrete, jumping from one data value to the next at the ends of the intervals. Conover (1971) outlines the procedure required to estimate the interval for small sample sizes and includes a table of the binomial distribution.

The prediction interval can be calculated using Equation 13 and Equation 14 (Helsel and Hirsch 2002).

$$P_L = X_{(\alpha/2)} * (n+1)$$

Equation 13

$$P_U = X_{(1-\alpha/2)} * (n+1)$$

Equation 14

Where: P_L = Corresponding quantile to lower value of prediction interval
P_U = Corresponding quantile to upper value of confidence interval
n = Sample size
X = Percentile of data included in prediction interval, 100*(1-α) percent of the data falls within the range

Again, interpolation may be required between the closest order statistics since the quantiles are calculated in the equations and not the corresponding interval values.

2.4.4 Data Reported Below Detection Limits

Stormwater quality results can occur in concentrations that are below laboratory MDLs. These results are still very useful and should never be discarded, but extra care is required when analysis is conducted. It is common practice to substitute half of the detection limit for a value reported below MDL (Geosyntec and WWE 2009, Carleton et al. 2000, Hunt et al. 2008). Substitution with any other value, which usually is either the MDL or zero, will cause severe bias in summary statistics (Antweiler and Taylor 2008, Geosyntec and WWE 2009). Substitution methods will always have a negative impact on statistical summaries of the data, especially the variance and mean.

Other methods have been developed to enhance the estimation of the mean and standard deviation. Regression on Order Statistics (ROS) is a method that calculates summary statistics with a regression equation and can be a useful way to replicate censored data. "Robust" ROS methods utilize all results above the MDL and then replicates data below the MDL assuming an underlying distribution (Helsel 2005). This method is best suited for small sample sets where a single detection limit is imposed (Helsel 2005, Geosyntec and WWE 2009) and can be calculated easily using statistical software. Another widely advocated method is the Kaplan-Meier method, where an empirical cumulative distribution function is generated for the dataset based on survival probability. It is better suited for numerous MDLs, which could occur if data was gathered from multiple sources (Helsel 2005, Geosyntec and WWE 2009). It is fully nonparametric and capable of producing reliable summary statistics if the median value of the dataset is known and above the detection limit.

It is recommended that the "robust" ROS method be utilized if summary statistics are calculated for a single stormwater sampling study because the Kaplan-Meier method is not as well suited (Geosyntec and WWE 2009). Recent research has indicated that substitution using half of the MDL will still produce summary statistics that are adequate (Antweiler and Taylor 2008). Nonparametric methods of statistical analysis, like the Rank-Sum test, will be resilient against a substitution method because it accounts for ties in the dataset (Gilbert 1987).

3.0 STORMWATER SAMPLING IN FORT COLLINS, CO

A stormwater sampling program was conducted in Fort Collins, CO, for two volume-based stormwater BMPs. The Udall Natural Area (Udall WP) and Howes St. BMP are two "end of the pipe" BMPs that were implemented to treat stormwater runoff before it enters the Cache la Poudre River. The Udall WP was built as a series of two wet ponds that each provides flow attenuation using water quality orifices. The facility was built with a larger WQCV than required and provides a long HRT for pollutant removal from stormwater runoff. The Howes St. BMP was not built to capture the WQCV because of land constraints at the time of construction. The facility is comprised of a constructed wetland channel that empties to an old oxbow pond. Under low flow conditions, it was assumed that the facility had the capacity to remove pollutants similarly to a wetland. However, the outlet does not include a water quality mechanism, and water freely discharges through two outlet pipes during storms. Short HRTs resulted from the uncontrolled outlet, and it appeared that the facility operated more like a small WP during storms. Stormwater sampling was conducted at both sites from late 2009 through 2011.

3.1 Site Descriptions

The Udall Natural Area (Udall WP) and Howes St. BMP are both located in downtown Fort Collins, CO. The City of Fort Collins (City) is comprised of twelve stormwater drainage basins, and both study BMPs were located in the Old Town Drainage Basin, as shown in Figure 11. The Old Town Drainage Basin covers 2,120 acres and was completely developed at the time of the study consisting primarily of residential, commercial, and industrial land uses (Rocky Mountain Consultants 2001).

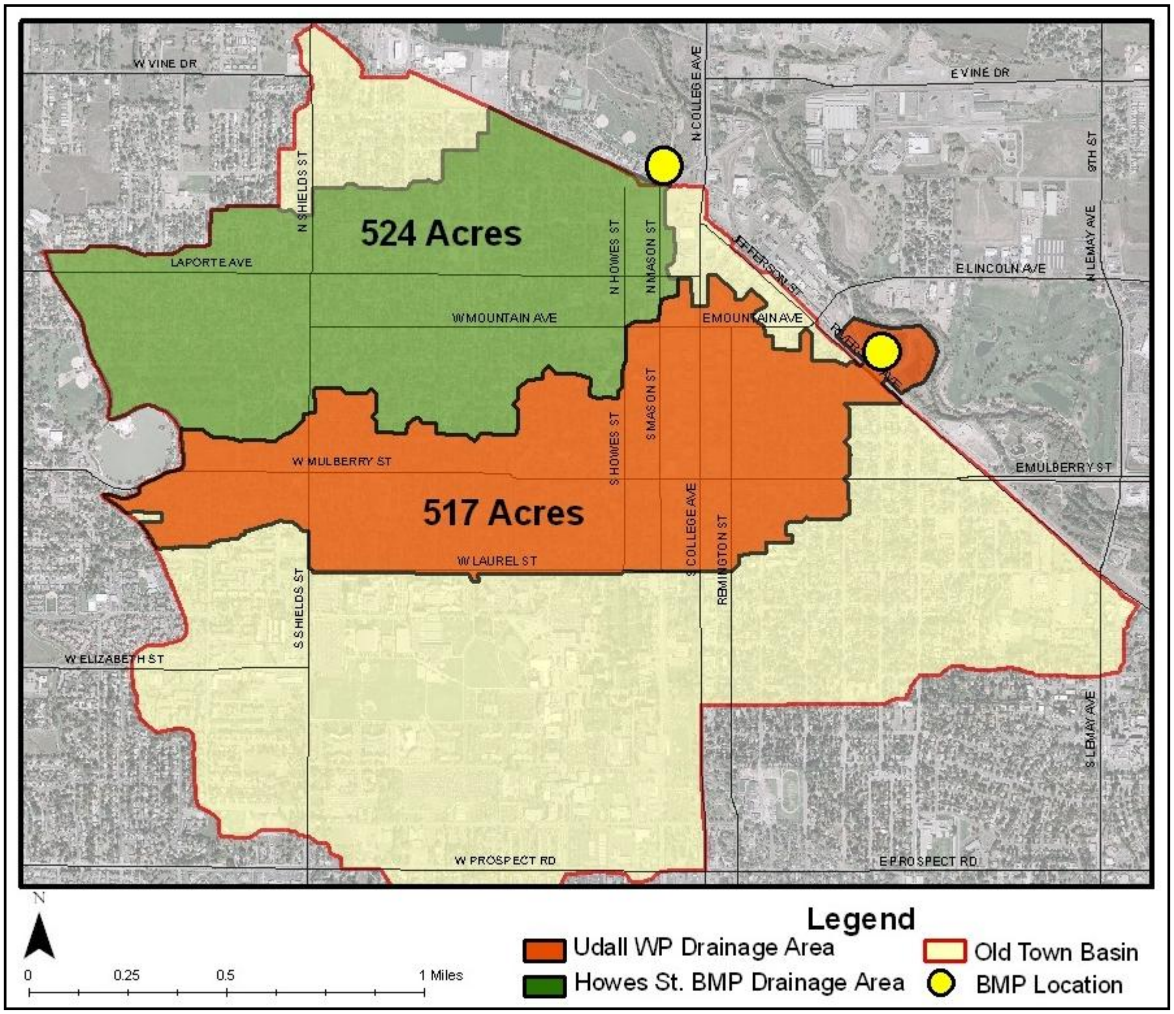


Figure 11: Contributing Area for Udall WP and Howes St. BMP (Fort Collins Utilities 2009)

The Udall WP is located on the southeast corner of Lincoln Avenue and Riverside Avenue along the Cache la Poudre River in Fort Collins, CO. Runoff from approximately 517 acres of the Old Town Drainage Basin discharges to the site as shown in Figure 11. The facility was completed in 2004 and is oversized for the current contributing area due to plans for future expansion. Original sizing of the BMP provided a WQCV capable of treating 660 acres (Knuth 2004). During dry weather, a permanent volume of approximately 3.0 acre-ft has been observed in the ponds due to constant baseflow entering the facility (Knuth 2004). Stormwater flows through a forebay and a sedimentation basin before entering two wet extended detention ponds. It then proceeds through a small pre-existing wetland (unmonitored) before ultimately reaching the Cache la Poudre River. Automated sampling equipment was installed at three locations as shown in Figure 12. Incoming stormwater samples were taken at the Oak St. Outfall, which is the inlet of the Udall WP. Automated sampling also occurred at the Pond 1 outlet and the Pond 2 outlet. Ground level images for the facility are shown in Figure 14.

The Howes St. BMP is located north of downtown Fort Collins. Influent runoff enters the BMP from the Howes St. Outfall, northwest of the intersection of College Avenue and Cherry Street. Approximately 524 acres drain to the Howes St. Outfall where runoff enters a wetland channel before proceeding to a wetland pond area (Fort Collins Utilities 2009). Unlike the Udall WP, the Howes St. BMP is undersized and only treats a portion of the WQCV. Furthermore, a water quality outlet structure is not installed at the pond outlet, and the wetland pond area existed prior to development. An automated sampler was placed at the Howes St. Outfall (the BMP inlet) to collect runoff before it entered the facility. From there, water is conveyed north through a small wing-walled structure along the wetland channel until it reaches the wetland pond. A double culvert lets water out of the facility and into the Cache la Poudre River. Samples were also taken at the outlet culvert to collect effluent stormwater leaving the facility. Figure 13 displays the layout of the Howes St. BMP; Figure 15 shows ground level images.

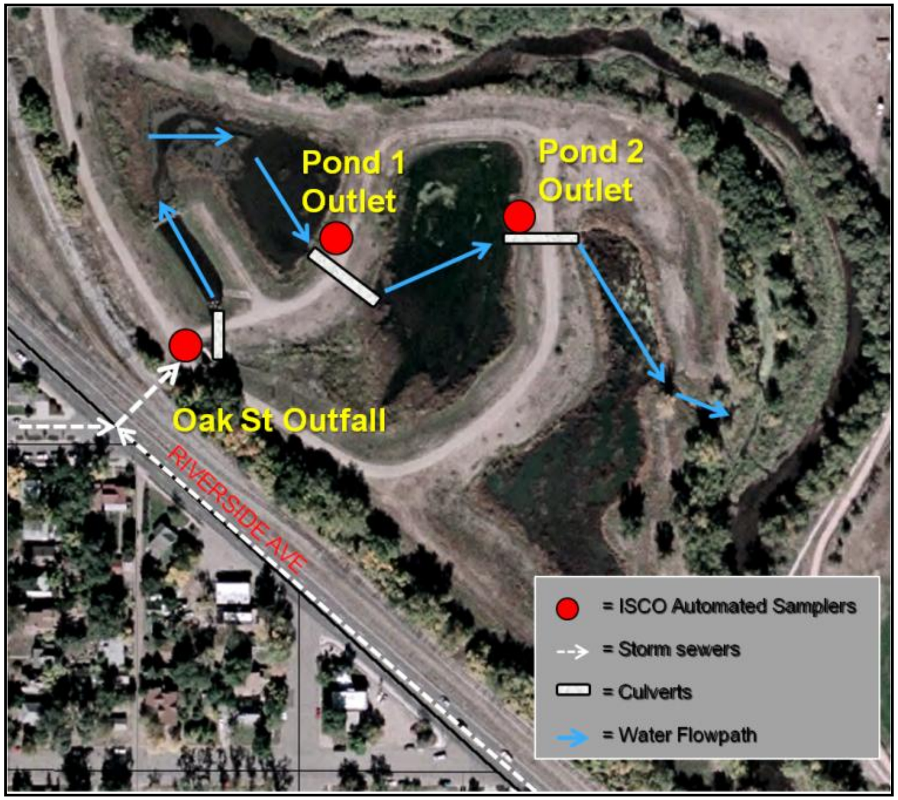


Figure 12: Udall WP Layout

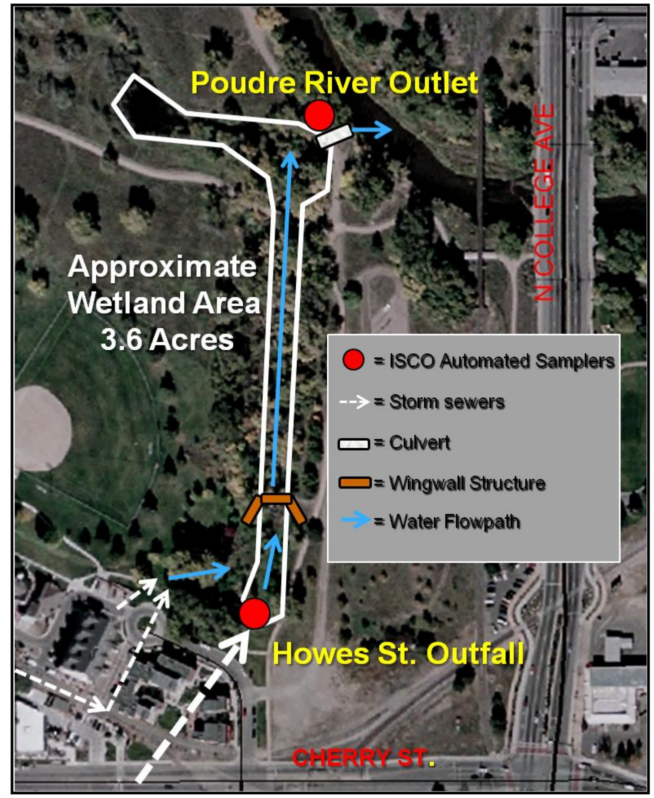


Figure 13: Howes St. BMP Layout

a. Sedimentation Basin and Pond 1 During an Event (Spring 2010)

b. Pond 2 Full During an Event (Spring 2010)

c. Pond 1 With Little Algae Growth (July 2010)

d. Pond 2 With Little Algae Growth (July 2010)

Figure 14. Udall WP Images

a. Wetland Channel and Wingwall Structure During an Event (Spring 2010)

b. Wetland Channel Entering Pond Storage Area (Summer 2011)

c. Pond Storage Area (Summer 2011)

d. Outlet of Howes St. BMP and Pond Storage Area (Summer 2011)

Figure 15. Howes St. BMP Images

Southwest of the Howes St. BMP is the Martinez PUD which contributes runoff to the wetland that does not enter through the Howes St. Outfall. A drainage swale from the site conveys stormwater to the wetland channel downstream of the sampling location.

Both BMP watersheds are comprised mostly of residential and commercial land uses. A GIS layer from the City was used to determine the land use percentage for each BMP contributing area (Fort Collins Utilities 2009). Table 4 shows the land use as a percentage of the total contributing area for each BMP.

Table 4. Land Use as a Percentage of the Total Contributing Area for Each BMP

Land Use Type	Percentage of Total Drainage Area	
	Howes St. BMP (%)	Udall WP (%)
Commercial	5.8	21.0
Industrial	0.3	0.9
Medium Density Residential	30.2	32.4
Low Density Residential	47.1	24.8
Institutional	2.7	2.8
Public Buildings	5.2	10.0
Open Space/Parks/Cemetary	8.1	7.3
Vacant	0.6	0.8

Two major differences existed in the land use of each watershed. Approximately 21.0% of the Udall WP contributing area is comprised of commercial area while only 5.8% of the Howes St. BMP is comprised of commercial area. Furthermore, approximately 24.8% of the Udall WP contributing area is comprised of low-density residential homes while only 5.8% of the Howes St. BMP is comprised of low-density residential homes. Thus, the major difference between the two watersheds is that a larger portion of the Udall WP contributing area is commercial and a larger portion of the Howes St. BMP is low density residential.

The total contributing area, percent impervious, BMP storage size, calculated WQCV required, and design drawdown times for the Udall WP and Howes St. BMP are shown in Table 5. The total contributing area was found using the delineated watershed boundaries from a GIS layer obtained from the City (Fort Collins Utilities 2009). Percent impervious values were detailed in an ICON Engineering design report that focused on a water quality master plan for downtown Fort Collins (ICON 2006). Current BMP storage size values for the Udall WP were reported by Knuth (2004). For the Howes St. BMP, flow records were used to estimate the storage size that the BMP provided during storms, which was between 3 to 5 acre-ft. Similarly, the design drawdown time for the Howes St. BMP was calculated using flow records since the outlet does not contain a water quality feature. The design drawdown times for the Udall WP were stated in a report by Rocky Mountain Consultants (2001).

Table 5. BMP Specifications for the Howes St. BMP and Udall WP

BMP Characsterisitics	Howes St. BMP	Udall WP		
		Pond 1	Pond 2	Total
Total Contributing Area (acres)	524	-	-	517
Percent Impervous of Contributing Area (%)	52	-	-	64
Current BMP Storage Size (acre-ft)	3 to 5*	7.4	9.8	17.2
Calculated WQCV (acre-ft)**	8.3			10.8
Design Drawdown Time (hrs)	10 to 30*	40	40	80+

* Observed BMP storage utilized and drawdown time from calculated from flow records

** Howes St. BMP WQCV for a wetland pond, Udall WP WQCV for an extended detention basin

3.2 Sampling Equipment

3.2.1 Equipment at the Udall WP

At the Udall WP, three sampling locations were managed in order to collect water samples and flow information from storm events. A double-bubbler gauge station was installed at each location, which incorporated anti-freeze filled double-bubbler reference tubes, a Campbell CR10 fully programmable datalogger and controls, solar charged 12-volt batteries, and compressed nitrogen supplied at 5 psig. Bubbler gauges measure the depth of flow by forcing air into submerged polyethylene tubes and measuring the pressure needed to force a bubbler out of a tube. This pressure is linearly related to the depth of the water. Stage measurements at the Udall WP inlet, Pond 1 outlet, and Pond 2 outlet were converted to flow estimates in real-time using rating curves programmed into the CR10 dataloggers. For a description and plot of each developed rating curve, see Appendix A. Each sampling location at the Udall WP was equipped with an ISCO model 2700 or 3700 portable sampler, which automatically pumped flow-weighted aliquot samples into separate bottles when signaled by the dataloggers.

Flow readings were taken every minute by the dataloggers, but only hourly values were stored to prevent frequent filling of the storage memory and to limit redundant data readings. Supplemental data values were recorded when the stage changed more than 0.05 ft from the previously stored value and when water quality samples were collected in order to obtain better data resolution during storm events. Stored information included a timestamp, depth of water, calculated discharge, cumulative volume during sampling events, and number of collected samples during sampling events. In addition to data records, the dataloggers were programmed to recalibrate hourly to ensure accurate pressure readings.

At the Pond 1 and Pond 2 outlets, water was discharged through water quality orifice plates designed to slowly release stored water. It was observed that the orifices were usually about 50% clogged due to debris and algae from the ponds. This assumption was built into the rating curves for the site, but flow records were later adjusted based on a storm-by-storm assessment. Visual inspections were conducted during the course of a storm to estimate the amount of clogging at the orifice plate. For a description and plot of each developed rating curve, see Appendix A.

3.2.2 Equipment at the Howes St. BMP

At the Howes St. BMP, there were two sampling locations where hydraulic information was recorded and water quality samples were taken. The inlet of the facility was equipped with an ISCO model 3220 data logger connected to a pressure transducer located in the Howes St. Outfall channel. Pressure readings were converted to depth measurements by the datalogger and the flow was calculated using a developed rating curve for the location that was stored in the datalogger. For further description and a plot of the developed rating curve, see Appendix A. Continuous flow monitoring at the site was impossible because the depth of baseflow was insufficient to cover the entire pressure transducer. Therefore, the datalogger was programmed to record only when the depth exceeded 0.15 ft. Flow data and sample collection times were plotted on a revolving scroll and were not stored electronically in the ISCO 3220 datalogger. Methods were developed to minimize the chance of data transfer errors when sampling personal transcribed the printed values into electronic records. An ISCO model 3700 portable sampler connected to the datalogger was used to pump flow-weighted aliquot samples into separate bottles when signaled.

At the Howes St. BMP outlet, an ISCO model 6712 portable sampler was used to record flow data and collect water quality samples. Unlike the other ISCO portable samplers used in this study, the model 6712 has a built-in datalogger. The sampler was connected to a submerged pressure transducer placed in the center of the wetland pond. Measurements were collected in five-minute intervals using the bottom of the outlet culvert as a reference depth of zero. Pressure readings were converted to depth measurements by the sampler and the flow was calculated using a developed rating curve for the location that was stored in the sampler. Sampling events were triggered when the pond depth increased more than a preset threshold, which was usually around 0.5 inches in a 15-minute time span. Once a sampling event was initiated, flow-weighted aliquot samples were collected in separate bottles. For further description and a plot of the developed rating curve, see Appendix A.

Total inflow estimates for the Howes St. BMP were complicated by two factors. Primarily, the inlet to the BMP contains an east and west culvert that are separated by a concrete divider. Only one of the culverts was monitored during storms because equipment from the other culvert failed early in the sampling program. Prior to the equipment failure, it was observed that the majority of the flow entering the Howes St. BMP came through the east culvert, where flow-monitoring equipment was functional. Approximately 15% more flow enters the BMP from the unmonitored culvert. The EMC values collected from the site should be accurate, but estimates for the total volume of runoff entering the BMP contained substantial error. Furthermore, additional runoff entered the BMP just downstream of the sampling location. The Martinez PUD is an adjacent development that drains to a swale before runoff enters the Howes St. BMP. The swale enters just downstream of the monitoring location at the BMP inlet. It was assumed that a proportional amount of inflow entered the BMP from the swale for each storm. These two complications made comparisons between the total inflow and total outflow of runoff difficult, but EMC values were collected successfully.

3.3 Hydrology

Equal interval samples were collected at each sampling location and composited later for a representative EMC for each storm. In order to collect runoff from an event, an appropriate sampling interval was required for collection of aliquot samples. The ISCO samplers contain 24 individual bottles that can hold samples collected during an event. In Fort Collins, a storm event of 0.5 inches or more will occur around eight times per year (WWCC 2011). A storm depth of 0.5 inches was used as the sampling program design storm because it would be large enough to flush pollutants out of the watershed and would occur frequently. Sampling intervals at each location were determined using the estimated runoff that would be produced for a 0.5 inch storm and dividing it by 16 bottles (i.e. 0.5 inches storm should fill 16 bottles). Setting the interval based on 16 bottles allowed flexibility for slightly larger or slightly smaller storms.

The Soil and Crop Science (SCS) empirical model for soil abstractions was used to calculate the expected runoff volume. Watershed areas obtained using the GIS layer of BMP contributing areas that were provided by the City (Fort Collins Utilities 2009). An assumed curve number of 94 was used for each urban watershed (Viessman and Lewis 2003). The design storm, watershed area, and assumed curve number were used to generate a total expected runoff volume with the SCS model according to Equation 15. The total expected runoff was divided by 16 to find the required sampling interval at each location.

$$R = \left[\frac{(P - I_a)^2}{(P - I_a) + S}\right] A * \left(\frac{43{,}560}{12}\right)$$

Equation 15

Where: R = Accumulated direct runoff (cf)

P = Accumulated rainfall (in)

Ia = Initial abstraction estimate = 0.2*S

S = Potential maximum retention = [(1000/94) -10] where CN = 94

A = Contributing watershed area (acres)

Sampling intervals were adjusted if frontal systems were predicted for the area. Quantitative Prediction Forecasts (QPFs) for the nation were examined from the National Oceanic and Atmospheric Administration (NOAA) website. QPFs displayed total storm depth estimation up to five days into the future but had a low resolution. If significantly larger events were forecasted, the sampling intervals were increased to capture a larger percentage of the storm. This procedure was conducted successfully during the June 11, 2010, sampling event, where over 1 inch of rain was forecasted to fall over the course of a weekend. Adjusting the sampling interval for each event proved to be impossible when slight variations in the forecast were encountered due to the limited accuracy of the QPFs. Furthermore, summertime sampling consisted primarily of rapidly developing thunderstorms that could not be forecast accurately.

Precipitation data was collected from a variety of sources. A tipping bucket rain gauge with 0.01 inch resolution was installed at the CTL Thompson office buildings near the Cache la Poudre River in Fort Collins, CO. Data was used from the Fort Collins Flood Warning System (FTCFWS) which included a network of rain gauges spaced throughout the City each having a resolution of 0.04 inches. Data was collected from the FTCFWS gauges at the Utility Service Center, Lincoln Avenue, and City Park due to their proximity to the contributing areas of the Howes St. BMP and Udall WP. In addition, real-time monitoring of the FTCFWS during rainfall events was useful for coordination among sampling team members. Data was obtained from the Colorado Climate Center (CCC) who maintains a weather station at Colorado State University (CSU), which is near both BMP watersheds, and a weather station at Christman Field on the West side of the City. The Christman Field weather station has a heated rain gauge capable of converting snowfall to equivalent inches of rain and was only used when rain turned to snow during a sampling event. Both weather stations have a 0.01 inch resolution. Figure 16 illustrates the rain gauges throughout the City of Fort Collins that influence the contributing areas of the study BMPs.

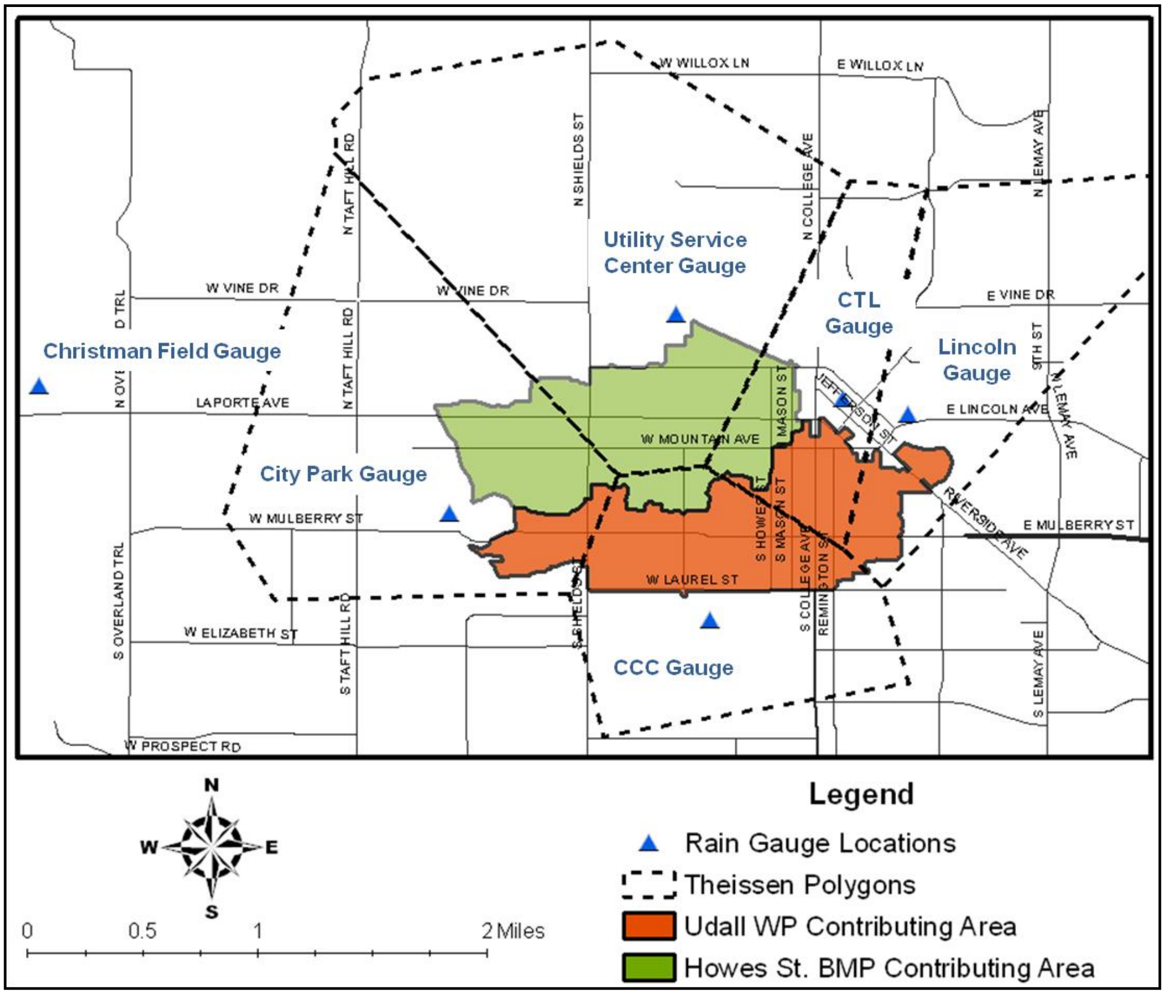


Figure 16: Rain Gauge Locations and Theissen Polygons

During the course of sampling, rainfall patterns and total depths of precipitation varied significantly across the City. Influent volumes were sometimes significantly different between the two BMPs and using a single raingage to represent rainfall over the entire watershed would incorrectly bias the depth estimate. In order to better estimate the total storm depths at each BMP, Theissen polygons were constructed using ArcGIS software to determine the relative influence of each raingage on the BMP watersheds. All of the available rainfall gauge data was utilized to estimate a composite storm depth for each event at each BMP. Figure 16 shows the constructed Theissen polygons and

Table 6 shows the relative importance of each gauge when calculating the composite precipitation estimate.

Table 6. Relative Influence of Rain Gauges for Composite Precipitation Estimates (%)

Gage Name	Udall WP	Howes St. BMP
CCC Weather Station	50	8
City Park	14	32
CTL Thompson	20	17
Lincoln	16	0
Utility Service Center	0	43
Christman Field	Only Used if Snow	Only Used if Snow

3.4 Water Quality Sampling Constituents

Sampling for water quality constituents is often limited by the project budget due to high cost of laboratory testing. A main objective of this study was to sample enough parameters to adequately portray the chemical and physical process occurring within the BMPs. It is recommended that a sampling program analyze nutrients, total recoverable metals, dissolved metals, bacteria, oxygen demanding substances, and TSS from stormwater runoff (U.S. EPA 1983, Geosyntec and WWE 2009). Quantifying additional parameters and ions are also useful in order to better describe the toxicity and speciation of metals, nutrients, and other pollutants. The water quality constituents measured in this study are listed below.

- **Total Recoverable Metals:** Cadmium (TR Cd), Chromium (TR Cr), Zinc (TR Zn), Lead (TR Pb), and Copper (TR Cu).
- **Dissolved Metals:** Cadmium (D Cd), Chromium (D Cr), Zinc (D Zn), Lead (D Pb), and Copper (D Cu).

- **Bacteria:** *Escherichia coli* (E. coli).
- **Oxygen Demanding Substances**: carbon oxygen demand (COD) and total organic carbon (TOC).
- **Solids:** total suspended solids (TSS)
- **Nutrients:** nitrate (NO_3), nitrite (NO_2), ammonia (NH_3), total Klendenjal nitrogen (TKN), and total phosphorus (TP). Total nitrogen (TN) was either measured directly or calculated as the sum of $NO_2 + NO_3$ + TKN.
- **Ions:** chloride (Cl^-), magnesium (Mg), sodium (Na), calcium (Ca), potassium (K), and sulfate (SO_4^{2-}).
- **Additional Parameters:** specific conductivity (SC), pH, temperature, dissolved oxygen (DO), total hardness (hardness), and alkalinity (Alk).

Most stormwater constituents were analyzed at the Fort Collins Pollution Control Lab (PCL). Analysis for two stormwater events was conducted at a CSU lab instead of the PCL. The full sampling suite available from the PCL could not be analyzed at the CSU lab. Field readings of stormwater runoff were taken using a YSI Pro Plus device capable of measuring pH, SC, temperature, Cl^-, and DO. Readings were also taken in lab for composite pH, SC, and Cl^- EMC values. Composite Cl^- results were also analyzed separately at the PCL. E. coli grab samples were taken during storm events and analyzed with Coliscan Easy Gel (Micrology Labs 2011).

3.5 Quality Assurance/Quality Control Methods

In order to ensure the quality of the stormwater sampling results, several measures were taken to prevent cross-contamination and to ensure that constituent holding times were not exceeded. Sampling bottles were washed between each sampling event with soap and water and then polished with nitric acid to remove residual pollutants and trace metals. Ice was placed in the ISCO samplers just prior to an event or during an event to keep collected aliquot samples cool while subsequent samples were taken. Once a runoff event was over, the samples were collected and composited into a representative storm EMC as quickly as possible. After being composited, the samples were split into individual containers for lab analysis and preserved with ice, nitric acid, phosphoric acid, or sulfuric acid if required. Different lab tests required different acids, and some tests required no acid preservation. Table 7 displays how the composite EMCs were divided and preserved for submission to the PCL. All samples were iced after compositing to keep the temperature near 4^{o}C until they were delivered to the PCL. Grab samples for E. coli were conducted within six hours of collection as recommended by the manufacturer (Micrology Labs 2011).

Table 7. Fort Collins Sampling Preservation Sheet

Constituents	Required Volume (mL)	Method	Bottle Type	Preservation	Holding Time	Notes
Total Recoverable Metals + Total Hardness	1000		1 L Poly (Acid washed in 1+1 HNO3)	Acidify with HNO_3, Cool	6 months	5mL of 35% HNO3 per 500 mL of sample for preservation
Dissolved Metals + Dissolved Minerals	500		500 mL Poly (Acid washed in 1+1 HNO3)	Cool	6 months	PCL will filter and acidify
Alkalinity	250		250 mL Poly	Cool	14 day	
TSS	250		250 mL Poly	Cool	7 days	
Nitrate + Nitrite Sulfate, Chloride	125		125 mL Poly	Cool	48 hours	Requested by PCL that these items be grouped
Total Ammonia	125		500 mL Poly	Acidify with H_2SO_4, Cool	28 days	*Take Nitrate + Nitrite test from preserved bottle if not analyzed immediately, use 1 L bottle* Approx. 2mL of 25% H2SO4 required per 500 mL of sample for preservation
TKN	250					
Total Phosphorus	125					
COD	250		250 mL Poly	Cool	28 days	
TOC	250		250 mL Poly	Acidify with H_3PO_4	28 days	Approx. 1mL of concentrated H3PO4 per 100 mL of sample for preservation
Total	**3.125**	**L**	**(8 Total)**			

*All ISCO bottles should be acid washed in 1+1 solution of reagent grade HNO3

** All bottles sent from FTC PCL are already washed

*** Preserve carefully…use pH meter to assure that final pH is between 1 and 2.

3.6 Stormwater Sampling Results

Results are included for storms that were sampled between October 2009 and April 2011. For each storm event, the hydrograph was analyzed at each sampling location to determine the total volume of the storm and the volume of the storm that was collected by sampling equipment. If less than 60% of the total storm hydrograph was not represented by aliquot samples, a representative EMC was not obtained and results from that event were discarded from analysis. Since each sampling location was analyzed separately for each storm, paired influent and effluent data were not always obtained.

Constant baseflow was subtracted from flow measurements after a storm to isolate the event response at each location. Baseflow at each site varied from storm to storm and was determined using the average baseflow values from the flow record for 24 hours before an event.

Additional flow record adjustments were necessary at Pond 1 and Pond 2 of the Udall WP because the rating curve was constructed assuming that the water quality orifices were always 50% clogged. Over the course of the study, it was observed that the orifices would start unclogged at the beginning of a storm and then clog during the drawdown period. At any given time, the orifices could be approximately 25% to 90% clogged during the drawdown period. Storm flow records were adjusted to reflect an estimated average clogging percentage during the course of a storm. The average clogging percentage was determined by assuming that the volume of water passing through the Udall WP inlet would be equal to the volume of water passing through each pond outlet. Assuming equal influent and effluent storm volumes was justified since there was negligible infiltration and negligible evapotranspiration during the course of a runoff event. Both ponds are adjacent to the Cache la Poudre River, and it was observed that the high water table during spring and summer prevented any substantial infiltration from happening. Evapotranspiration estimates during the warmest part of the summer would remove an order of magnitude less volume of water from the ponds than the runoff volume a small event would produce (Mecham 2006). Flow records at each pond outlet were adjusted by first subtracting the baseflow, and then multiplying each value by an adjustment coefficient until the total storm volume was equal to the storm volume at the inlet.

Lab results that were less than the MDL were replaced with a value equal to one-half of the detection limit. Due to the long drawdown time at Pond 1 and Pond 2, results were often submitted to the lab in separate batches and then a storm EMC was calculated later based on the proportion of the total storm volume that each batch represented. Occasionally, a given parameter would be reported above the MDL for one batch and below the MDL for another batch of the same storm event. Batch results that were less than the MDL were replaced with a value equal to one-half of the detection limit, and then a flow-proportioned EMC was calculated for the storm. It was decided that the ROS method of substitution for EMCs below the MDL was not applicable for this study. ROS assumes an underlying distribution in order to generate replacement values for EMCs that are below the MDL. The ROS method would be heavily influenced by the substituted values that were required to generate EMCs when separate batches were submitted to the lab. In order to stay consistent, all results that were reported below the MDL were replaced with a value equal to half of the MDL.

3.6.1 Sampling Results Summary

Table 8 shows a summary of the storms that were sampled. Storm notes, summaries, and special circumstances were compiled and can be found in Appendix B. Individual EMCs for each storm and each water quality parameter are tabulated in Appendix C for each sampling location.

Table 8. Summary of Storms Sampled from 2009 to 2011

	Howes St. BMP		Udall WP		
Storm Date	**Howes Inlet**	**Howes Outlet**	**Udall Inlet**	**Udall Pond 1**	**Udall Pond 2**
10/27/2009		X	X	X	X (red)
3/20/2010		X			
4/21/2010	X (red)	X (red)	X	X	X
4/28/2010	X	X	X	X	X
5/11/2010	X	X (red)	X		
5/26/2010	X		X		
6/11/2010	L		L		
7/4/2010	X	X	X	X	X
8/8/2010	L	L	L	L	L
10/22/2010				X	X
11/9/2010	X	X	X		X
4/13/2011	X	X (yellow)	X	X	X (red)
4/24/2011	X	X (yellow)	X	X	X

X = Full Sampling Suite from PCL Lab
L = Limited Sampling from CSU Lab
(red) EMC Not used in Analysis-Did not meet screening criteria
(yellow) Equipment problems but believed to be representative EMC

Table 9 displays the summary water quality values from the Fort Collins sampling project. Average EMC and median EMC values are displayed for each constituent according to the sampling location. The D/N column lists the number of detectable samples obtained/total number of samples unless a single value is presented, which is the total number of samples. Note that some of the field-measured values are not EMCs and that E. coli data is comprised of grab samples.

Table 9. Summary Water Quality Values from the Fort Collins Sampling Project

Constituent	Units	MDL	Howes Inlet			Howes Outlet			Udall Inlet			Udall Pond 1			Udall Pond 2		
			D/N	Avg EMC	Median EMC	D/N	Avg EMC	Median EMC	D/N	Avg EMC	Median EMC	D/N	Avg EMC	Median EMC	D/N	Avg EMC	Median EMC
Conventional																	
Suspended Solids	mg/L		9/9	261	103	7/7	60.0	40.0	11/11	172	100	8/8	40.5	40.0	7/7	23.0	22.0
Alkalinity	mg/L		9/9	40.4	41.6	6/6	94.7	91.7	10/10	37.6	36.0	7/7	71.7	70.0	7/7	122	96.0
Hardness	mg/L		7/7	67.3	61.0	6/6	142	143	9/9	74.4	67.0	7/7	104	91.0	6/6	149	125
Organics																	
Chemical Oxygen Demand	mg/L		6/6	154	101	5/5	195	139	8/8	190	129	6/6	100	65.5	4/4	71.5	52.5
Total Organic Carbon	mg/L		9/9	24.3	23.8	7/7	49.1	21.4	11/11	29.9	24.5	8/8	31.8	21.0	7/7	25.2	20.6
Nutrients																	
Ammonia (NH3) as N	mg/L	0.10	7/7	0.96	0.88	7/7	0.51	0.47	8/9	0.91	0.91	5/7	0.50	0.60	4/6	0.28	0.24
Nitrite (NO2) as N	mg/L	0.05	3/6	0.06	0.05	6/6	0.08	0.05	2/8	0.05	0.03	1/5	0.03	0.03	3/5	0.04	0.03
Nitrate (NO3) as N	mg/L	0.05	7/7	1.71	0.71	6/6	0.82	0.64	8/9	0.66	0.70	5/6	0.92	0.86	4/5	0.97	0.87
Nitrate + Nitrite as N	mg/L	0.10	7	1.76	0.75	6	0.86	0.65	9	0.70	0.72	7	0.81	0.67	5	1.01	0.90
Total Kjeldahl Nitrogen	mg/L	0.50	7/7	4.31	3.28	7/7	2.28	1.23	8/9	4.21	2.79	7/7	1.99	1.84	6/6	1.64	1.65
Organic N	mg/L		7	3.35	2.40	7	1.76	0.81	9	3.30	1.79	7	1.49	1.32	6	1.37	1.36
Total Nitrogen	mg/L		9	5.14	4.03	7	2.70	1.68	11	4.35	2.71	8	2.63	2.50	7	2.33	1.87
Total Phosphorous as P	mg/L		9/9	0.45	0.36	8/8	0.23	0.19	11/11	0.36	0.25	8/8	0.22	0.12	7/7	0.12	0.08
Metals																	
Cadmium (D)	ug/L	0.50	0/3	0.25	0.25	0/1	0.25	0.25	0/4	0.25	0.25	0/2	0.25	0.25	0/2	0.25	0.25
Cadmium (TR)	ug/L	0.50	1/3	0.57	0.25	0/3	0.25	0.25	1/4	0.51	0.25	0/3	0.25	0.25	0/2	0.25	0.25
Chromium (D)	ug/L	5.00	0/3	2.50	2.50	0/0	-	-	0/4	2.50	2.50	0/2	2.50	2.50	0/2	2.50	2.50
Chromium (TR)	ug/L	5.00	2/4	4.70	4.49	1/3	4.25	2.50	3/4	5.49	5.74	1/3	2.79	2.50	0/2	2.50	2.50
Copper (D)	ug/L	5.00	4/6	5.92	6.11	2/3	4.92	5.19	7/8	9.22	8.91	4/6	5.33	6.00	5/6	4.78	5.05
Copper (TR)	ug/L	5.00	4/4	15.5	8.60	4/4	11.7	11.4	6/6	23.0	21.7	4/4	11.6	10.4	3/3	7.44	6.44
Lead (D)	ug/L	5.00	0/3	2.50	2.50	0/1	2.50	2.50	0/4	2.50	2.50	0/2	2.50	2.50	0/2	2.50	2.50
Lead (TR)	ug/L	5.00	2/3	17.3	7.17	1/3	6.45	2.50	3/4	17.0	13.4	1/3	3.88	2.50	1/2	3.17	3.17
Zinc (D)	ug/L	5.00	6/6	24.6	23.7	3/3	17.3	12.9	8/8	41.8	34.4	6/6	28.2	26.9	6/6	20.3	18.2
Zinc (TR)	ug/L	5.00	5/5	97.5	62.8	4/4	79.8	75.2	6/6	128	127	5/5	62.9	67.2	3/3	39.8	36.7
Ions																	
Calcium (D)	mg/L		6/6	10.5	9.60	5/5	30.1	29.7	8/8	12.6	10.8	6/6	21.6	19.8	4/4	25.2	25.8
Potassium (D)	mg/L		6/6	6.01	5.34	4/4	13.6	9.77	9/9	9.12	5.29	6/6	6.47	4.32	4/4	3.58	3.36
Magnesium (D)	mg/L	0.100	6/6	2.36	2.19	5/5	14.1	8.35	9/9	4.46	2.56	7/7	8.91	7.53	5/5	10.4	8.62
Sodium (D)	mg/L		6/6	5.90	4.70	4/4	19.9	12.2	8/8	10.2	7.07	6/6	17.6	10.3	4/4	10.7	10.1
Chloride	mg/L		5/5	8.52	7.30	5/5	59.9	39.1	7/7	24.0	9.10	6/6	65.8	17.8	4/4	19.1	18.8
Sulfate	mg/L	5.00	3/3	5.57	5.61	2/2	18.0	18.0	2/3	4.31	5.04	3/3	11.1	10.6	2/2	14.8	14.8
CSU Lab Tests																	
Total Dissolved Solids	mg/L		2/2	107	107	1/1	160	160	2/2	85.5	85.5	1/1	141	141	1/1	261	261
Total Carbon	mg/L		2/2	35.2	35.2	1/1	38.9	38.9	2/2	35.8	35.8	1/1	49.0	49.0	1/1	77.7	77.7
Inorganic Carbon	mg/L		2/2	7.84	7.84	1/1	17.4	17.4	2/2	6.88	6.88	1/1	14.4	14.4	1/1	24.3	24.3
Field Measured			Range	Avg	Median	Range	Avg	Median	Range	Avg	Median	Range	Avg	Median	Range	Avg	Median
Temp (grab samples)	°C		2.5 - 22.1	11.9	11.5	2.8 - 17.4	11.4	12.1	2.2 - 17.6	12.6	13.8	3.6 -21.1	11.7	11.8	2.4 -20.9	11.2	10.4
DO (grab samples)	mg/L		5.0 - 12.8	8.1	7.4	3.5- 12.9	7.5	6.8	5.6 - 12.2	8.1	8.0	1.7 - 10.7	6.6	6.6	1.3 - 11.3	6.6	7.1
Conductivity (EMCs)	uS/cm		59.7 - 270	114	100	79.5 - 512	291	227	61.7 - 365	141	90.8	104 - 631	241	198	107 - 1207	336	212
pH (EMCs)			7.3 - 9.5	8.4	8.4	6.8 - 9.3	8.0	7.9	7.3 - 9.4	8.2	8.3	7.2 - 8.5	7.9	7.9	7.3 - 8.4	7.8	7.9
Chloride (EMCs)	mg/L		5 - 126	59	63	12 - 1384	281	93	7 - 286	105	65	25 - 827	226	108	39 - >1500	134	126
Bacteria			Range	GeoMean	Median	Range	GeoMean	Median	Range	GeoMean	Median	Range	GeoMean	Median	Range	GeoMean	Median
E. coli (grab samples)	#/100 mL		400 - 34,400	3,661	3,150	400 - 165,000	14,240	16,600	667 - 47,350	4,268	3,900	100 - 68,500	5,095	4,000	200 - 150,000	5,381	7,000

Halfway through the first season of sampling, testing for D Cd, TR Cd, D Cr, TR Cr, D Pb, and TR Pb were discontinued due to frequent results that were reported as less than the MDL. There was some evidence of TR Pb, TR Cr, and TR Cd removal in each BMP, and dissolved fractions of these metals were almost always less than the MDL. Additional samples for copper and zinc were collected. Comparison between zinc and copper removal rates at each BMP could be extrapolated for other heavy metals assuming that they are approximately as easy to remove, especially when TSS is removed as well.

Dissolved minerals from stormwater runoff are not usually considered pollutants, but these constituents were analyzed to enable the use of chemical software in the future if metal speciation were investigated for individual storms. Ca, Mg, and Na tended to increase from pond inlet to outlet at both facilities. This result simply implies that the baseflow had a higher dissolved mineral content than stormwater runoff. Stormwater runoff displaced the stored water in the wet ponds, and the EMC values collected at pond outlets had the characteristics of the stored water. Precipitation events in Fort Collins usually occurred less frequently than the time required to fill the ponds with baseflow. K increased at the Howes St. BMP but decreased from the inlet to the Pond 1 outlet and Pond 2 outlet at Udall. The decrease may have been due to the limited sample sizes at the Pond 1 and Pond 2 outlets.

Similar findings were shown by the Alk, Hardness, sulfate, and Cl^- results. Baseflow had a higher mineral content than stormwater runoff which explains why the Hardness was higher at pond outlets (separate PCL lab tests were conducted to determine Mg, Ca, and Hardness concentrations). Furthermore, the baseflow had higher Alk concentrations than the stormwater runoff. Sulfate concentrations increased from pond inlet to outlet at both facilities and could be present in groundwater from leaching of deposits of magnesium sulfate or sodium sulfate in the ground (Epsom salts or Glauber salts, respectively). Cl^- also increased from inlet to pond outlet at each site because there were higher concentrations in the baseflow than the stormwater runoff.

Note that most storms were not sampled during snowfall events when deicing material may have been put on City streets. Common deicing materials include sodium chloride and magnesium chloride. The stormwater runoff during winter months could have higher Cl^- concentrations, Mg concentrations, and/or Na concentrations than the baseflow.

Values collected by the YSI meter were not investigated in detail in this thesis. Grab samples for DO and temperature were not representative of overall impact of runoff event because they were not EMCs. Temperature values ranged from 2.2^{o}C to 22.1^{o}C showing that a wide variety of storms were collected during different weather conditions. DO grab samples were usually above 5.0 mg/L, indicating that severe oxygen depletion during an event was rare.

EMC pH values were within expected ranges and were slightly alkaline at all locations. Consistently, the pH of Pond 1 and Pond 2 at Udall was between 7.5 and 8.5, indicating that the stored water was well buffered and resilient to inlet pH ranges, which rose as high as 9.4. The Howes St. BMP outlet did not have as consistent pH values as the Udall pond outlets, which was probably due to the small amount of stored baseflow at the pond. SC and Cl^- EMC values indicated that more ions existed at pond outlets than at the inlets. This result coincides with the high mineral content of the ponds and was likely caused by stored baseflow in the ponds.

Other grab sample values for SC, pH, and Cl^- were collected by sampling personnel, although these results are not presented in this thesis. In the future, this data could be used to estimate pollutant concentrations at the specific time of collection. Also, please note that the YSI meter Cl^- EMC values were an order of magnitude higher than the PCL Cl^- EMC values which brings into question the validity of the Cl^- sensor used on the YSI meter. The YSI meter collected reliable SC values that could be used in lieu of the Cl^- results if a relationship between SC and Cl^- was established for each watershed.

3.6.2 Ranksum Statistical Significance Test Results

Formal hypothesis testing was conducted to determine the level of significance between the medians of the sampling sites. The nonparametric Ranksum test was selected as the most appropriate method to determine differences in median values. The Ranksum test did not require an assumed underlying distribution, utilized all EMC values that met screening criteria, and reported the level of significance that two medians were statistically different. Alternatively, the nonparametric Sign test requires paired storm data, which would have limited the number of usable EMCs to approximately half of those utilized by the Ranksum test. Parametric methods of hypothesis testing (T-test and paired T-test) were not used because the total number of data points was small.

For each pollutant studied, the inlet EMC values were compared to outlet EMC values to determine if the medians differed statistically. At the Udall WP, the inlet was compared to each pond outlet, and the Pond 1 outlet was also compared to the Pond 2 outlet to determine how beneficial the second pond was for pollutant removal. Table 10 shows the confidence level of median differences using the Ranksum test. Percentages appearing in red signify that the inlet median concentration was lower than the outlet median concentration. Percentages that are in bold were statistically significant at a 90% or greater level. The Ranksum test in MATLAB utilizes a two-tailed test. A 90% significance level for a two-tailed test is equivalent to a 95% confidence level for a one-tailed test because all of the uncertainty is shifted to one side of the distribution.

Table 10. Confidence Level (%) Between Median Differences Using Ranksum Test

Pollutant	Howes Inlet to Howes Outlet	Udall Inlet to Pond 2 Outlet	Udall Inlet to Pond 1 Outlet	Pond 1 Outlet to Pond 2 Outlet
TSS (mg/L)	**96.9**	**100.0**	**99.8**	**99.7**
COD (mg/L)	-6.9	71.7	70.1	23.8
TOC (mg/L)	0.0	27.6	3.2	4.5
TR Cu (ug/L)	-31.4	**90.5**	82.9	60.0
D Cu (ug/L)	26.2	**96.9**	**94.1**	41.8
TR Zn (ug/L)	-9.5	**90.5**	87.5	85.7
D Zn (ug/L)	61.9	**94.1**	77.2	86.8
TP (mg/L)	80.0	**97.3**	72.8	71.9
TN (mg/L)*	88.6	65.0	-40.4	37.2
TKN (mg/L)	87.2	**91.2**	82.6	46.6
NH_3 (mg/L)	**98.4**	**98.3**	**93.0**	79.3
NO_2+NO_3 (mg/L)	5.5	-69.3	-45.3	-16.0
Organic N (mg/L)**	83.5	67.2	53.0	-5.5
E. coli (#/100 mL)***	-94.8	-25.3	-40.2	0.0

Negative values (in red) show increase in median from inlet to outlet
* TN was measured directly by CSU for two events, otherwise it was calculated by adding TKN + NO_2 + NO_3
** Organic N was estimated for each storm by subtracting TKN - NH_3
*** E. coli grab samples were analyzed, no EMCs were collected for E. coli

The statistical results indicated statistically significant lowering of pollutant EMC values at the Howes St. BMP, especially if the significance level was relaxed to 80% or greater. The Howes St. BMP significantly reduced TSS and NH_3 at a greater than 90% significance level and also reduced TP, TN, TKN, and Organic N at a greater than 80% significance level. There was no statistically significant removal or addition of COD, TOC, TR Cu, D Cu, TR Zn, D Zn, or NO_2 + NO_3. E. coli grab sample concentrations were significantly higher at the Howes St. outlet than at the inlet. Overall, water quality enhancement at the site was achieved, but not as consistently as at the Udall WP.

The Udall WP showed statistically significant reductions in TSS, TR Cu, D Cu, TR Zn, D Zn, TP, TKN, and NH_3 at a 90% confidence level or greater. From the inlet to the Pond 1 outlet, there were significant reductions in TSS, D Cu, and NH_3. Additional TSS removal from the Pond 1 outlet to the Pond 2 outlet was significant. The statistical results justify the two-pond system because insignificant water quality improvements were obtained from the inlet to the Pond 1 outlet for several pollutants but the overall removal rate was significant from the inlet to the Pond 2 outlet. Although there was rarely a statistically significant reduction between Pond 1 and Pond 2, Table 10 clearly shows that water quality enhancement from Pond 2 was important for the overall system.

One important thing to remember is that a statistically significant result does not indicate the magnitude of the water quality enhancement. For example, the TSS effluent concentration was higher at the Pond 1 outlet than the Pond 2 outlet at a 99.7% significance level. However, the inlet TSS median was 100 mg/L at the Udall WP, the Pond 1 outlet median was 40 mg/L, and the Pond 2 Outlet was 25 mg/L. The majority of pollutant removal occurred in Pond 1. Pond 2 achieved a significant lowering of TSS from 40 mg/L to 25 mg/L, but it did not remove as much TSS load as Pond 1.

3.6.3 Efficiency Ratio Calculations

The efficiency ratio (ER), which is the decimal equivalent of percent removal, was calculated using the mean EMC at each sampling location using Equation 7. The ER describes the average change in pollutant concentration when the inlet is compared to the outlet for a BMP. Since the Udall WP has an intermediate sampling location (inlet to Pond 1), the ER was computed for runoff moving from the inlet to Pond 1 outlet, from the Pond 1 outlet to the Pond 2 outlet, and from the BMP inlet to the Pond 2 outlet.

Table 11 shows the ER at the Howes St. BMP from the inlet to the outlet. Table 12 shows the computed ER values for the Udall WP and includes the intermediate ER values. Table 13 compares the inlet to outlet ER at the Howes St. BMP the Udall WP. Also included in Table 13 is the intermediate performance of the Udall WP, which shows the ER from the inlet to the Pond 1 outlet. Negative values mean that a pollutant increased in concentration from inlet to outlet.

Table 11. Efficiency Ratio (ER) for the Howes St. BMP

Pollutant	Units	Mean EMC at Inlet	Mean EMC at Outlet	ER
Total Suspended Solids	mg/L	261	60	0.77
Chemical Oxygen Demand	mg/L	154	195	-0.26
Total Organic Carbon	mg/L	24.3	49.1	-1.02
Ammonia	mg/L	0.96	0.51	0.46
Nitrate + Nitrite	mg/L	1.76	0.86	0.51
Total Kjeldahl Nitrogen	mg/L	4.31	2.28	0.47
Organic Nitrogen*	mg/L	3.35	1.76	0.47
Total Nitrogen*	mg/L	5.14	2.70	0.48
Total Phosphorous	mg/L	0.45	0.23	0.49
Dissolved Copper	ug/L	5.92	4.92	0.17
Total Recoverable Copper	ug/L	15.5	11.7	0.25
Dissolved Zinc	ug/L	24.6	17.3	0.30
Total Recoverable Zinc	ug/L	97.5	79.8	0.18
E. coli **	#/100 mL	3,661	14,240	-2.89

* Total Nitrogen and Organic Nitrogen calculated from other nitrogen species
** Geometric mean of grab samples

Table 12. Efficiency Ratios (ERs) for the Udall WP

Pollutant	Units	Mean EMC at Inlet	Mean EMC at Pond 1	Mean EMC at Pond 2	ER Inlet to Pond 1	ER Pond 1 to Pond 2	ER Inlet to Pond 2
Total Suspended Solids	mg/L	172	40.5	23.0	0.76	0.43	0.87
Chemical Oxygen Demand	mg/L	190	99.8	71.5	0.47	0.28	0.62
Total Organic Carbon	mg/L	29.9	31.8	25.2	-0.06	0.21	0.16
Ammonia	mg/L	0.91	0.50	0.28	0.46	0.44	0.70
Nitrate + Nitrite	mg/L	0.70	0.81	1.01	-0.15	-0.25	-0.44
Total Kjeldahl Nitrogen	mg/L	4.21	1.99	1.64	0.53	0.17	0.61
Organic Nitrogen*	mg/L	3.30	1.49	1.37	0.55	0.08	0.58
Total Nitrogen*	mg/L	4.35	2.63	2.33	0.39	0.12	0.46
Total Phosphorous	mg/L	0.36	0.22	0.12	0.39	0.46	0.67
Dissolved Copper	ug/L	9.22	5.33	4.78	0.42	0.10	0.48
Total Recoverable Copper	ug/L	23.0	11.6	7.44	0.50	0.36	0.68
Dissolved Zinc	ug/L	41.8	28.2	20.3	0.33	0.28	0.51
Total Recoverable Zinc	ug/L	128	62.9	39.8	0.51	0.37	0.69
E. coli **	#/100 mL	4,268	5,095	5,381	-0.19	-0.06	-0.26

* Total Nitrogen and Organic Nitrogen calculated from other nitrogen species

** Geometric mean of grab samples

Table 13. Comparison of Howes St. BMP ER to Udall WP ER

Pollutant	Howes St. BMP ER Inlet to Outlet	Udall WP ER Inlet to Pond 1	Udall WP ER Inlet to Pond 2
Total Suspended Solids	0.77	0.76	0.87
Chemical Oxygen Demand	-0.26	0.47	0.62
Total Organic Carbon	-1.02	-0.06	0.16
Ammonia	0.46	0.46	0.70
Nitrate + Nitrite	0.51	-0.15	-0.44
Total Kjeldahl Nitrogen	0.47	0.53	0.61
Organic Nitrogen	0.47	0.55	0.58
Total Nitrogen	0.48	0.39	0.46
Total Phosphorous	0.49	0.39	0.67
Dissolved Copper	0.17	0.42	0.48
Total Recoverable Copper	0.25	0.50	0.68
Dissolved Zinc	0.30	0.33	0.51
Total Recoverable Zinc	0.18	0.51	0.69
E. coli	-2.89	-0.19	-0.26

In the past, the ER has been used as the overall measure of efficiency for a BMP, but the ER values can be misleading for a multitude of reasons. Primarily, the ER is heavily dependent on incoming pollutant concentrations. For example, the ER for TSS at the Howes St. BMP was approximately equal to the ER from the Udall inlet to the Pond 1 outlet. This was because the average influent concentration of TSS at Howes St. was 120 mg/L greater than the average influent at Udall. The mean EMC at the Pond 1 outlet was actually 20 mg/L cleaner than the mean TSS effluent from the Howes St BMP. It is also a poor measure of BMP effectiveness because mean EMC values are used instead of median EMC values. With small datasets, the median is a more robust measure of the central tendency of the data and is not as heavily influenced by single events.

Nevertheless, the ER is presented here to allow easy comparison to past stormwater studies and is a useful tool in exploratory data analysis. The Udall WP had a better ER for every pollutant category when compared to the Howes St. BMP except NO_2+NO_3 and TN. Furthermore, the mean EMC values suggested that the brunt of the pollutant removal occurred from the inlet of the Udall WP to Pond 1 for TN and TP removal, total recoverable metals removal, and TSS removal. In general, the Udall WP performed better than the Howes St. BMP for water quality enhancement. From the inlet of the Udall WP to the Pond 1 outlet, removal rates for TSS and nutrients were close to those at the Howes St. BMP. The major deficiency for the Howes St. BMP was the poor removal of heavy metals, especially the total recoverable metals that are primarily removed through sedimentation. It is important to cross-reference the ER tables with the statistical results shown in Table 10. For example,

Table 13 shows a 51% reduction in nitrate for the Howes St. BMP but there was only 5% confidence that a statistically significant change was observed. No further attention to the traditional ER is presented in this thesis because the ER was used only as an exploratory analysis tool. Better methods of analysis are presented in subsequent sections.

3.6.4 Relative Efficiency of Howes St. BMP to Udall WP

A relative ER was calculated using Equation 8 to compare pollutant removal rates between two BMPs with C_{limit} being the mean effluent EMC of the Udall WP. Pollutant removal rates at the Udall WP were usually better than the removal rates at the Howes St. BMP, and may be representative of a "best case scenario" due to the long HRT provided by the extended detention outlet structures and large storage capacity of the ponds. The relative ER was calculated for the Howes St. BMP compared to each pond at the Udall WP as shown in Table 14. Mathematically, the relative ER was meaningless if there was a negative removal rate from inlet to outlet at the Howes St. BMP and could not be computed for a few constituents.

Table 14. Relative ER of the Howes St. BMP to Pond 1 and Pond 2 at the Udall WP

Pollutant	Relative ER Howes St. BMP to Udall Pond 1 Outlet	Relative ER Howes St. BMP to Udall Pond 2 Outlet
Total Suspended Solids	0.91	0.84
Chemical Oxygen Demand	-	-
Total Organic Carbon	-	-
Ammonia	0.96	0.65
Nitrate + Nitrite	0.95	0.98
Total Kjeldahl Nitrogen	0.88	0.76
Organic Nitrogen	0.85	0.80
Total Nitrogen	0.97	0.87
Total Phosphorous	0.97	0.66
Dissolved Copper	1.70	0.88
Total Recoverable Copper	0.97	0.47
Dissolved Zinc	-	1.69
Total Recoverable Zinc	0.51	0.31
E. coli	-	-

- Relative ER could not be computed

According to Table 14, the Howes St. BMP removed 91% of the influent TSS as Pond 1 and 84% as Pond 2 at Udall. However, other pollutants were not removed from the water column as effectively. Between 85 to 97% of the nutrients were removed from

Howes St. compared to Pond 1. Between 65 to 88% of the nutrients were removed from Howes St. compared to Pond 2, with the exception of nitrate + nitrite where approximately equal removal rates were achieved. TR Cu was removed at a similar rate to Pond 1, but the only 47% of the TR Cu was removed at Howes St. when compared to Pond 2. TR Zn was not removed effectively when compared to either pond at Udall.

3.6.5 Relative Efficiency to C*

A relative ER was calculated using Equation 8 with C_{limit} being the minimum irreducible concentration (C*) of a pollutant. Table 15 shows the relative ER when an assumed C* value was used as the limit of effluent concentration.

Table 15. Relative Efficiency of the Howes St. BMP and Udall WP to C*

Pollutant	Assumed C* Value (mg/L)	Relative ER to C* Howes St. BMP	Relative ER to C* Udall Inlet to Pond 1 Outlet	Relative ER to C* Udall Inlet to Pond 2 Outlet
Total Suspended Solids	20	0.83	0.87	0.98
Total Kjeldahl Nitrogen	1.2	0.65	0.74	0.85
Total Nitrogen	1.9	0.75	0.70	0.82
Total Phosphorous	0.15	0.73	0.66	1.14

The relative ER ratio to C* indicates how close a BMP's removal rate was to the theoretical limits. Pond 2 at Udall essentially achieved the maximum reduction in TSS and TP and eliminated approximately 85% of TKN and 82% of the TN compared to what could theoretically be removed. Pond 1 at Udall also had a high removal rate for TSS, but the nutrient removal rates were 74% for TKN, 70% for TN, and 66% for TP. The results indicate that the major benefit of Pond 2 at Udall was the additional removal of TP, TKN, and TN that occurred. The Howes St. BMP treated 83% of the theoretically removable TSS, but only treated around 65% of the removable TKN, 75% of the TN, and 73% of the TP. The relative ER calculation is heavily influenced by influent concentrations, and is misleading because the Howes St. BMP appeared to treat effluent TSS to a similar concentration as Pond 1 at Udall, when in fact it did not. The average outlet concentration at the Howes St. BMP was 65 mg/L while the average outlet concentration at Pond 1 was 38 mg/L.

3.6.6 Standard Boxplots of Stormwater Pollutants

Standard boxplots were created to display the sampling results. Differences in medians were significant when the notch of one box interval did not overlap with the notch of another box, as explained in the Graphical Methods section of this thesis. The definitions of the components of a standard boxplot are displayed in Figure 10. Figure 17 through Figure 30 show the boxplots generated for numerous pollutants investigated in this study. Note that the E. coli results were all grab samples instead of EMCs.

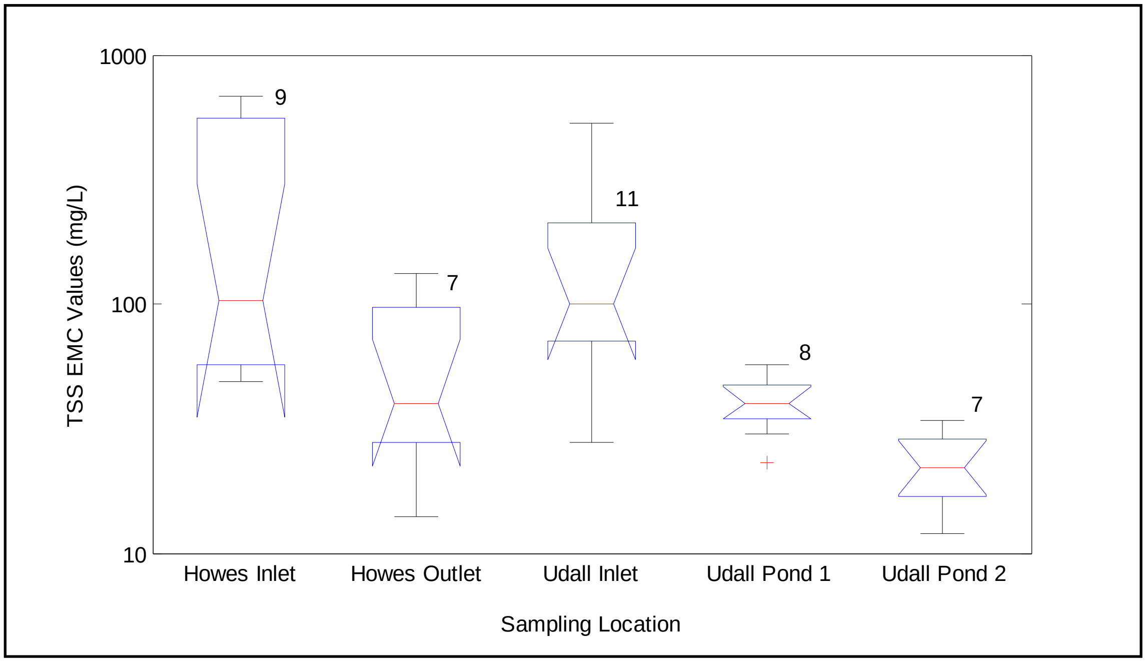


Figure 17. Standard Boxplot of TSS EMC Results for All Sampling Locations

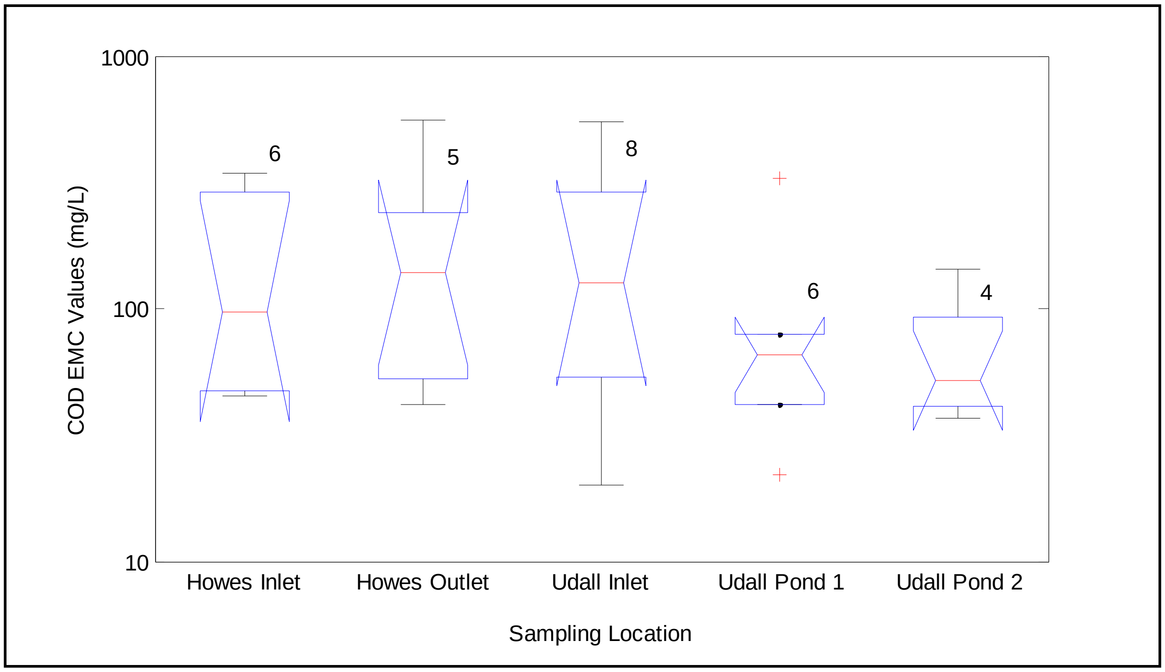


Figure 18. Standard Boxplot of COD EMC Results for All Sampling Locations

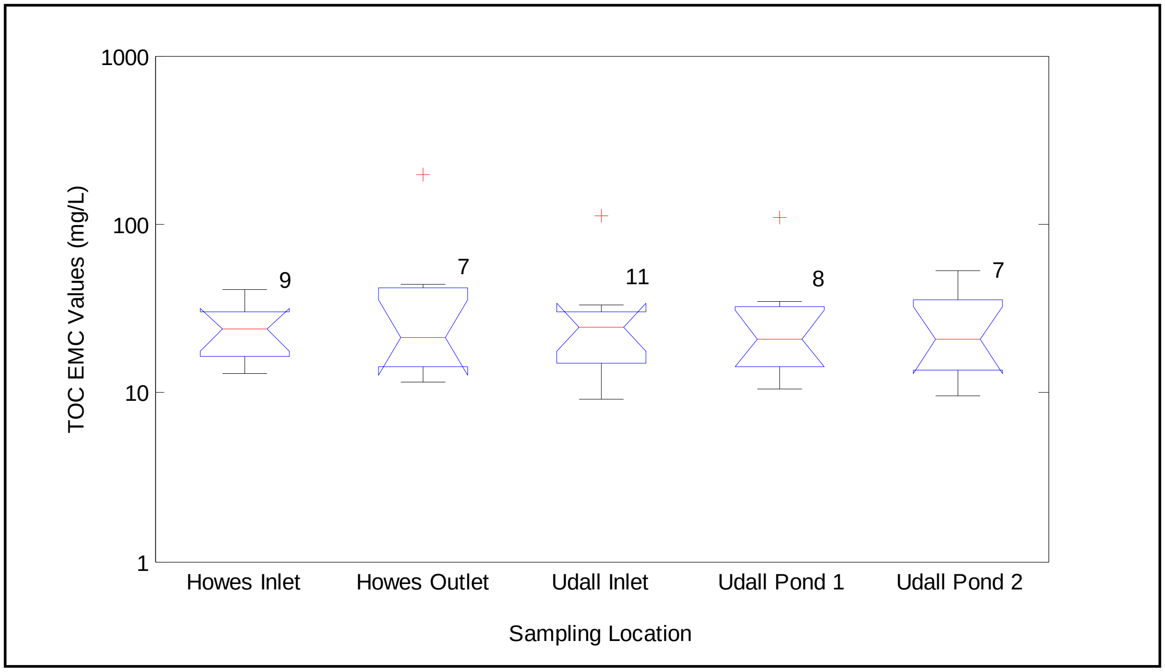


Figure 19. Standard Boxplot of TOC EMC Results for All Sampling Locations

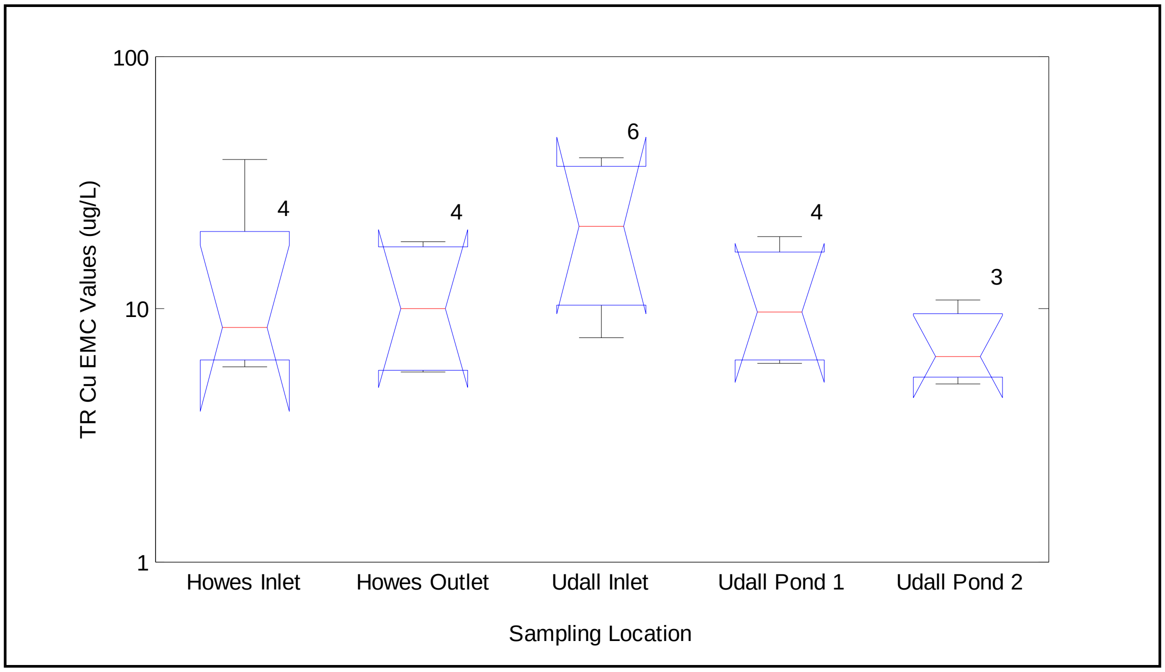


Figure 20. Standard Boxplot of TR Cu EMC Results for All Sampling Locations

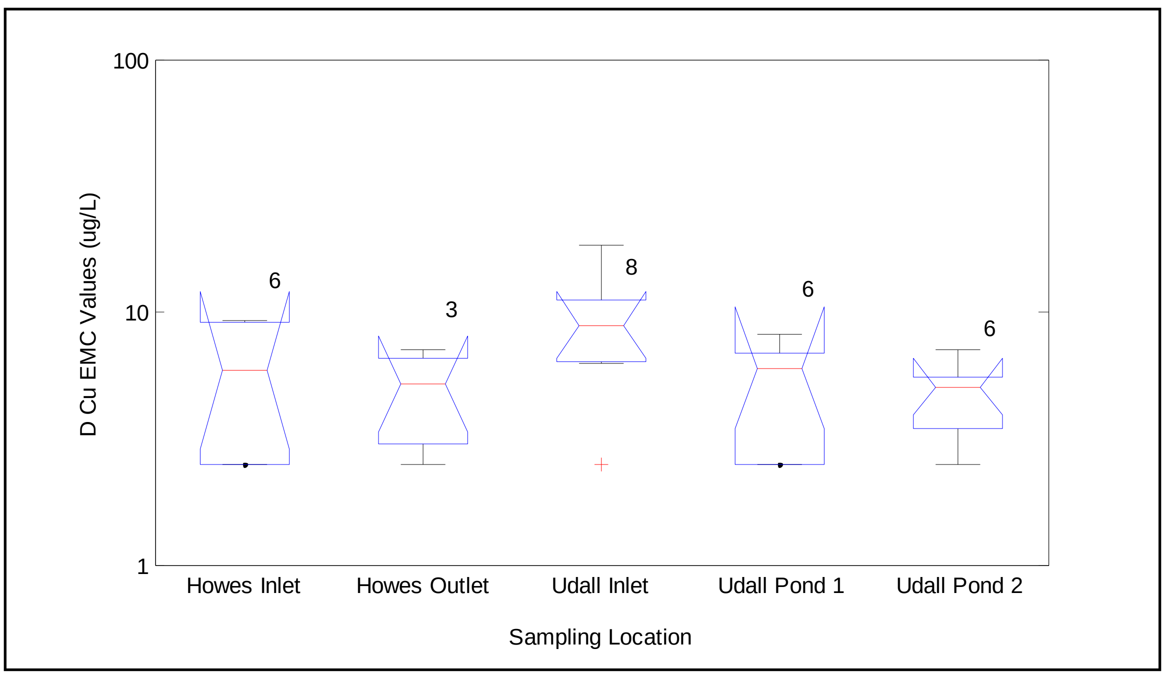


Figure 21. Standard Boxplot of D Cu EMC Results for All Sampling Locations

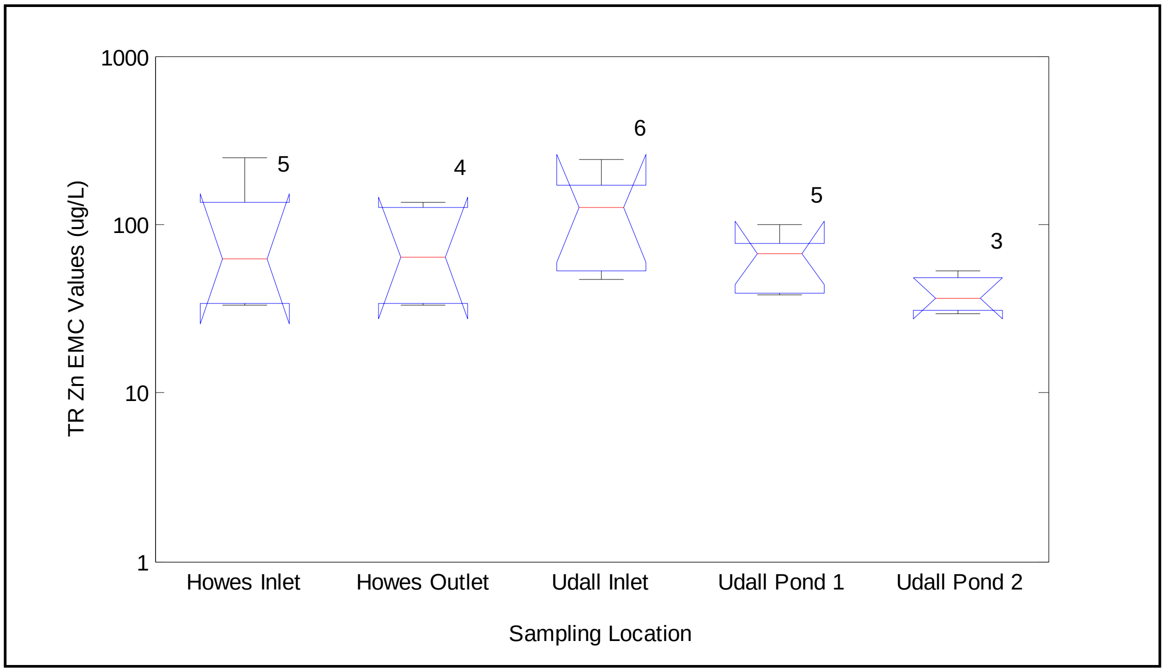


Figure 22. Standard Boxplot of TR Zn EMC Results for All Sampling Locations

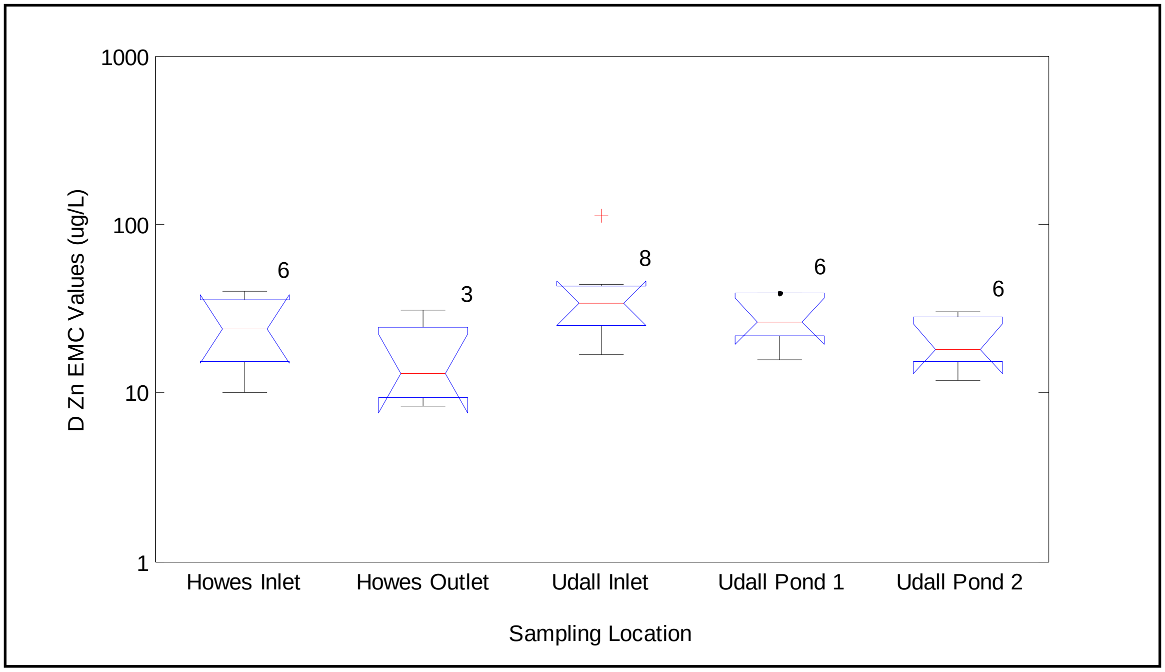


Figure 23. Standard Boxplot of D Zn EMC Results for All Sampling Locations

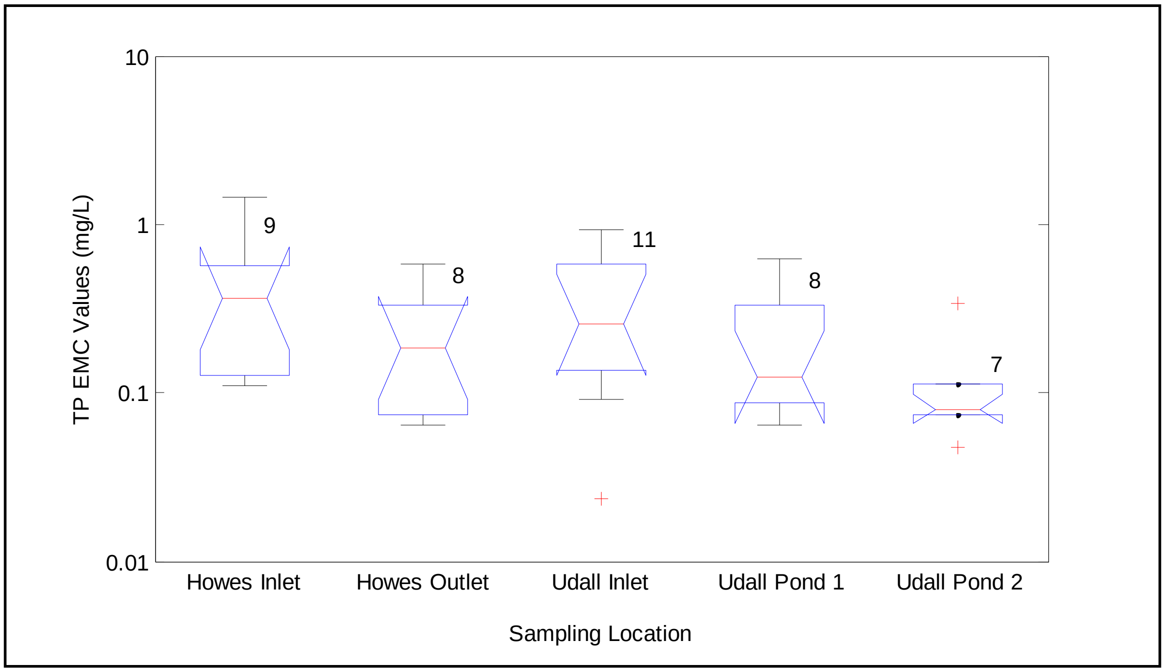


Figure 24. Standard Boxplot of TP EMC Results for All Sampling Locations

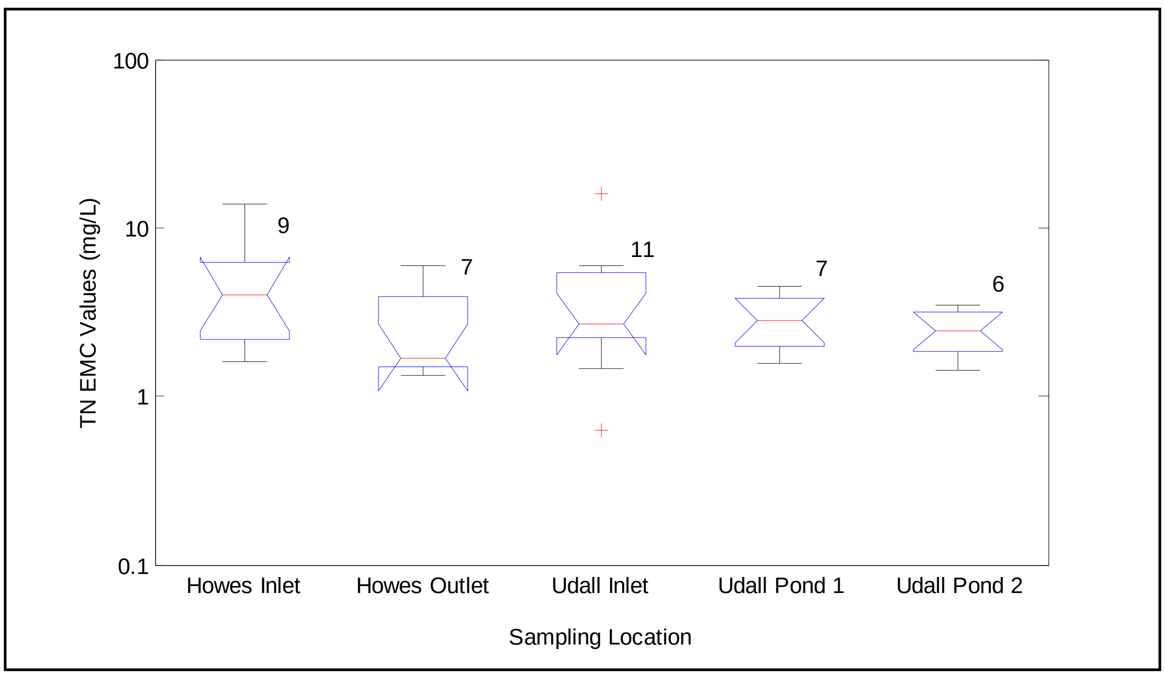


Figure 25. Standard Boxplot of TN EMC Results for All Sampling Locations

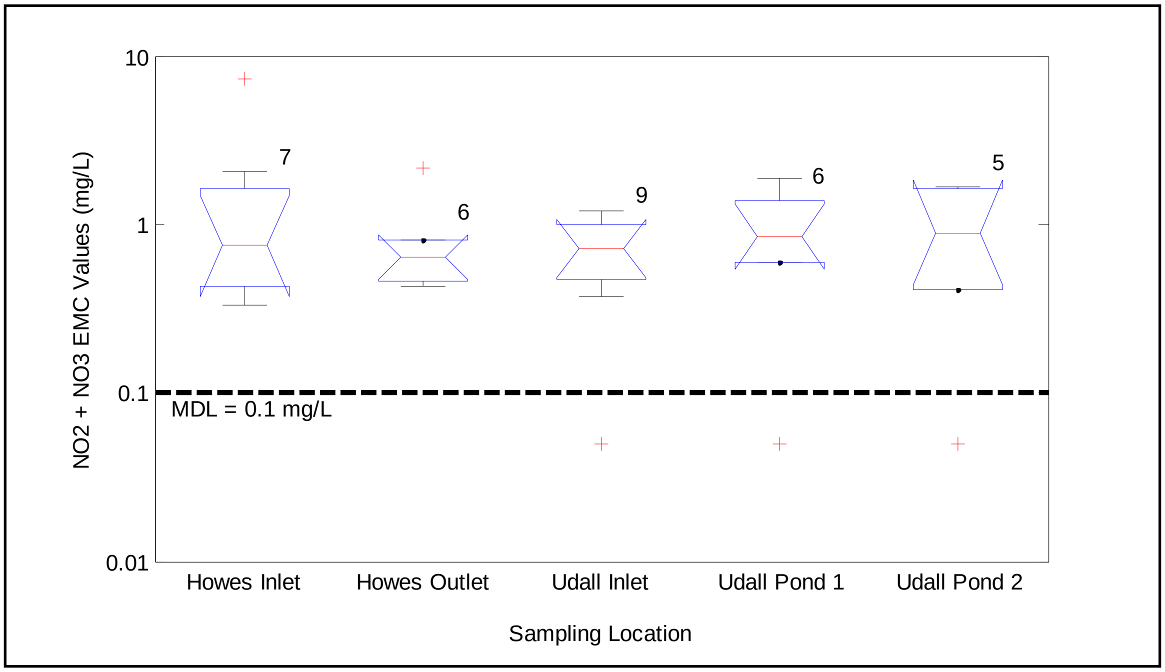


Figure 26. Standard Boxplot of NO_2 + NO_3 EMC Results for All Sampling Locations

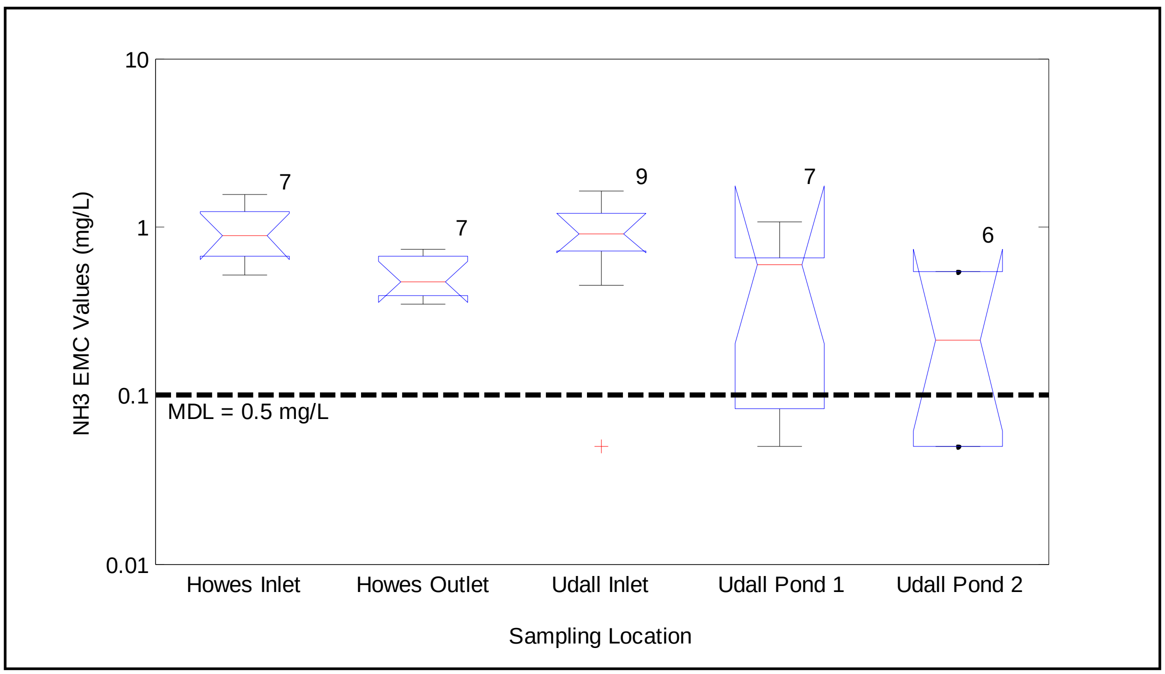


Figure 27. Standard Boxplot of NH_3 EMC Results for All Sampling Locations

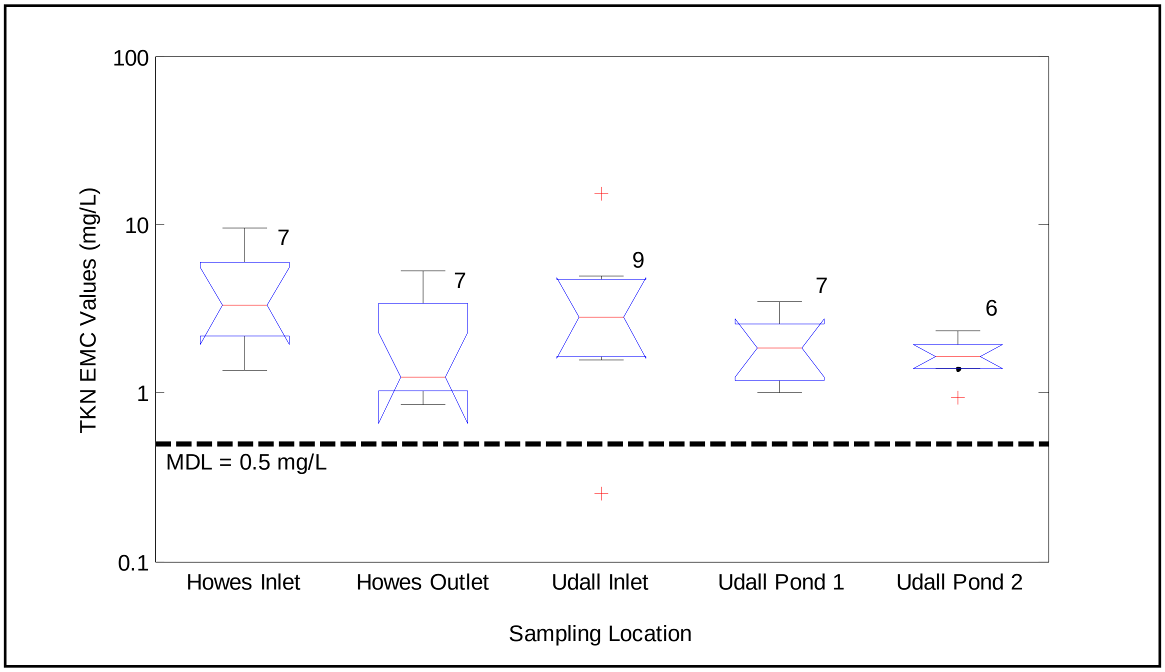


Figure 28. Standard Boxplot of TKN EMC Results for All Sampling Locations

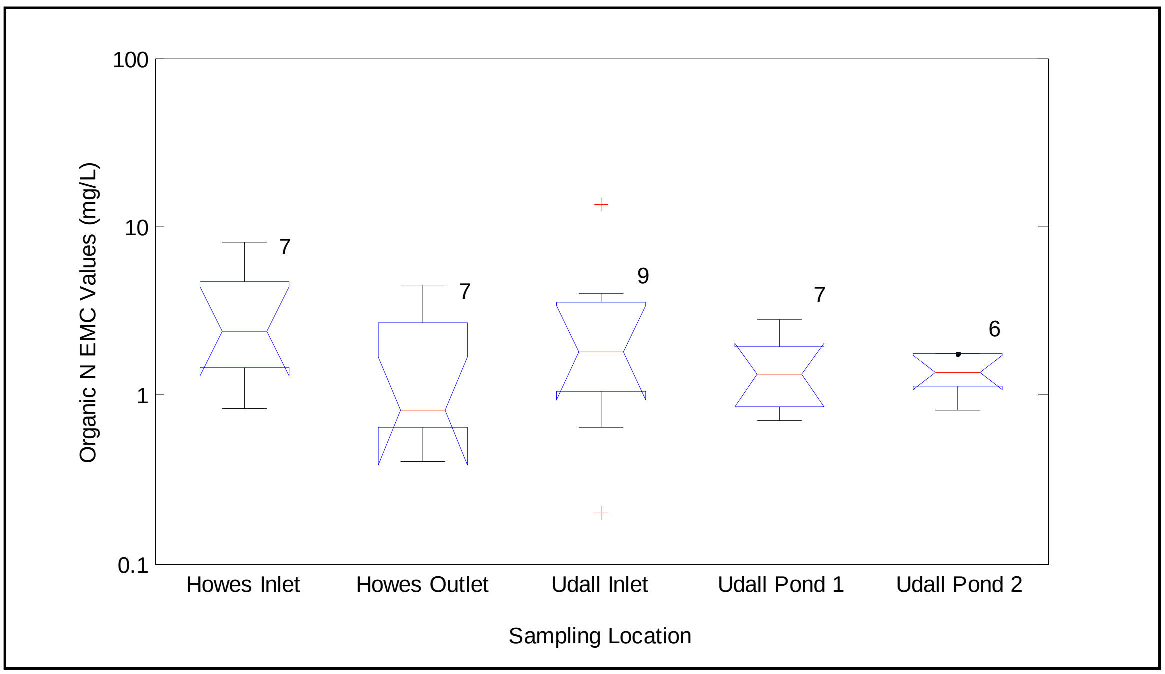


Figure 29. Standard Boxplot of Organic Nitrogen EMC Results for All Sampling Locations

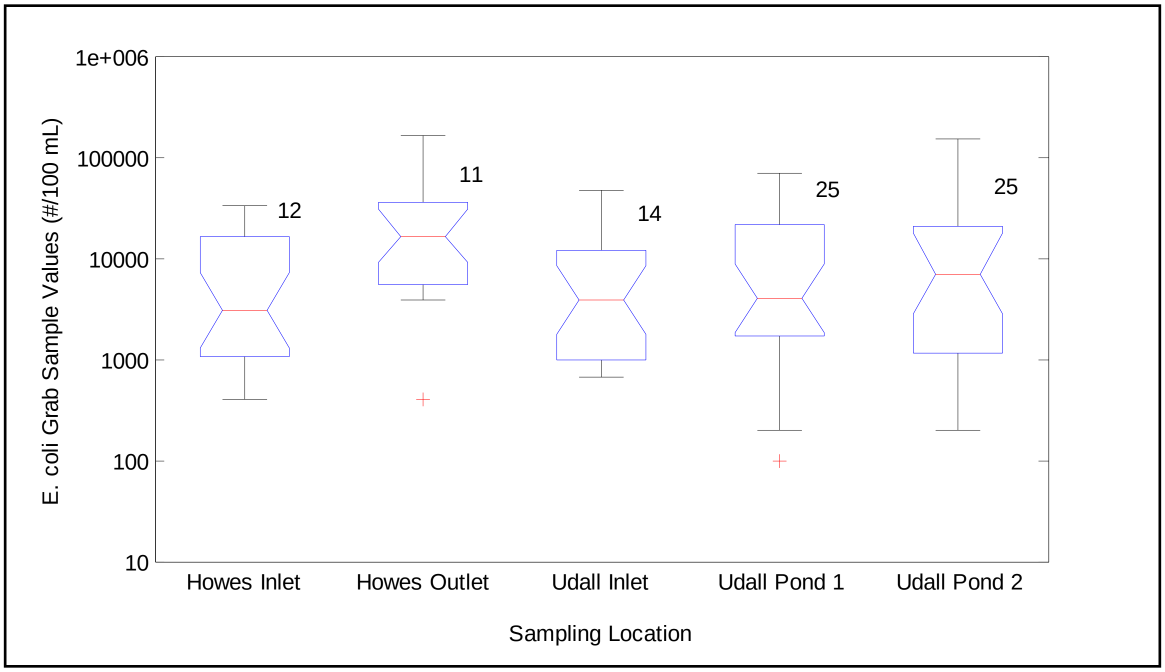


Figure 30. Standard Boxplot of E. coli Grab Sample Results for All Sampling Locations

From Figure 17, it is clear that both facilities had excellent TSS removal rates. The median influent TSS values at both locations were similar, but the Udall WP consistently removed more TSS from runoff. There was implied significance between the inlet and outlet concentrations at the Howes St. BMP and between the inlet, outlet of Pond 1, and outlet of Pond 2 at Udall. These results matched the Ranksum results. The Howes St. BMP had a median effluent concentration that was identical to the Pond 1 effluent at Udall, but the figure clearly shows that there was more variability in observed values. The short boxplot at Pond 1 of Udall indicates that the facility was more consistent in TSS removal than the Howes St. outlet, which had a wider boxplot.

Figure 18 shows the COD EMC results and there was no statistically significant reduction in COD at either facility, which was consistent with the Ranksum results. The figure indicates that observed values tended to be lower at the Pond 1 and Pond 2 outlets when compared to influent values. Figure 19 shows that no significant reduction in TOC was observed at either facility, which was also consistent with the Ranksum results. COD and TOC are both estimates for the oxygen depleting potential of runoff. From the figures, it is reasonable to conclude that neither facility was highly effective at improving the oxygen demand from the runoff.

Figure 20 and Figure 21 show the TR Cu and D Cu EMC results, respectively. The first important thing to note is that the total number of samples was low, especially for TR Cu. The City PCL failed to deliver numerous values at each site (3 storms at all locations) which would have been extremely helpful in increasing the statistical certainty of perceived differences. Nevertheless, the boxplots suggest that TR Cu was removed at the Udall WP and not at the Howes St. BMP. Specifically, the difference between the inlet and Pond 2 outlet at Udall was significant. Furthermore, the inlet TR Cu concentrations at the Udall WP were higher than the inlet concentration at the Howes St. BMP. This was to be expected because the Udall WP watershed has a larger percentage of heavily trafficked roads and commercial areas. A statistically significant reduction in D Cu was also observed at the Udall WP from the inlet to the Pond 1 outlet, and from the inlet to the Pond 2 outlet. No significant reeducation was observed at the Howes St. BMP, but only three effluent values were available.

Figure 22 shows the TR Zn EMC results and Figure 23 shows the D Zn EMC results for the sampling sites. The median TR Zn and D Zn at the Udall inlet were higher than the Howes St. inlet, but the difference was not as pronounced as the influent copper concentrations (shown on previous page). Overall, the plots indicate that a statistically significant reduction in total and dissolved zinc occurred at the Udall WP from the inlet to the Pond 2 outlet. There is evidence that some D Zn was removed at the Howes St. BMP, but the limited sample size prevented any strong conclusions from being made. Similarly to the TR Cu results, there were approximately three storms worth of TR Zn values that were never analyzed by the City PCL. Despite the limited sample size, Figure 22 shows that TR Zn was removed at the Udall WP. D Zn is not as easy to remove from the water column, and the median effluent at the Pond 2 outlet was actually higher than the median effluent at the Howes St. BMP outlet. This may be from the higher inlet concentrations of D Zn at the Udall inlet.

Figure 24 displays the TP results for the sampling locations. The plot indicates that the Howes St. BMP removed TP at a significant level, which was a stronger result than the Ranksum test. Furthermore, the Udall WP had excellent TP removal from inlet to Pond 1 outlet, and then from Pond 1 to the Pond 2 outlet.

Figure 25 shows the TN results for the sampling locations. The figure implies that a significant reduction in TN occurred at the Howes St. BMP but not at the Udall WP. Usually, TN was not measured directly for an event but was calculated by adding the other nitrogen species that were analyzed. Figure 26 shows that NO_2 + NO_3 was not removed effectively by either BMP, but according to Figure 27, there was removal of ammonia. NH_3 was removed significantly at the Howes St. BMP and there was a tight grouping of effluent results. At the Udall WP, there was also significant NH_3 removal, but a wide range of values were observed at each pond outlet. The broader range of values at Udall may be attributed to algae growth and die-off, which was observed during sampling, and which occurred to a greater degree than at the Howes St. BMP. Figure 28 shows the TKN results and Figure 29 shows the calculated Organic N results. The TKN test measures the total Organic N + NH_3 content in the water. Organic N was estimated by subtracting NH_3 results from TKN for each storm. A significant reduction in TKN occurred at the Howes St. BMP and from the inlet to the Pond 2 outlet at Udall. Organic N was also removed to significant degree at the Howes St. BMP, but the results are not as clear for the Udall WP. Results for TKN and Organic N correlated well with the Ranksum statistical testing, but tended to imply significant differences in concentration more often. There was a reduction of median from inlet to Pond 1 and Pond 2, but significant differences were not observed according to Figure 29.

Finally, E. coli grab sample results are presented in Figure 30. An important note for the plot is the scale of observations, which ranged from only 100 E. coli colonies per 100 mL to over 100,000. A wide range of E. coli results is common for stormwater sampling (Clary et al 2008, Geosyntec and WWE 2010). At the Howes St. BMP, there was a statistically significant increase in E. coli concentration from inlet to outlet. There were numerous possible E. coli sources: the facility is situated next to horse trail, it houses wildlife in the pond, and has additional influent water that enters the facility below the monitored inlet. E. coli is not easily removed from stormwater and the designated use of the Cache la Poudre River through the City does not require low E. coli concentrations necessary for swimming. At the Udall WP, there was an increase of median E. coli concentrations from the inlet to each outlet, but not at a significant level. A prior investigation had suggested that each pond "grows" E. coli and results were presented where E. coli at the Pond 2 outlet were two orders of magnitude greater than the inlet (Knuth 2004). Results from this thesis showed no substantial growth of E. coli from the facility.

3.6.7 Effluent Probability Method

One of the best ways to visually display the results is with a probability plot because all EMC values are shown. When combined with formal statistical tests, strong conclusions can be made regarding the degree of treatment from BMPs. Numerous plots were created to compare the inlet and outlet concentrations of various pollutants. The exceedence probability was calculated based on the Cunnane formula and plotted against the corresponding EMC value. The 50% exceedence probability, by definition, is the median of the observations. When inlet and outlet lines did not overlap, there was a strong indication of significant treatment. Steeper lines signified greater variance in observed values.

Figure 32 through Figure 37 display the probability plots generated for the pollutants measured in this study. Some charts display lab results that were below the MDL and the points have been colored yellow. For D Cu, the MDL changed throughout the course of the sampling season so some values below the line labeled "MDL" were actually quantified. As a final caution, when two results were identical, a single point was plotted with the interpolated rank, which is common practice. For example, a single point is plotted under the MDL for the Pond 1 outlet for D Cu in Figure 33. There were actually 2 values reported below the MDL with ranks of 1 and 2 when ordered from smallest to largest. The results were combined into a single point for the plot at a rank of 1.5 and a value of half of the MDL (MDL = 5 ug/L so 2.5 ug/L was plotted).

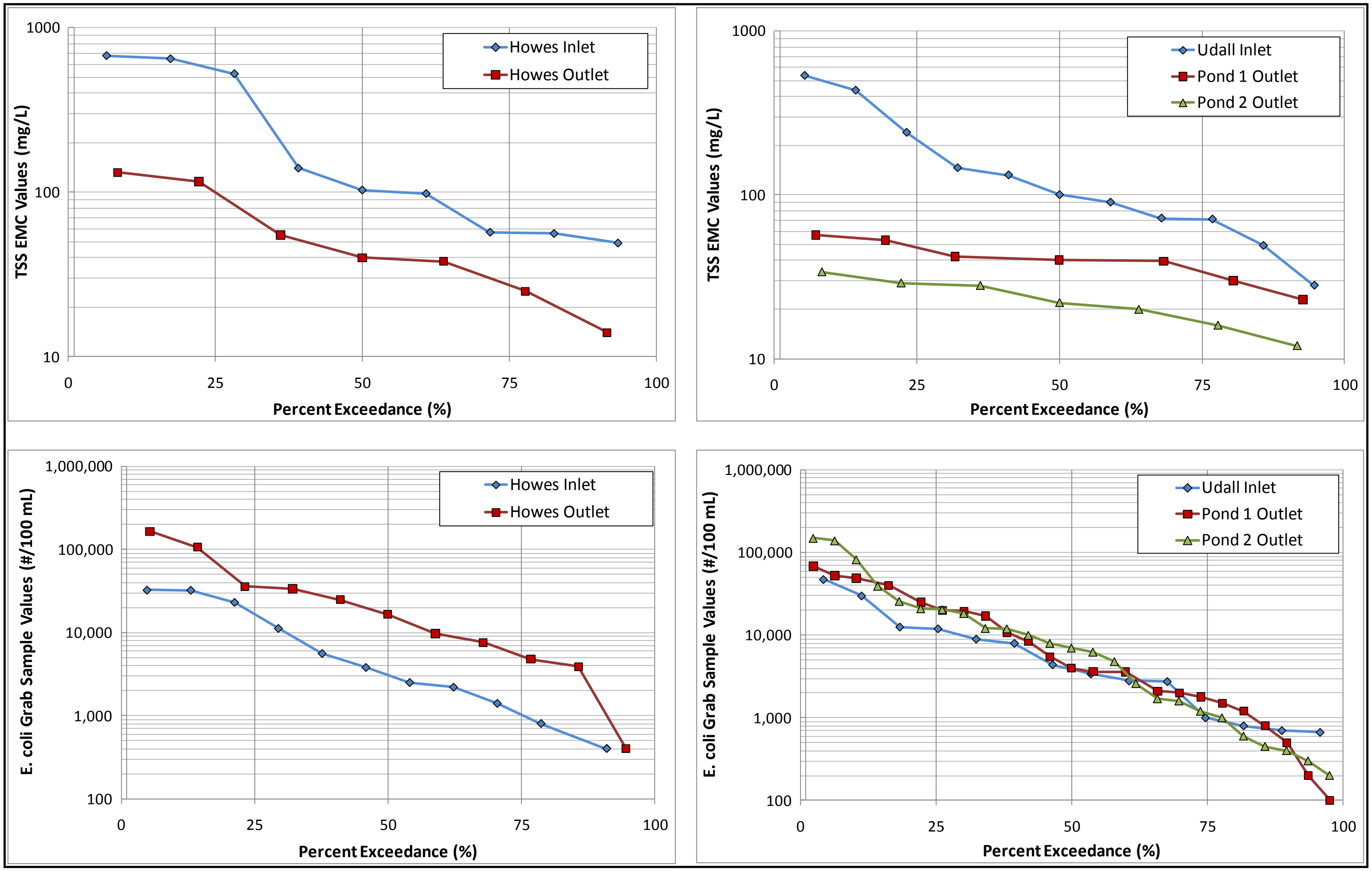


Figure 31. Probability Plots for TSS EMC Values and E. coli Grab Sample Values

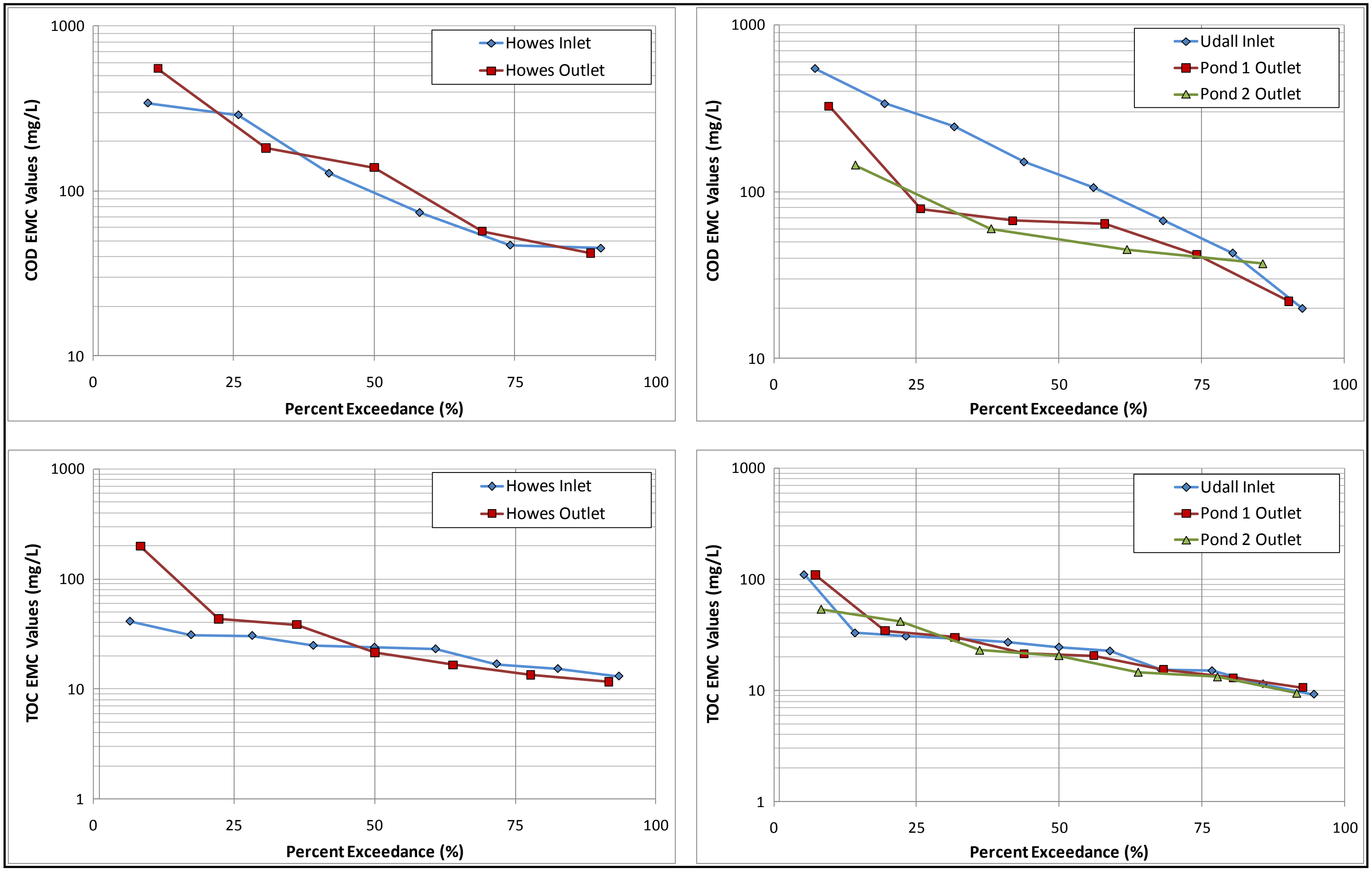


Figure 32. Probability Plots for COD and TOC EMC Values

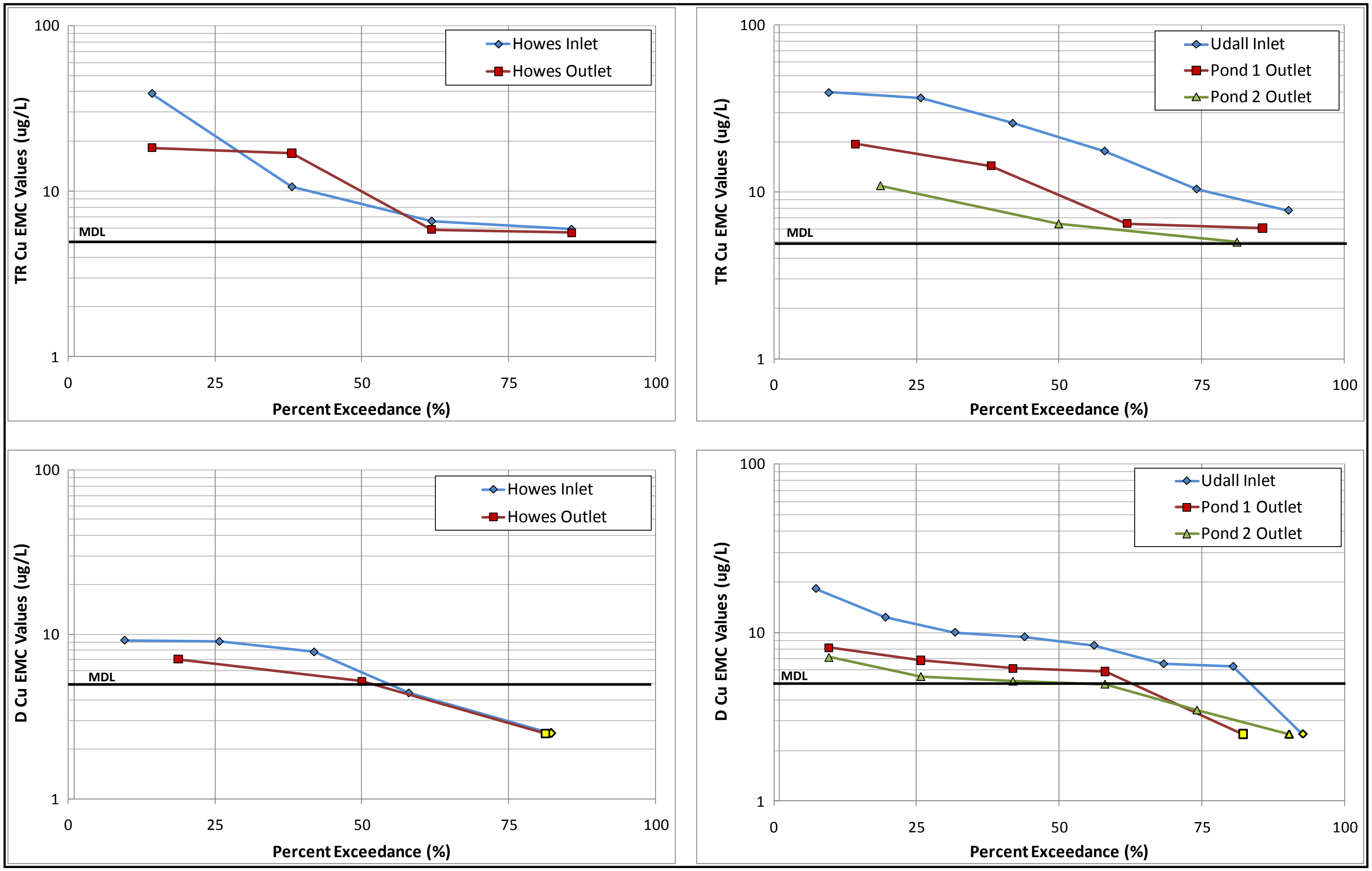


Figure 33. Probability Plots for TR Cu and D Cu EMC Values

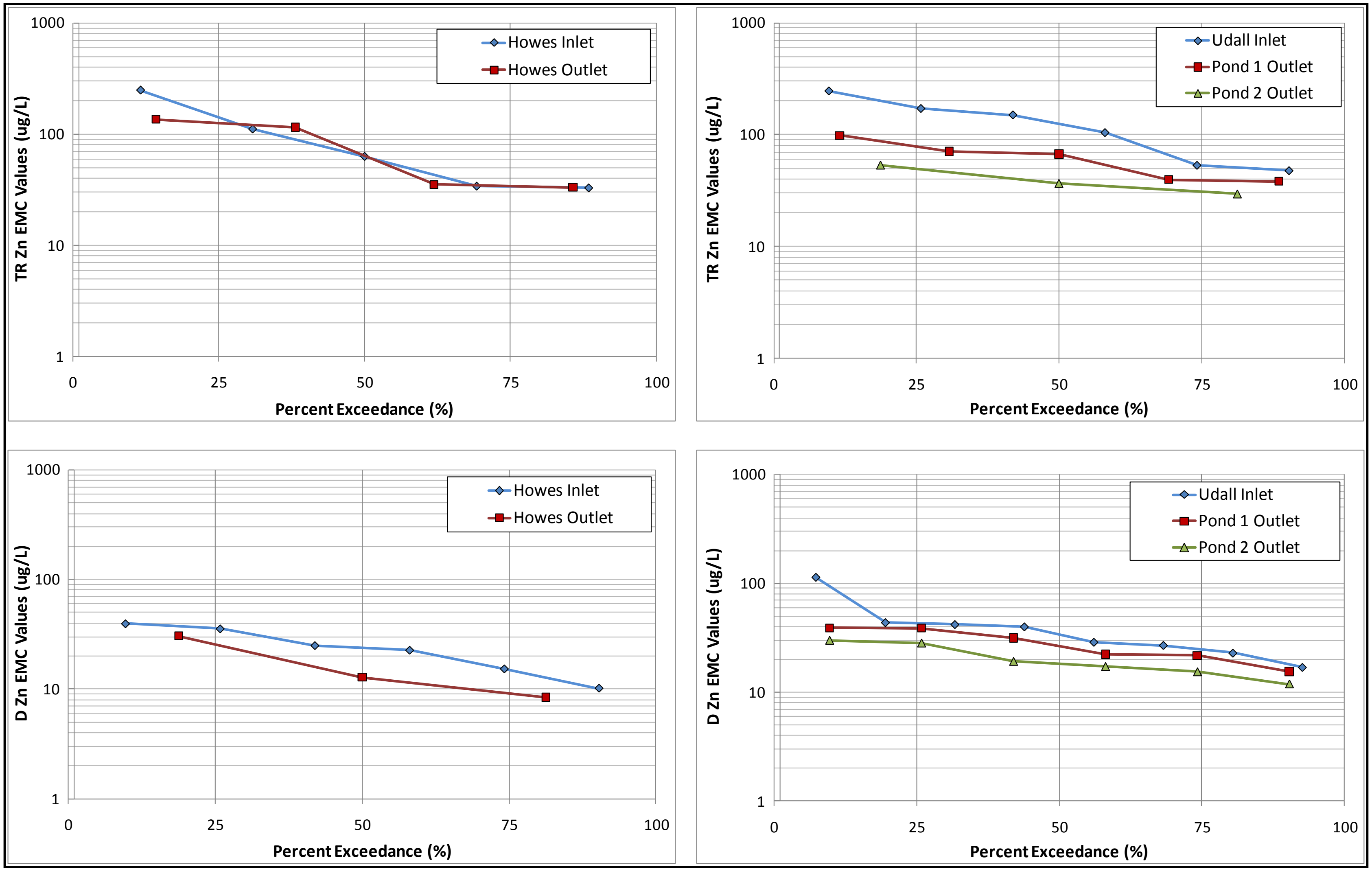


Figure 34. Probability Plots for TR Zn and D Zn EMC Values

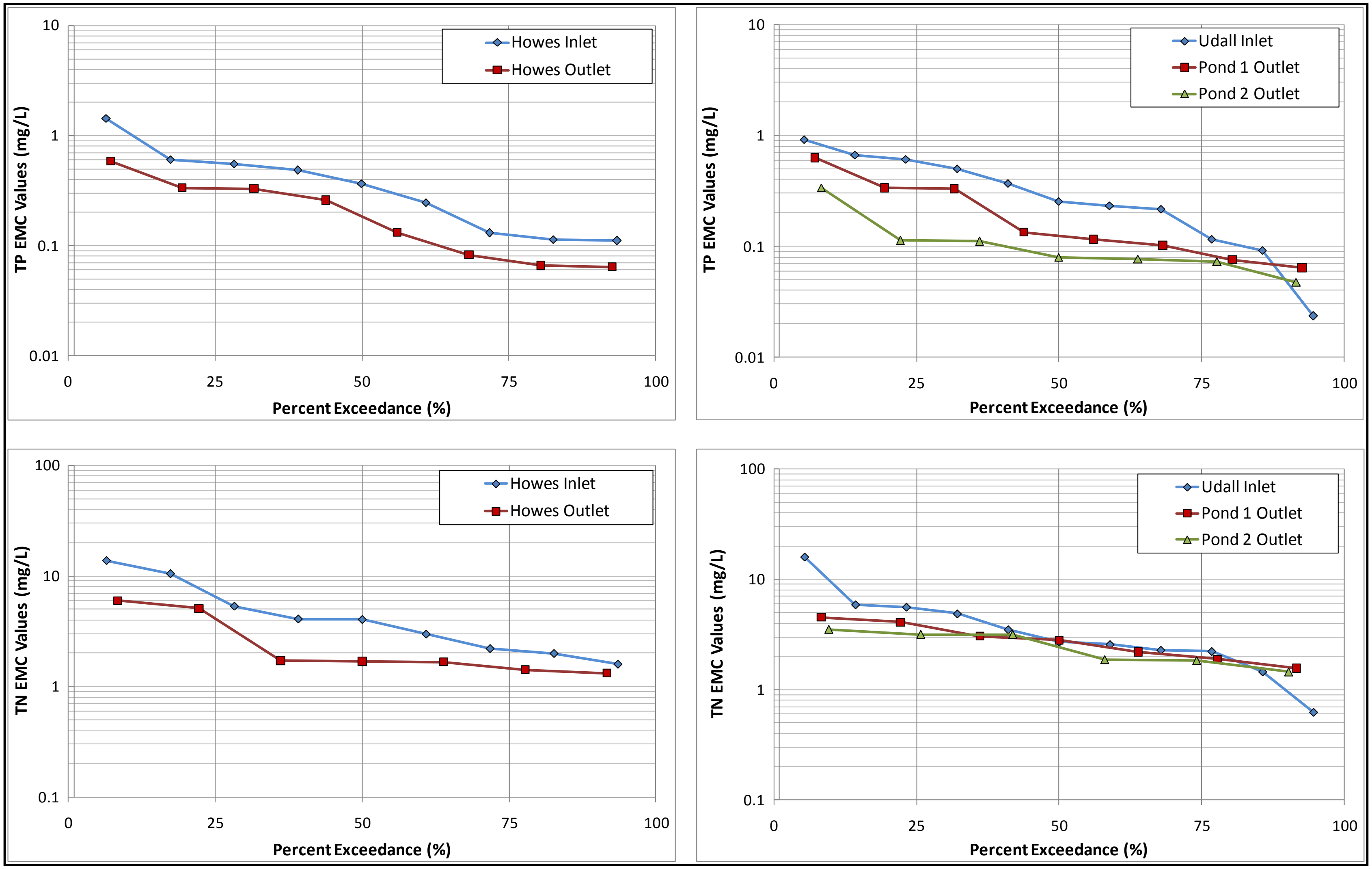


Figure 35. Probability Plots for TP and TN EMC Values

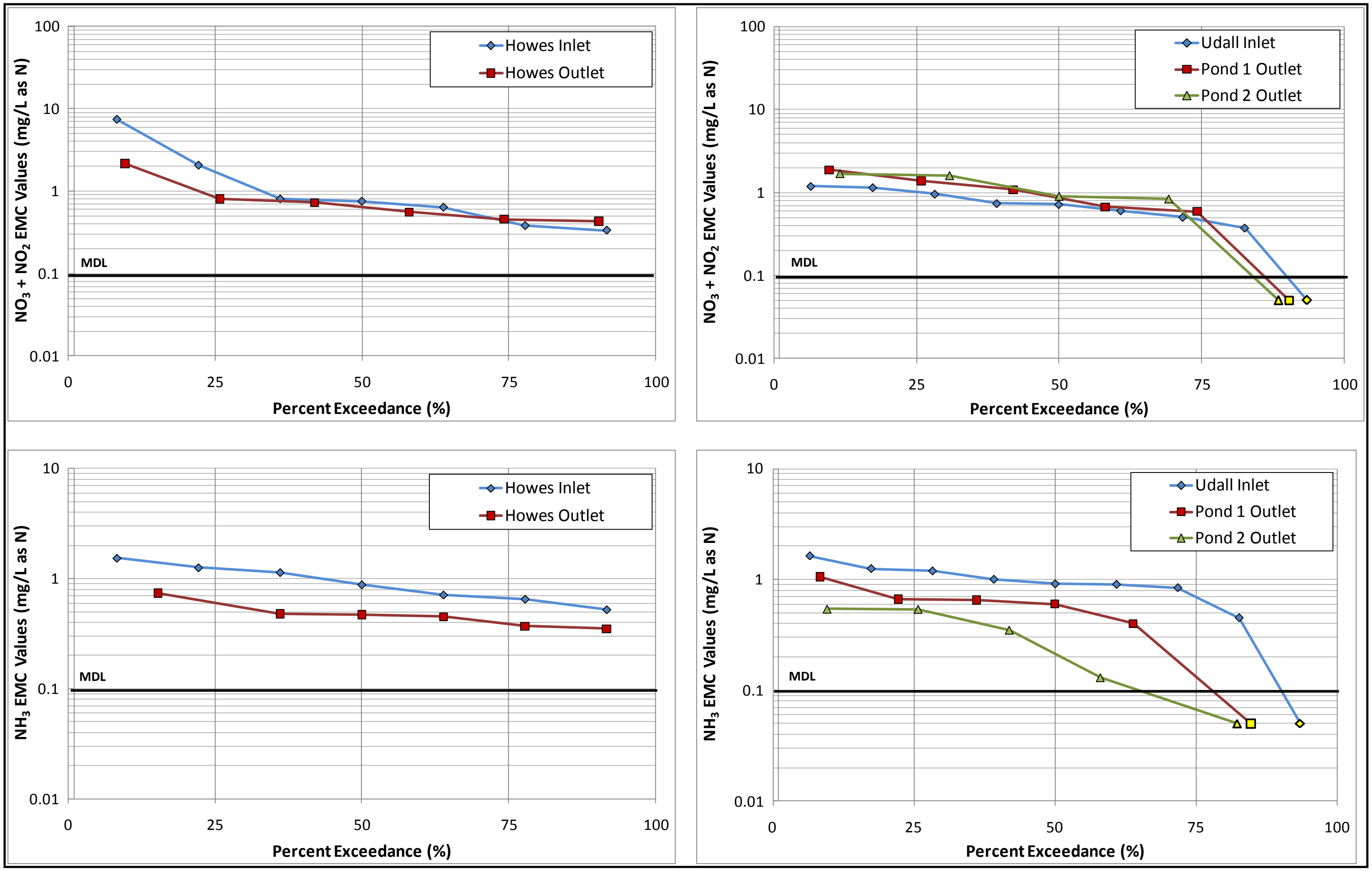


Figure 36. Probability Plots for NO_2+NO_3 and NH_3 EMC Values

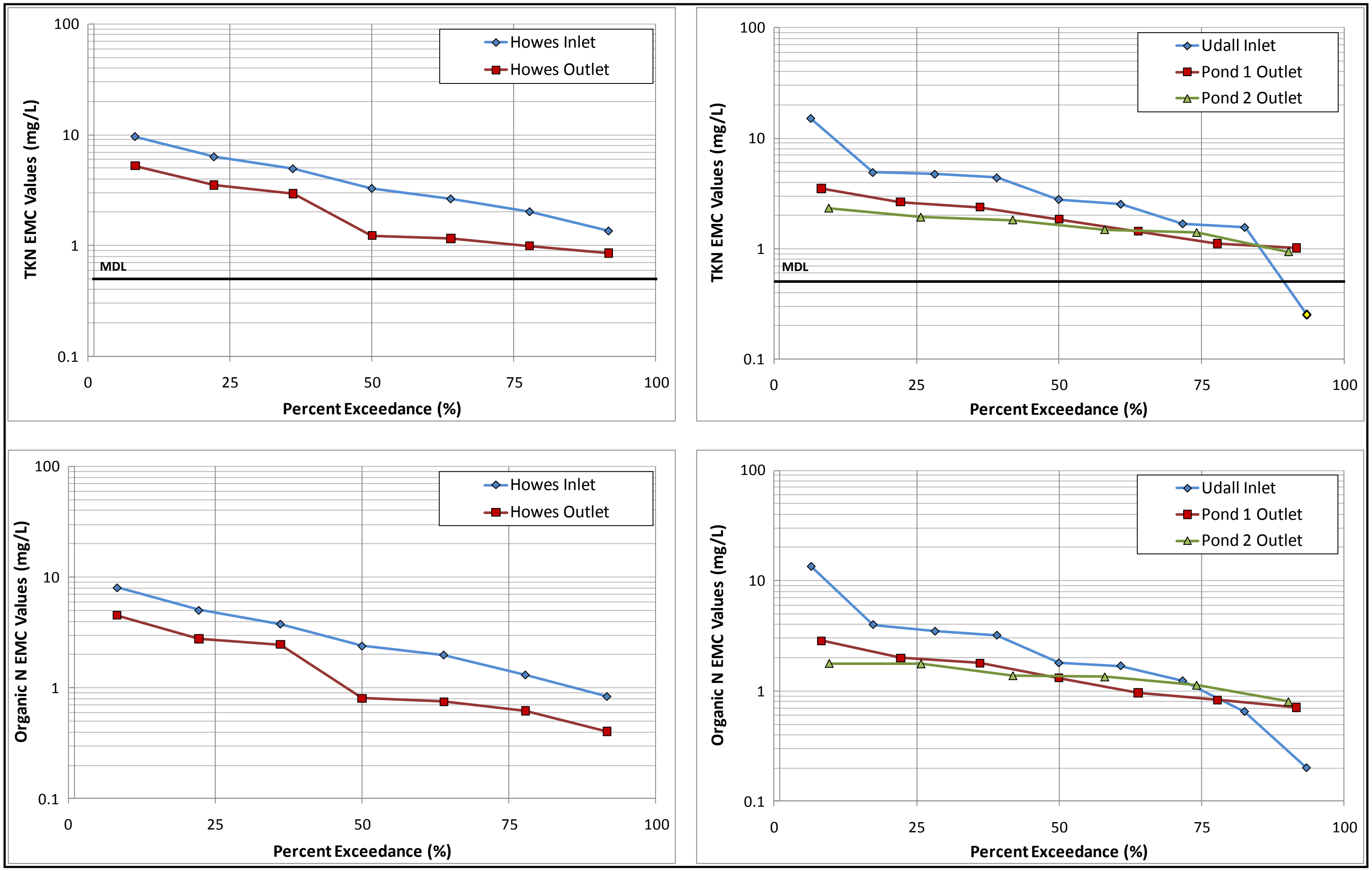


Figure 37. Probability Plots for TKN and Organic N EMC Values

Figure 31 shows the probability plots for both TSS and E. coli at the sampling locations. For TSS, the probability plots demonstrate significant removal at both the Howes St. BMP and the Udall WP. There is no overlap between the inlet line and the outlet line for the Howes St. BMP, which implies that there was an overall reduction in TSS. The slope of the outlet line is steep indicating a lot of variability in the observed EMC values. Contrastingly, the outlet concentrations at Pond 1 and Pond 2 at Udall are flatter when plotted. This implies that treatment that is more consistent at the Udall WP. The median effluent value at the Howes St. BMP was identical to the median effluent at the Pond 1 outlet, but the steeper slope at Howes St. indicates that the performance could be enhanced. E. coli EMCs at the outlet of Howes St. were significantly higher than at the inlet. Note that there was extreme variability in the number of E. coli colonies counted per 100 mL. At Udall, the lines intersect numerous times which indicates that E. coli was not significantly increased or decreased from the inlet to either pond outlet.

Figure 32 displays the probability plots for both COD and TOC at the sampling locations. COD was not significantly removed at the Howes St. BMP. The figure indicates that COD may have been reduced at the Udall WP, but the results are not very straightforward and some overlapping of lines occurred. The Ranksum results indicated that the median EMC at the Pond 2 outlet was less than the median inlet EMC concentration at a 71.7% significant level and the standard boxplot (Figure 18) suggested a significant reduction occurred between the inlet and Pond 2 outlet. TOC was not significantly reduced at either facility.

Figure 33 shows the probability plots for both TR Cu and D Cu at the sampling sites. The total number of data points at the Udall pond outlets and the Howes St. BMP were low so it is difficult to draw strong conclusion from the plots. There was an indication at the Udall WP that TR Cu was significantly reduced from inlet through each pond. There was not an indication of any TR Cu removal at the Howes St. BMP. Furthermore, a reduction in D Cu at the Udall WP seems likely, although there was not much benefit from Pond 2. At Howes St., there was no perceivable reduction in D Cu.

Figure 34 shows the probability plots for both TR Zn and D Zn at the sampling sites. Zinc was more abundant than copper at each site, but it is less toxic and thus is of less concern. The figure indicates that TR Zn was removed at a significant level at Udall through each pond, but no significant removal occurred at the Howes St. BMP. Furthermore, the figure shows that D Zn was removed by each pond at Udall. Interestingly, the figure also suggests a significant removal at the Howes St. BMP, but only three outlet values were available for the plot.

Figure 35 shows the probability plots for both TP and TN at each sampling location. Significant TP reduction was achieved at both facilities and the figure shows significant removal from the Pond 1 outlet to the Pond 2 outlet as well. Effluent TP from the Howes St. BMP looks very similar to the effluent TP at the outlet of Pond 1 at Udall. TN was significantly reduced at the Howes St. BMP but not at the Udall WP, according to the figure. Subsequent plots for individual nitrogen species suggest significant removal, but overall the TN was not reduced at the Udall WP.

Figure 36 shows the probability plots for NO_2 + NO_3 (nitrate) results and the NH_3 (ammonia) results for each sampling location. There was no significant reduction in nitrate at either facility. Ammonia was reduced significantly at the Howes St. BMP and at each pond at the Udall WP. The EMC curve at the Pond 1 outlet appears to be nearly identical to the effluent curve at the Howes St. BMP if the lowest plotted point is ignored.

Figure 37 shows the probability plots for TKN results and Organic N results for each sampling location. An outlier was recorded at the Udall inlet, which caused the lines to cross for TKN and for Organic N, which is a component of TKN. There was a significant reduction in TKN and Organic N at the Howes St. BMP. There was some indication of TKN and Organic N removal at the Udall ponds but not at a significant level, and no additional removal was provided by Pond 2.

3.7 Summary and Conclusions

The Udall WP and the Howes St. BMP improved stormwater runoff quality by removing pollutants. Overall, both facilities were effective at removing TSS, TP, TKN, and NH_3 from stormwater runoff. The Udall WP also removed dissolved and total recoverable zinc and copper, and possibly lowered the COD of effluent. At Udall, the brunt of the pollutant reduction took place in Pond 1, but the consistently cleaner effluent at Pond 2 was significant.

The Howes St. BMP lowered the median effluent of TSS to the same concentration as Pond 1 at Udall. However, much more variability existed in observed values. TSS is removed primarily through adsorption and sedimentation; both removal mechanisms are enhanced when longer HRTs are provided. The Howes St. BMP does not have a controlled outlet with a water quality structure and it did not provide an HRT that was as long as the Udall WP during events. Figure 38 shows the effluent TSS effluent values vs. HRT for the Howes St. and Udall BMPs.

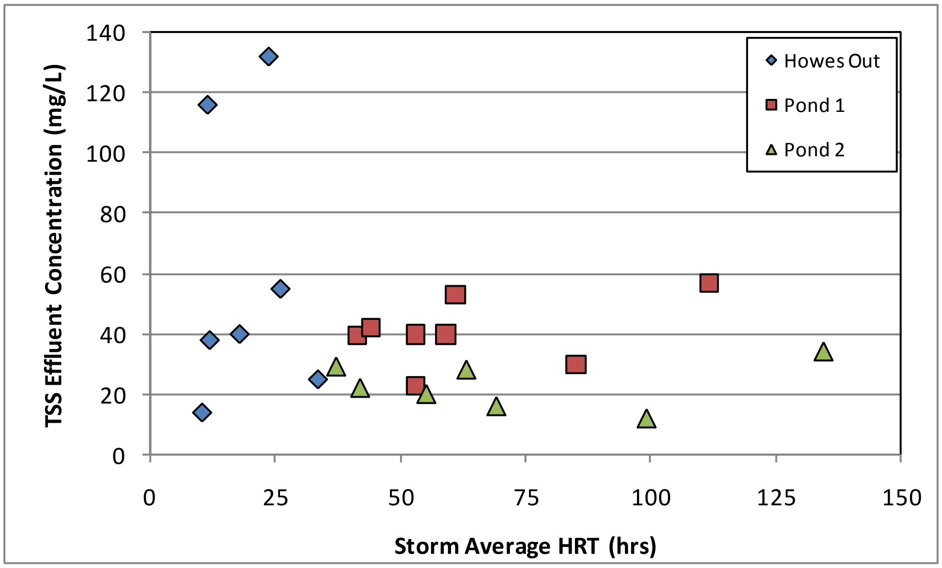


Figure 38. TSS Effluent Concentrations vs. HRT for the Howes St. and Udall BMPs

The Udall WP treated TSS to consistent levels because it provided long HRTs. Since incoming TSS concentrations varied depending on the event, there were times when the Howes St. BMP had low TSS in the effluent even when a low HRT was provided. The capacity for longer HRTs at a facility is dependent on the outlet configuration and the storage capacity of the facility. A large portion of stormwater runoff treatment occurs between runoff events for wet ponds. The Howes St. BMP did not restrict outlet flow during events and did not store large volumes of water between runoff events, which resulted in less consistent runoff treatment. The facility could be improved by adding a water quality outlet to provide longer HRTs for all storms and utilize more of the storage capacity of the site.

There was no evidence of dissolved or total metals removal at the Howes St. BMP. There was a lack of available data points, especially for total recoverable metals, but comparison with the Udall WP sampling results revealed that observable trends for reduction of TR Zn and TR Cu were seen with only three or four EMC values. Heavy metals will often adsorb to solids and be removed through sedimentation. D Cu and D Zn are not removed as easily through sedimentation so the significant removal at Udall may be attributed to adsorption and biological uptake. The longer HRTs at the Udall ponds provided more opportunity for biochemical interactions. Extending the HRT at the Howes St. BMP should allow the facility to reduce effluent TR Zn and TR Cu concentrations and may even reduce the dissolved metals concentrations.

There was strong evidence that the Howes St. BMP removed significant quantities of TP and multiple nitrogen species. A significant portion of TP will adsorb to TSS and be removed through sedimentation. The remaining TP can be removed through biological uptake from plants. The Udall WP removed essentially all of the available TP that would be expected and the Howes St. BMP removed 73% of the available TP according to Table 15. Nitrogen is removed primarily through biological uptake instead of sedimentation like TSS, TP, or heavy metals. At the Howes St. BMP, water flowed through a wetland channel before entering the pond, and the overall facility was fairly effective at removing nitrogen. At the Udall WP, there was less removal of TN, but certain species of nitrogen were removed or converted to less toxic forms. NH_3 was reduced significantly from inlet through Pond 1, and then reduced further before exiting Pond 2. TKN was reduced from the inlet to Pond 1, but not through Pond 2. One possible explanation for the removal of NH_3 with unchanging TKN concentrations was algal growth in the ponds that was observed over the course of sampling. NH_3 may have been reduced through photosynthesis from the algae. TKN was not reduced because it is a measure of NH_3 + Organic N, and Organic N increases from plant die-off. In short, the Udall WP may have removed NH_3 by converting it to other forms of nitrogen like

Organic N. Neither facility removed appreciable amounts of nitrate. Figure 39 shows the extensive algal blooms that occur during the late summer months at the Udall WP, when precipitation events are scarce.

Figure 39. Algal Bloom at the Udall WP (August 2011)

Statistically, COD was not removed at an appreciable amount at either facility according to the Ranksum results. However, the standard boxplot and probability plot both implied that COD was removed from the inlet to Pond 1 at Udall. TOC was not reduced at either facility. Table 16 shows the ratio of median EMC COD:TOC at each sampling location. At the Howes St. BMP, the ratio increased slightly from inlet to outlet, which may indicate that a shift occurred away from organic oxygen demand toward chemical demand. At Udall, there was a decrease in ratio, which may indicate that there was a shift away from chemical demand toward organic demand.

Table 16. Median COD:TOC Ratio at Each Sampling Location

	TOC (mg/L)	COD (mg/L)	COD:TOC Ratio
Howes St. BMP Inlet	101	23.8	4.2
Howes St. BMP Outlet	139	21.4	6.5
Udall Inlet	129	24.5	5.2
Udall Pond 1	65.5	21.0	3.1
Udall Pond 2	52.5	20.6	2.5

The major benefit of Pond 2 at Udall was further reduction in TSS, TP, and heavy metals. However, Pond 1 lowered influent pollutant concentrations more efficiently than Pond 2 did and the median TP value was actually lower than the corresponding irreducible minimum concentration. If Pond 2 had not been constructed the facility would still be successful in providing water quality enhancement. The overall facility was costly to construct and would have performed adequately without a second pond. Comparatively, the Howes St. BMP infrastructure was a much better value, despite the fact that it was not built to store the required WQCV. If the outlet were controlled so that it could provide more consistent effluent quality, it would likely be regarded as the better facility overall.

Table 2 in the Literature Review section shows median effluent EMCs for numerous BMP types from the BMP Database. The median effluent EMC at Pond 1 and Pond 2 of the Udall WP was higher in every pollutant category except for TP (and ignoring lead) when compared to other WPs. The Howes St. BMP did not perform as well as a WP or constructed wetland when compared to other BMPs from the BMP Database. Each watershed for the Fort Collins sampling study was large and urbanized, which is not true for all of the facilities analyzed in the BMP Database. This analysis primarily focused on quantifying pollutant removal from inlet to outlet because there is great variability in influent concentrations of pollutants in different hydrological regions and different watersheds. If anything, these findings highlight the fact that excellent pollutant removal can be achieved at a site without matching results from another BMP and illustrate the importance of setting regional goals for water quality enhancement.

3.8 Recommendations for Further Research

There are several avenues of further research that could be conducted to study how the extent pollutant removal. Some ideas for future research include:

- Chemical modeling software could be used with existing storm date to determine/confirm the speciation of metals based on the lab results. Major anions and cations were quantified along with total metal results, which would enable a more detailed investigation to determine the concentrations of toxic concentrations.

- Updated analysis could be conducted using new stormwater data. At the time this thesis was written, there were approximately five more storms that had been sampled, but results had not been obtained. More data points would enable greater certainty in conclusions because there is extreme variability in stormwater pollutant concentrations.

- Changes could be made to the Howes St. BMP and additional stormwater samples could be collected. It is recommended that the Howes St. BMP have a water quality outlet installed to provide a longer HRT and more consistent TSS removal. Additional stormwater sampling at the facility after modifications would provide valuable information to determine if longer HRTs during storms would provide enough treatment to be worthwhile, assuming that the permanent pool of stored water remained unchanged.

- Modifications could be made at the Udall WP since there was strong evidence that the HRT through Pond 1 was sufficient for pollutant removal. When samples were collected, there was frequent clogging of the water quality orifices. The orifices could be widened to reduce the potential for clogging which would reduce the overall HRT the facility could provide during an event. Collecting additional stormwater samples after modifications could be useful to verify that negative ramifications would not result from reducing the HRT.

4.0 BMP HYDRAULIC RETENTION TIME AND WATER QUALITY

4.1 Introduction

An examination of several existing stormwater studies was conducted to determine the affect of BMP hydraulic retention time (HRT) on effluent water quality. Results from individual storm events were assessed using data provided in the International Stormwater BMP Database (BMP Database). Results from the Fort Collins sampling program were also included.

The HRT that a BMP can provide during a storm governs the potential for pollutant removal processes like sedimentation and adsorption. The average storm HRT can be defined using the total storm runoff volume that filled the BMP and the average storm discharge from the outlet structure using Equation 16. The HRT is directly related to the overall storage size of the BMP because attenuating runoff over a longer period of time requires a larger facility.

$$Average\ Hydraulic\ Retention\ Time = \frac{Storm\ Runoff\ Volume}{Average\ Storm\ Discharge}$$

Equation 16

The HRT was estimated for each storm event at individual BMPs and compared to the corresponding effluent total suspended solids (TSS) concentration, total recoverable zinc (TR Zn) concentration, total recoverable copper (TR Cu) concentration, and total phosphorous (TP) concentration, respectively. Statistical hypothesis testing of the data was performed to determine if there was a difference in effluent water quality when longer HRTs were provided.

4.2 Collecting BMP Study Data

Storm data was collected from two primary sources. The Fort Collins Stormwater Sampling project provided storm data for the Howes St. BMP and the Udall WP (data from both Pond 1 and Pond 2 was used) . Sampling results from other studies were collected from the BMP Database and included sixteen other WP and EDB sites.

The BMP Database is a collection of stormwater studies for various types of BMPs. The Master BMP Database v11-02-10 was used in this investigation and was freely available online. Studies are user-submitted and contain a broad range of information that can include watershed characteristics, physical specifications of the study BMP, water quality results for individual storms for various constituents, precipitation totals for individual storms, flowrates, the total volume of runoff for individual storms, and numerous other fields. Each study does not necessarily contain all of the information previously listed.

Storm information was collected for EDBs and WPs by querying the water quality data and storm flow data for each BMP. Some studies did not contain water quality information or flow information and were not included in this analysis. Furthermore, studies that only included grab sample water quality data were omitted from analysis. Studies were omitted from analysis if they did not contain reliable information that could be used to estimate the average storm HRT. Table 17 lists the BMPs used in this investigation from the BMP database and the two sites that were part of the Fort Collins sampling program. The table also lists the method that was used to estimate the average storm HRT, which is explained in greater detail in the next section. Individual storm water quality data for TSS, TP, TR Zn, and TR Cu was collected for each BMP and matched to the storm flow and precipitation data.

Table 17. BMPs Included in Investigation

BMPs Included in Analysis	BMP Type	Method to Estimate HRT
15/78	EDB	Fraction Full
5/56	EDB	Fraction Full
605/91 edb	EDB	Fraction Full
Lex Hills Pond	EDB	Fraction Full
Manchester	EDB	Fraction Full
5/605 edb	EDB	Fraction Full
Greenville Pond	EDB	Fraction Full
Shop Creek Pond (90-94)	WP	Fraction Full
Shop Creek Pond (95-97)	WP	Fraction Full
La Costa WB	WP	Fraction Full
BMP 12	WP	Fraction Full
BMP 13	WP	Fraction Full
BMP37	WP	Fraction Full
Shawnee Ridge Retention Pond	WP	Fraction Full
Madison, WI, Wet Pond Monroe St.	WP	V-notch Model
Beltway 8 - Surge Basin	WP	Peak Flow Approximation
Central Park Wet Pond	WP	Outlet Flow Duration
Howes St. Pond	WP	Outlet Flow Duration
Udall Natural Area	WP	Outlet Flow Duration

4.3 Hydraulic Retention Time Estimation

Using the best available data, the HRT was estimated for each storm event. A method was developed to reasonably estimate the storm HRT based on the BMP brimfull-drawdown time and the fraction that the BMP filled during a storm. The method, referred to as the "Fraction Full Method," used a lognormal approximation to calculate a storm HRT based on the total storm volume and BMP surcharge volume. Studies that lacked the necessary information for the Fraction Full Method were only included if another method existed whereby storm HRTs could be reasonably estimated. These other methods included development of a unique model for a BMP with V-notch orifices to estimate the HRT, using the effluent start and stop timestamps from a storm to estimate the HRT, and using the peak flowrate from a storm to estimate the HRT.

4.3.1 Development of the Fraction Full Method

The Fraction Full Method was developed to estimate the average HRT that a BMP provided during a storm based on the BMP surcharge volume, the total runoff volume produced by a storm, and the design brimfull drawdown time. The method was developed to account for the variation in magnitudes of the average effluent discharge that occurs from storm to storm at a BMP's outlet.

Several BMPs were hydraulically modeled in order to determine how the average HRT was affected by the total volume of a storm. The U.S. EPA Stormwater Management Model v5.0 (SWMM) was used to develop an HRT curve for the time required to completely drain each BMP. A BMP was considered empty when less than 1% of the total surcharge volume remained in the BMP. SWMM models were only created for BMPs when supplemental information about the physical characteristics of the site was included in the BMP Database. These input parameters included the maximum depth of the BMP, the top surface area when the BMP was filled to the brim, and the bottom surface area when the BMP was empty. The brimfull drawdown time specified in the BMP Database is the time required for the BMP surcharge volume (water quality volume) to empty if completely filled.

A spreadsheet program was used in conjunction with SWMM to generate a rating curve for each BMP that would cause the modeled drawdown time in SWMM to match the brimfull drawdown time specified in the BMP Database. Outlet structures were simulated using the UDFCD spreadsheet program UD_Detention (v2.2). The program, freely available on the UDFCD website, is a Microsoft Excel based calculator that computes the rating curve for a BMP based on an orifice plate that has holes spaced four inches apart vertically, and multiple orifices can be specified for each row. Each BMP's total surcharge volume and height were required to generate an initial rating curve. Then, SWMM was used to hydraulically route flow through an outlet structure with the rating curve developed in UD_Detention. Each BMP was assumed to have a trapezoidal storage pattern that varied by depth according to the specified bottom and top surface areas. The BMP was initially full at the beginning of a simulation and water exited the BMP at the outlet according to the generated rating curve from UD_Detention. If the drawdown time from SWMM did not match the design brimfull drawdown time, the orifice holes were altered in UD_Detention and a new rating curve was generated. This process was iteratively repeated until the rating curve from UD_Detention produced results in SWMM that matched the given brimfull drawdown time.

Table 18 displays the physical characteristics of the BMPs that were modeled using SWMM.

Table 18. Physical Characteristics of BMPs for the Fraction Full Method

BMP Type	BMP Name	Bottom Surface Area	Top Surface Area	BMP Surcharge Volume	Calculated Depth	Brimfull Drawdown Time	Half-Full Drawdown Time
		ft^2	ft^2	ft^3	ft	hrs	hrs
Extended Detention Basins (EDBs)	605/91	608	1,229	2,457	2.7	72	-
	Manchester	2,670	3,270	8,927	3.0	72	-
	5/605 EDB	5,261	6,439	12,878	2.2	72	-
	5/56	6,700	8,260	13,795	1.8	72	-
	15/78	8,760	10,515	39,642	4.1	72	-
	Greenville	37,600	37,600	338,026	9.0	74.75	-
Wet Ponds (WPs)	La Costa WB	11,900	12,000	9,150	0.8	24	-
	BMP 13	7,406	15,070	30,441	2.7	42.5	30
	BMP 12	1,742	24,757	127,627	9.6	33	28
	BMP 37	22,603	30,139	338,880	12.9	21.3	18.45
	Shawnee Ridge	96,100	199,508	1,347,644	9.1	13	12.5
	Shop Creek Pond	60,984	97,575	399,447	5.0	30	21

Deciding the threshold for when a BMP should be considered "empty" was slightly subjective for the SWMM models. Water at low stages in the pond did not produce enough head to generate significant discharge rates. A perpetual water level existed in the modeled BMP indefinitely because no infiltration or evaporation was allowed. The volume of stored water that indefinitely remained in a BMP was very small, but a threshold needed to be established to govern when a BMP was considered empty. In order to determine a lower threshold, the UD_Detention spreadsheet was used in conjunction with SWMM for a theoretical BMP with a brimfull drawdown time of 40 hours. The UD_Detention spreadsheet automatically calculates the required orifice sizes for a BMP that is designed to drain in 40 hours. Using SWMM, a theoretical pond designed to drain in 40 hours was constructed with the generated rating curve from

UD_Detention. After 40 hours, the pond still had a small residual volume that was less than 1% of the total storage volume. The BMPs were considered "empty" when they had reached a total volume of 1% or less under the assumption that their outlets would be designed to empty the stored runoff in a similar fashion.

Analysis of the developed HRT curve for each BMP was performed by plotting the amount of storage in each structure (BMP Fraction Full) against the time required to drain the BMP. Figure 40 shows a typical HRT curve that resulted from the analysis for the 605/91 EDB which had a brimfull drawdown time of 72 hours. From the curve, it is clear that the discharge rate varied depending on how full the BMP was during the drawdown period.

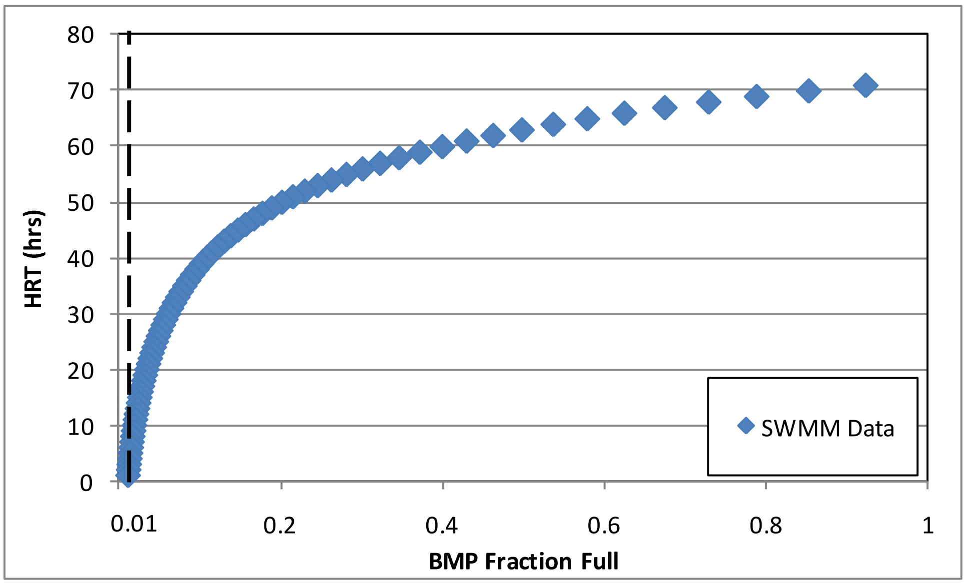


Figure 40. Modeled SWMM HRT Curve for 605/91 EDB

The relationship between HRT and the BMP Fraction Full was approximately linear when the natural log of the BMP Fraction Full was taken. Equation 17 shows how the HRT was calculated as a function of the BMP Fraction Full.

$$HRT = a * ln(BMP\ Fraction\ Full) + b$$

Equation 17

Where: HRT = Hydraulic Retention Time (hrs)

BMP Fraction Full = Volumetric storage fraction of the BMP water quality surcharge area (less than 1 but greater than 0.01)

a = Slope coefficient of the best fit line when HRT is plotted against ln(BMP Fraction Full)

b = Specified brimfull drawdown time in the BMP Database

Note that the natural log of a fraction less than one will always result in a negative number. Therefore, the slope coefficient (a) multiplied by BMP Fraction Full represents how much less time is required for BMP to drain than the brimfull drawdown time when the BMP stores less than the BMP surcharge volume.

Figure 41 shows the validity of assuming a linear relationship for HRT vs. ln (BMP Fraction Full) for the 605/91 EDB. The figure shows that an excellent linear approximation resulted from the log transformation.

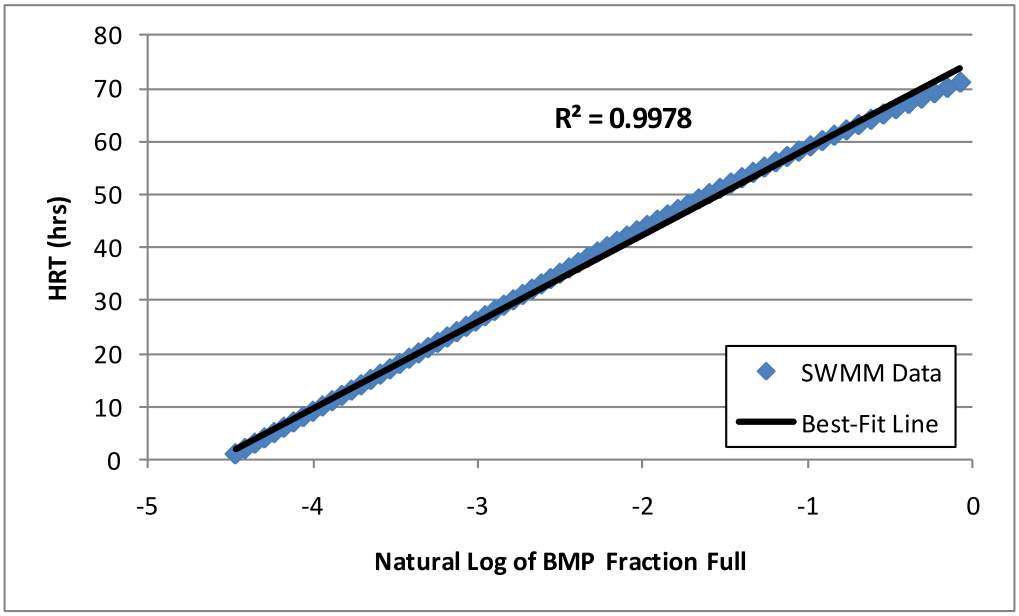


Figure 41. Log-transformed HRT Curve for the 605/91 EDB

The lower threshold used to define when a BMP was considered empty is related to the slope coefficient (a) of Equation 17. In fact, Equation 18 shows how the slope coefficient can be calculated directly when the threshold (defined here as 1% of the BMP surcharge volume) and brimfull drawdown time (b) are known.

$$HRT = a * ln(BMP\ Fraction\ Full) + b$$

$$0 = a * ln(0.01) + b$$

$$a = \frac{-b}{ln(.01)}$$

$$a = \frac{-b}{-4.605}$$

Equation 18

A drawback of this method is the dependency of the slope coefficient on the lower threshold when a BMP was considered empty. Since the assumed threshold appears in the denominator of Equation 18, a smaller threshold value will result in a larger slope coefficient. If the threshold was taken to be 5% of the water quality volume, the slope coefficient is over 1.5 times higher. Using a higher threshold changes the entire HRT curve and implies that the BMP drains more quickly.

However, a major benefit of this method is that an HRT curve for any BMP can be developed by assuming a lower threshold if the brimfull drawdown time is known. The lognormal approximation is a simple way to estimate the HRT that a BMP can provide and is more accurate than assuming a linear drawdown rate (which assumes that the average discharge is constant at a BMP outlet). Anything more complicated would require additional assumptions about the drainage pattern of BMP outlet. Using Equation 17 and Equation 18 together, the HRT curve for a BMP can be estimated knowing only the brimfull drawdown time (b). Equation 19 shows the lognormal approximation of the HRT curve for the 605/91 EDB, where b equals 72 hours, as an example. Note that the lower threshold was assumed to be 1% of the total surcharge volume.

$$a = \frac{-72}{-4.605} = 15.63$$

$$HRT = 15.63 * ln(BMP\ Fraction\ Full) + 72$$

Equation 19

Figure 42 shows the SWMM HRT curve vs. BMP fraction full compared to the HRT curve using the Equation 19 for the 605/91 EDB. The figure clearly shows that there is excellent correlation between the developed equation and the SWMM results for the 605/91 EDB.

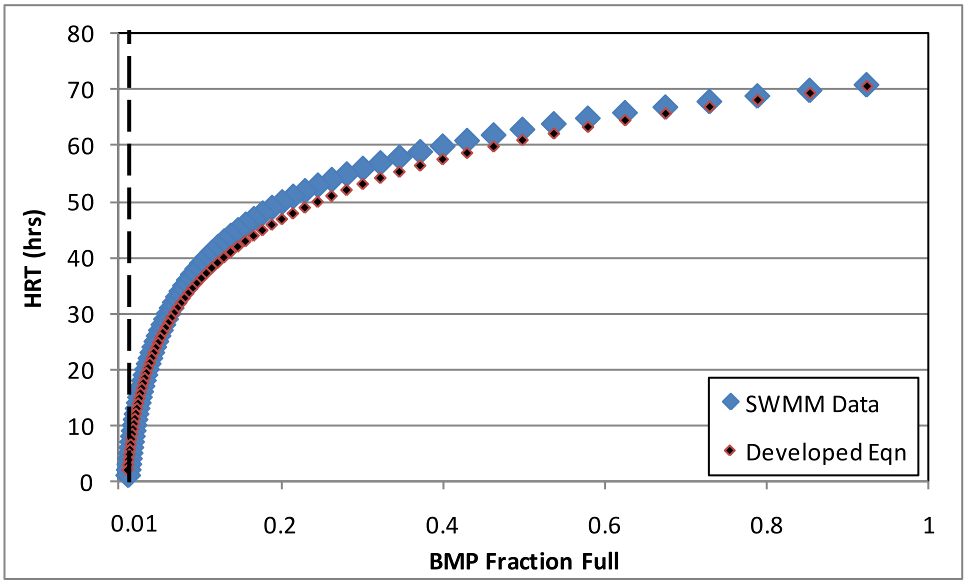


Figure 42. Comparison of Modeled Results and Developed Equation for 605/91 EDB

Some discrepancy existed between the predicted HRT using the lognormal approximation and the modeled SWMM results for other BMPs. However, the lognormal approximation yielded predicted HRT curves that were reasonably close to the modeled results using SWMM. In general, discrepancies between the SWMM results and predicated HRT values were less than five hours at any point along the HRT curve.

Four of the BMPs included in this investigation specified a half-full drawdown time in addition to the brimfull drawdown time, which allowed the slope coefficient to be calculated without assuming a lower threshold. Equation 20 shows how Equation 17 can be rearranged to calculate the slope coefficient when the half-full drawdown time is also known.

$$a = \frac{HRT_{1/2} - b}{ln(0.5)}$$

Equation 20

Where: a = Slope coefficient of the best fit line when HRT is plotted against ln(BMP Fraction Full)

b = Specified brimfull drawdown time in the BMP Database

$HRT_{1/2}$ = Specified half-full drawdown time in the BMP Database

When the slope coefficient was calculated using Equation 20, a unique lower threshold was also calculated based on the half-full drawdown time. Equation 21 presents the formula used to calculate the assumed lower threshold if the slope coefficient was found using brimfull and half-full drawdown times.

$$HRT_{1/2} = a * ln(T_{lower}) + b$$

$$ln(T_{lower}) = \frac{HRT_{1/2} - b}{a}$$

$$T_{lower} = exp^{\left(\frac{HRT_{1/2} - b}{a}\right)}$$

Equation 21

Where: T_{lower} = Lower threshold where BMP should be considered "empty"

a = Slope coefficient of the best fit line when HRT is plotted against ln(BMP Fraction Full)

b = Specified brimfull drawdown time in the BMP Database

$HRT_{1/2}$ = Specified half-full drawdown time in the BMP Database

Using the information supplied in the BMP Database, a formulation of Equation 17 was developed for 13 different BMPs. Table 19 shows the calculated parameters and range where the developed equation is valid for each BMP based on the lower threshold.

Table 19. Equation Parameters for BMPs Using the Fraction Full Method

BMP Type	BMP Name	Brimfull Drawdown Time	Half-Full Drawdown Time	a	b	Range where Equation is Valid
		hrs	hrs			(BMP Fraction Full)
Extended Detention Basins (EDBs)	605/91	72	-	15.6	72	0.01 to 1.00
	Manchester	72	-	15.6	72	0.01 to 1.00
	Lex Hills Pond	24	-	5.2	24	0.01 to 1.00
	5/605 EDB	72	-	15.6	72	0.01 to 1.00
	5/56	72	-	15.6	72	0.01 to 1.00
	15/78	72	-	15.6	72	0.01 to 1.00
	Greenville	74.75	-	16.2	74.75	0.01 to 1.00
Wet Ponds (WPs)	La Costa WB	24	-	5.2	24	0.01 to 1.00
	BMP 13	42.5	30	18.0	42.5	0.09 to 1.00
	BMP 12	33	28	7.2	33	0.01 to 1.00
	BMP 37	21.3	18.45	4.1	21.3	0.01 to 1.00
	Shawnee Ridge	13	12.5	0.7	13	0.01 to 1.00
	Shop Creek Pond	30	21	13.0	30	0.10 to 1.00

4.3.2 Application of the Fraction Full Method

The Fraction Full Method was used to estimate individual storm HRTs for 13 BMPs included in the investigation. In order to use the Fraction Full Method, an estimate was made regarding how full a BMP became during each storm. This was accomplished using the total storm volume for an event and dividing this value by the BMP surcharge volume. It was assumed that each BMP would fill at a much faster rate than it could drain during the course of a storm because of the outlet configuration. The time required to fill a BMP and the volume of water that exited a BMP before it reached maximum storage for an event was considered negligible. Equation 22 shows the relationship between the total storm volume and the fraction that a BMP filled during an event.

$$BMP\ Fraction\ Full = \frac{Total\ Storm\ Volume}{BMP\ Surcharge\ Volume}$$

Equation 22

Most BMP studies specified an influent total storm volume, which was used as the total storm volume for HRT computation. If multiple inlets existed in the BMP but a single outlet existed, the effluent total storm volume was used for storm HRT computation (occurred frequently with WPs). Finally, if the influent storm volume was not specified in the BMP Database, the effluent storm total was used for storm HRT computation.

Storms that were not large enough to generate a volume equal to the lower threshold were omitted from analysis. The lower threshold was usually set to 1% of the BMP surcharge volume, but BMP studies that provided a half-full drawdown time required the calculation of a unique lower threshold as shown in Equation 21. Table 19 displays the lower threshold for each BMP.

The Fraction Full method was based on a lognormal approximation which was valid if the total storm volume was less than or equal to the BMP surcharge volume. However, storms that were larger than 100% of the surcharge volume were not automatically eliminated from the dataset. It is possible that larger storm volumes resulted from low-intensity long-duration events that kept a BMP full for a longer time without causing an overflow above the water quality orifices. Runoff from these larger storms would exit the BMP at an average discharge rate that was assumed to be equal to the average discharge rate if the BMP drained from brimfull capacity.

However, very large storms were not included in the analysis. BMPs are typically designed with overflow locations to safely convey runoff from larger storms (U.S. EPA 1999, U.S. EPA 2006). Events with a total storm volume greater than 150% of the BMP surcharge volume were eliminated from analysis. These events were removed because it was impossible to verify whether bypassed flow above the BMP surcharge volume would proceed through the BMP outlet and be included in water quality sampling results, or if the bypassed flow exited the BMP from a separate overflow weir and was not sampled. Based on experience gained during the Fort Collins stormwater sampling project, it seemed reasonable to assume that if the total storm volume was 150% or less of the BMP surcharge volume, there would be minimal or no overflow. Storm events larger than 150% of the available surcharge volume would likely result in overflow conditions. Removing storms greater than 150% threshold eliminated approximately 33 storms from the total dataset, or 13% of the available storms. Including these data points would have biased the results toward storms that exceeded the design intentions for water quality enhancement.

When storm events produced volumes that were larger than the BMP surcharge volume but less than 150% of the BMP surcharge volume, the average drawdown discharge rate was used to estimate the storm HRT. Equation 23 shows how the average drawdown discharge is calculated using the brimfull drawdown time and the BMP surcharge volume.

$$Average\ Discharge\ Rate = \frac{BMP\ Surcharge\ Volume}{Brimfull\ Drawdown\ Time}$$

Equation 23

4.3.3 Assumptions of the Fraction Full Method

The Fraction Full Method was used to estimate the HRT for the majority of BMPs in the investigation. Several assumptions were made when developing the method and they are summarized below.

- It was assumed that all EDBs and WPs were constructed with equally spaced rows of orifices to control flow at the outlet unless otherwise specified. Riser pipes are also commonly used to regulate the flow at a BMP outlet and are hydraulically similar to evenly spaced orifice rows. The BMP Database did not specify outlet water quality structures for the BMPs included in this study.
- It was assumed that different specifications for orifice row spacing would not be a significant source of error when HRT curves were generated. When the outlet rating curves were developed, the centerlines of each orifice row were spaced four inches apart vertically according to design specifications typical for BMPs in the Denver region (UDFCD 2010). UD_Detention required four-inch spacing of orifice rows.
- It was assumed that the storage volume at any stage would be well approximated using a trapezoidal depth-storage relationship between the two surface areas specified in the BMP Database. The maximum depth of each facility was calculated by dividing the total surcharge volume by the average surface area. Application of the Fraction Full Method does not require information pertaining

to the physical storage characteristics of a BMP other than the total BMP surcharge volume. When the method was verified with SWMM models, the BMPs were assumed to have trapezoidal storage curves.

- BMPs were considered empty when all but 1% of the water quality storage volume had drained.
- During an event, it was assumed that a BMP would fill at a much faster rate than it would drain due to the controls on the orifice. The volume that a BMP filled to during a storm was assumed to be equal to the total storm runoff volume. Any runoff that exited a BMP before it filled to that volume was considered negligible.
- Storm HRTs were estimated using the Fraction Full Method when the total storm volume was greater than the lower threshold (1% unless a half-full drawdown time was specified) and less than 100% of the BMP surcharge volume. Storm HRTs were estimated using the average discharge rate from brimfull drawdown when the total storm volume was between 100 and 150% of the BMP surcharge volume. Results were not included if the storm volume was greater than 150% of the BMP surcharge volume.

4.3.4 V-notch Model

For the Madison, WI, Monroe St. WP (Madison WP), a unique procedure was developed to estimate the HRT based on supplemental information that was provided in the BMP Database. Additional data fields explicitly stated that the Madison WP outlet structure was configured with two large 90^o V-notch weirs.

Enough supplementary data was specified in additional data fields to generate a SWMM model of the Madison WP with two V-notch weirs. A depth-discharge relationship was specified which allowed the calculation of a discharge coefficient. The general form of the equation for a V-notch weir is presented in Equation 24 and the specified discharge coefficient matched recommended values in the SWMM help file. From the study information in the BMP Database, the flow of both V-notch weirs was equal to 5 cfs at 1 ft head and 80 cfs at 3 ft head. A C_{od} of 2.5 for each weir corresponds to a total discharge of 5 cfs at 1 ft head and 78 cfs at 3 ft head. It is believed that the SWMM model accurately portrayed the outlet conditions based on the specified rating curve from the BMP database.

$$Q = C_d * H^{5/2}$$

Equation 24

Where: Q = Discharge (cfs)

C_{od} = Discharge coefficient = 2.5

H = Head above V-notch invert (ft)

Other data fields for the Madison WP included a brimfull emptying time, half-full emptying time, BMP surcharge volume, flood control volume, bottom surface area, and top surface area. Supplemental information was provided which listed the pond average depth, maximum depth, bottom surface area, and top surface area in paragraph form. The two depth values from the paragraph of supplemental information were used to calculate the total pond depth, which was 3.9 ft. Upon inspection of the bottom surface area and top surface area from the paragraph of supplemental information, it was evident that the values were transcribed incorrectly into the usual BMP Database fields. A unit conversion error between square meters and hectares resulted in values that were exactly 10 times too large in the BMP Database fields. These values were reduced to their correct values in the SWMM model.

After careful consideration of other values specified in the data fields and verification with the developed SWMM model, it was evident that the brimfull emptying time listed in the BMP Database represented the time that it takes the entire storage volume (water quality surcharge volume plus flood control volume) to drain. Usually, this field represented the time required to drain the water quality volume only. The half-full emptying time represented the time required for half of the BMP surcharge volume to drain without including the flood control volume. These discoveries were verified in SWMM by generating a depth storage curve that matched the adjusted bottom and top surface areas with a total pond storage depth of 3.9 ft. The specified pond depth of 3.9 ft from the paragraph of supplemental information matched the calculated pond depth when the total storage volume (BMP surcharge volume plus flood control volume) was divided by the average pond surface area. In sum, it was possible to correct the erroneous values from the data fields using the supplemental paragraph of information and by generating a SWMM model.

Despite the difficulty in deciphering and adjusting the specified values for the Madison WP, it is believed that an accurate SWMM model was generated for the BMP. Figure 43 shows the developed SWMM model results based on the fraction that the water quality portion of the pond filled.

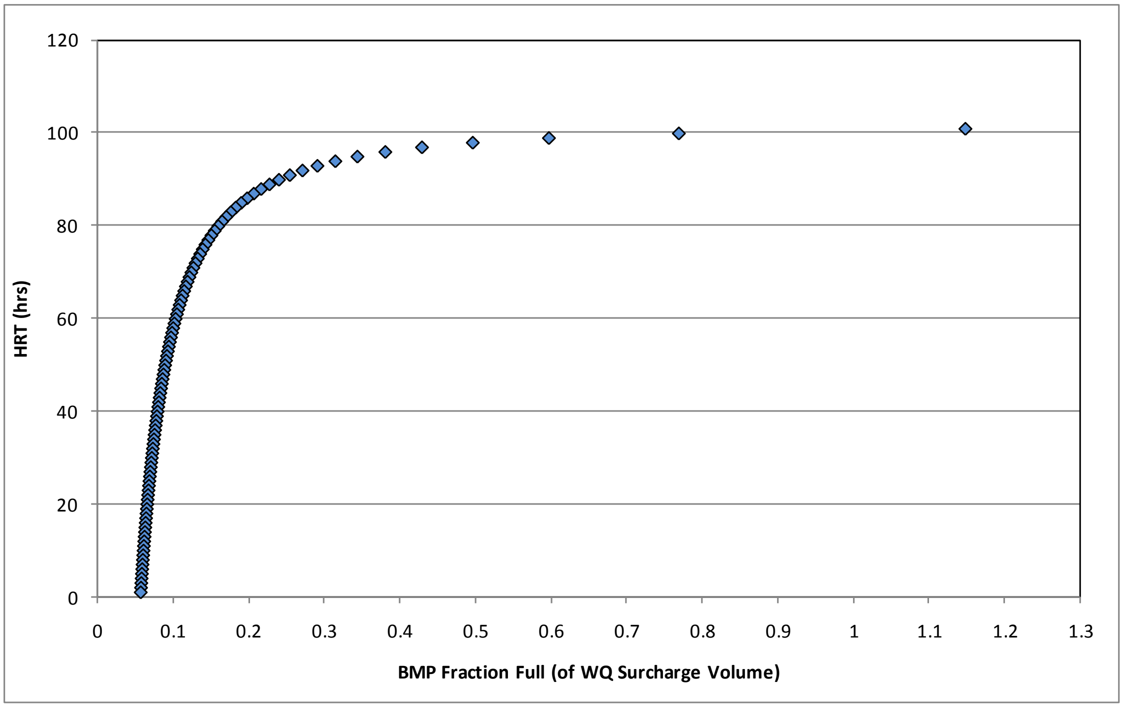


Figure 43. Developed HRT Curve for Madison WP

From the generated SWMM HRT curve, it appears that one benefit of using V-notch weirs to control the outlets of the Madison WP is that long average storm HRTs are provided for small storms. The drawback is that exceptionally large discharges occur for large storms and much of the stored volume is displaced within a few hours. For example, a storm producing 100% of the BMP water quality volume will take 99.1 hours to fully drain, but 50% of that volume is displaced in 0.7 hours. Approximately 260% of the Madison WP water quality storage volume is displaced in 3.6 hours when the flood control storage volume of the pond is utilized.

No single equation reasonably predicted the HRT based on the fraction that the pond filled during a storm. Four linearly interpolated lines were used to estimate the HRT. The lines are shown in Figure 44 and the values of the endpoints are displayed in Table 20.

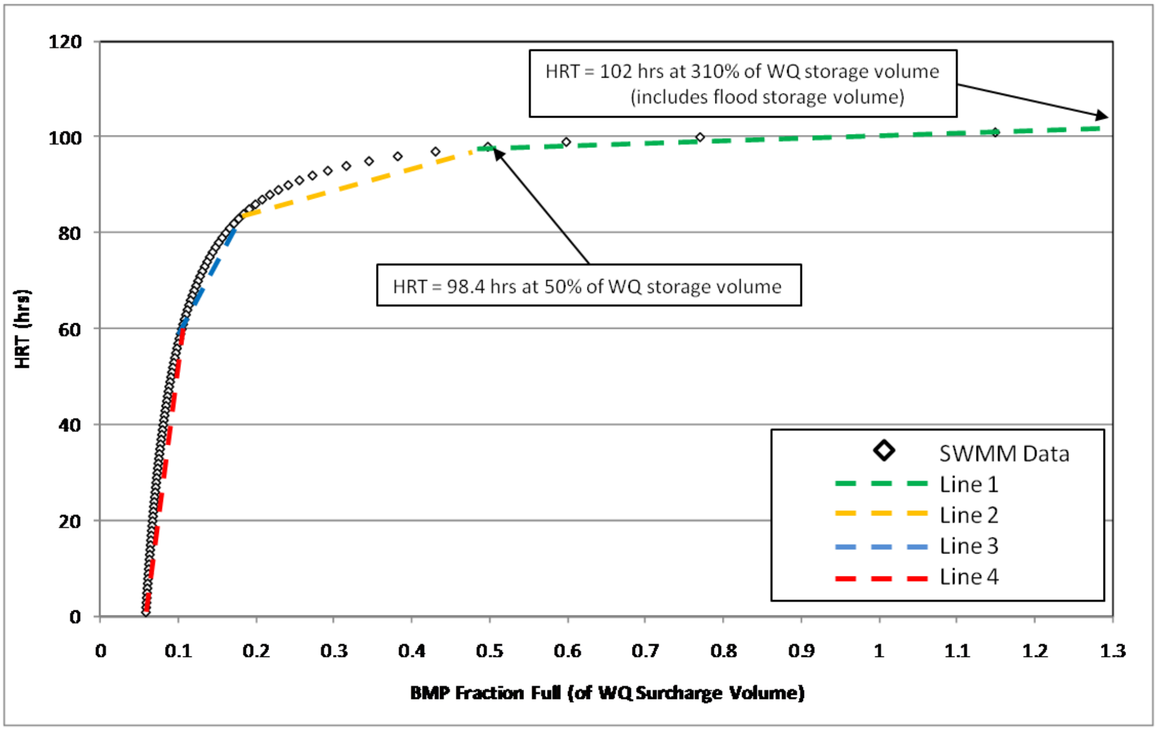


Figure 44. Interpolated Lines used to Approximate the HRT Curve for the Madison WP

Table 20. End Points of Interpolated Lines used to approximate the HRT Curve for the Madison WP

	Start HRT (hrs)	End HRT (hrs)	Start BMP Water Quality Volume Fraction Full	End BMP Water Quality Volume Fraction Full
Line 1	102	98.4	3.1	0.5
Line 2	98.4	86	0.5	0.2
Line 3	86	58	0.2	0.1
Line 4	58	0	0.1	0.05

4.3.5 Using Outlet Flow Duration for HRT Estimation

Estimates for storm HRTs were possible using the start time and end time of the hydraulic response to a storm. The elapsed time that water flows through the outlet of a BMP is equal to the storm average HRT. Expansion of the average HRT definition, shown in Equation 25, reveals why the effluent start and end times are equal to the average HRT.

$$Average\ HRT = \frac{Total\ Storm\ Volume\ (V)}{Average\ Storm\ Discharge\ (Q_{avg})}$$

$$Average\ HRT = \frac{V}{Q_{avg}} = \frac{\sum Q\Delta t}{\frac{\sum Q}{n}} = \sum_{i=1}^{n} \Delta t$$

Equation 25

As shown in Equation 25, the storm volume for a period of time during an event is equal to the discharge rate for that period multiplied by the elapsed time that the discharge rate occurred. The total storm volume is equal to the sum of all incremental volumes for a storm. The average discharge rate is the sum of all discrete discharge values divided by the number of recorded values. When the average discharge rate is divided by the average flowrate, the mathematical result is identical to the elapsed time, or sum of all incremental times. Therefore, the total amount of time that water flows through a BMP outlet is equal to the average storm HRT that the BMP provided.

Data fields within the BMP Database sometimes included the effluent start and end time that could be used as an estimate of the storm HRT. Usually, the effluent start and end time values were deemed to be less accurate for HRT estimation than the total storm volume because the values rarely represented the time that water was actually flowing through the BMP outlet. Commonly, the effluent start and end time would be identical to the precipitation start and end time, be representative of when sampling personal collected samples and not necessarily when water was flowing through the outlet, or be omitted completely.

There was one study from the BMP database where the effluent start and end times were used for HRT estimation. The Central Park WP did not list a brimfull drawdown time so the Fraction Full Method could not be used to estimate the storm HRTs. Total storm times were examined carefully and did not match precipitation start and stop times.

The elapsed storm time was used to estimate the HRT of storms for the Howes St. BMP and Udall WP, which were part of the Fort Collins sampling program. Detailed hydrograph information was available for these two sites. There was no need to approximate the HRT using another method since the outlet flow duration was known.

4.3.6 Peak Effluent Flowrate Estimation of HRT

Several studies included the peak effluent flowrate (P_{eak}) for each storm event. Maximum flowrates can easily be orders of magnitude greater than the average flow rate during an event so P_{eak} was not used when other methods were available to approximate the storm average HRT. However, the Beltway 8 Surge Basin WP pumped water from a retention area into polishing ponds. P_{eak} was used to compute the HRT under the assumption that the pump would provide a relatively constant flowrate over the duration of the event. Effluent start and end times for the Beltway 8 Surge Basin WP were not consistent with the size of the BMP or the amount of rainfall and were deemed to be unreliable estimates of HRT. Equation 26 shows how the HRT was calculated assuming that P_{eak} is equal to the average flowrate of the event. The Beltway 8 Surge Basin WP was the only BMP where the peak flowrate was used to estimate the storm HRT.

$$Storm\ HRT = \frac{Total\ Storm\ Volume}{3600 * Q_{peak}}$$

Equation 26

Where: Storm HRT = Hydraulic retention time (hrs)

Total Storm Volume = Volume of storm (cf)

P_{eak} = Specified effluent peak flowrate for storm (cfs)

4.4 Analysis of Storm Data

Using the various methods explained in the previous section, the average HRT for each individual storm was calculated and paired to effluent water quality EMCs. The overall dataset contained 234 unique HRT values with one or more associated water quality constituents. Stormwater quality results were sorted from smallest HRT to largest HRT for each BMP type and water quality constituent. Graphical methods of analysis were used as aids to formal statistical tests and were used during exploratory data analysis (Gilbert 1987, Helsel and Hirsch 1992). Scatter plots were generated for each subset in order to identify outliers and to visually inspect the data for trends. Since each constituent was assessed individually for each BMP type, outliers were removed from each subset independently before any statistical analysis was performed. Outliers were defined as observations whose values were quite different from others in the data set (Helsel and Hirsch 1992). For this analysis, outliers that tended to have an overly significant influence in the variability or central tendency of the data subset were discarded. In general, an outlier was removed if it differed from other observations in the dataset by an order of magnitude or more.

Table 21 shows the data points removed from each subset based on visual inspection from scatterplots.

Table 21. Outliers Removed from Subset Based on Visual Inspection

BMP Type	Constituent	Outliers Removed from Analysis
WPs	TSS	Removed values above 150 mg/L (162, 228, 341), original median = 22 mg/L
	TP	Removed values above 4 mg/L (4.7, 5.0, 7.4, 10.4), original median = 0.2 mg/L
	TR Zn	Removed values above 400 ug/L (624,883), original median = 36.5 ug/L
	TR Cu	Removed 1 value(142 ug/L), original median = 7 ug/L
EDBs	TSS	Removed 1 value(260 mg/L), original median = 38 mg/L
	TP	No obvious outliers to remove
	TR Zn	Removed values above 300 ug/L (390,596,612), original median = 83 ug/L
	TR Cu	No obvious outliers to remove

In addition to outlier removal, there were datapoints from certain BMP studies that were omitted from the analysis. TR Cu results were not used for the Madison WP and the Shawnee Ridge WP because a high MDL at each site resulted in identical stormwater quality values. Every TR Cu result from the Madison WP stormwater study was equal to 25 ug/L, which indicated that a test method limitation was preventing actual EMC values from being reported. The Shawnee Ridge WP also reported identical results for several storms. Omitting the TR Cu results from both studies prevented biasing the analysis toward a substituted value that was independent of actual effluent concentrations in the runoff. Furthermore, at the Shawnee Ridge WP, there were several reported storm results where the permanent pool level was low initially because almost no effluent volume was displaced during an event. These events were not used in analysis. Only three study results were included in the final dataset from the Shawnee Ridge WP. The complete dataset used for the HRT analysis appears in Appendix D of this thesis.

The stormwater quality results were binned into different categories for statistical analysis in order to determine whether cleaner effluent resulted when longer storm HRTs were provided. Each water quality constituent was analyzed independently for WPs and for EDBs. Binning was necessary due to substantial scatter in the stormwater sampling results for similar HRT values. Choosing how to bin the data was influential for the statistical results, so two different binning procedures were developed in order to holistically approach the analysis:

1) Water quality results for WPs and EDBs were separated into unequally sized bins of common design drawdown times for analysis. Common drawdown times included 12, 24, 40, or 72 hours depending on the type of BMP (UDFCD 2010). It was required that at least 10 samples be included in each bin. Taking HRT bins around common design times ensured that results would be applicable for current design standards. Storm HRTs greater than 72 hours were rare for EDBs, so a bin boundary was established at 60 hours. A major drawback of this method was that sample size affected the bin confidence interval, prediction interval, and median. Therefore, statistical test results were influenced by differences in bin sample size and differences in effluent concentration.
2) Water quality results for WPs and EDBs were separated into bins of equal sample size regardless of the corresponding HRT for the bin boundary. It was required that bins have approximately 20 samples or more as long as an equal sample size existed in each bin. The advantage of this method was that sample size could not be the driving factor in perceived statistical differences or similarities because it was equal among the bins being compared. A disadvantage of the method was that HRT bins were not always in intervals common to BMP design standards, which made interpretation of results more difficult.

Identical nonparametric methods of statistical analysis were performed on the data subsets once the subsets were grouped. Nonparametric tests do not assume an underlying distribution, do not require transformation of the raw data, and are applicable with fewer data points. Assuming a distribution would have been problematic for a two reasons. It has been shown that influent and effluent constituent distributions changed from lognormal to normal when treated by a BMP (Van Buren et al. 1997). However, it is unclear what type of underlying distribution might exist behind binned groups of BMP water quality results, especially since each group contained pooled data from multiple BMPs. Additionally, the number of data points in each bin was allowed to be as low as 10 when unequal bin sizes were used. Helsel and Hirsch (2002) recommend at least 25-30 data points for student T-tests which eliminated this test as a viable option.

A Rank-Sum test was performed to determine how bin medians differed as storm HRTs increased using MATLAB software. The "Ranksum" function in MATLAB automatically adjusted for ties between data points, adjusted for a binomial or normal approximation for the test statistic depending on the total number of points, and displayed the degree of confidence that the medians differed (MATLAB 2009). Changes in variance were undetectable using the Rank-Sum test, so nonparametric prediction intervals and confidence intervals were calculated. These intervals were displayed on what the author has termed an "Interval Boxplot" which should not be confused with a standard boxplot. Interval Boxplots differ from standard boxplots in that confidence intervals and predictions intervals are displayed instead of quartiles and extreme values. Confidence intervals and prediction intervals were calculated about the median of each bin using the nonparametric methods explained in the Literature Review Section

(Equation 11 through Equation 14). A bin of grouped data with a narrow prediction interval can be interpreted as a having less variance in observations than a bin with wider intervals. A bin of grouped data with a narrow confidence interval suggests that the true median of the subset is less variable than one with a broad confidence interval. Figure 45 shows the definitions of an Interval Boxplot used in this thesis.

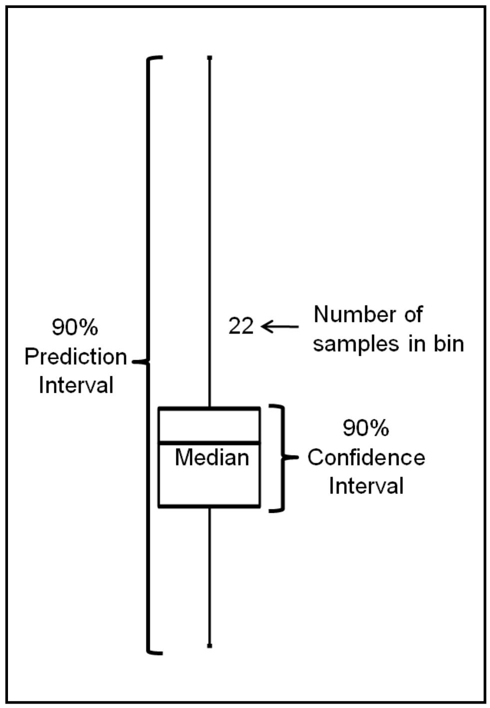


Figure 45. "Interval Boxplot" Definitions Using the Non-parametric Confidence Interval and Non Parametric Prediction Interval for a Median at a 90% Confidence Level

Figures were created to convey the results of each statistical analysis whether unequal bin sizes were used or equal bin sizes were used to group results. Each figure contains two plots and two tables of related information from the analysis. The upper left plot in each figure is the Interval Boxplot of the binned data and shows the median, nonparametric confidence interval, and nonparametric prediction interval for each bin. A small version of Figure 45 was included in the corner of each Interval Boxplot. The upper right plot of each created figure is a scatterplot of the dataset and is color-coded according to the bin boundaries of the Interval Boxplot. The lower left table of each figure shows the numeric values of the bin medians, confidence intervals, and prediction intervals that are plotted in the Interval Boxplot. The lower right table shows the MATLAB Ranksum results that compare bin medians and the associated significance level of the test. Perceived differences in bin medians were output as p-values from Ranksum test and the corresponding significance level of the p-value was calculated.

4.5 Results of HRT Analysis for WPs

This section includes the results of the HRT analysis for WPs. A summary of the inlet water quality data for each WP from the BMP Database was constructed using standard boxplots for each water quality constituent. Median values were also calculated and placed in a table for quick reference. Although BMPs should ultimately be judged by the quality of the effluent, it was helpful to quantify the influent water quality characteristics. Without knowing anything about the incoming water quality, it was difficult to determine whether perceived effluent enhancements were meaningful when longer HRTs were provided. The following subsections present the results of the statistical analysis for each constituent and show Interval Boxplots of the effluent characteristics when storm average HRTs were binned into unequal sample sizes and binned into equal sample sizes. Numerous figures were created and appear at the end of this chapter instead of appearing embedded in the text.

The Madison WP was initially included in the analysis and then a revised dataset was produced that omitted the Madison WP results. The outlet of the facility was comprised of two V-notch weirs that produced relatively constant average storm HRTs anytime approximately 20% to 100% of the BMP surcharge volume filled with runoff. Calculated average storm HRTs for this facility were determined to be an inappropriate performance metric since so much of the storm volume drained in the first couple of hours. According to the SWMM model produced for the site, around 80% of the volume would be expected to discharge through the weirs during the first 2% of the storm HRT. Relatively constant average storm HRTs were produced regardless of the storm volume, which resulted in a clustering of datapoints with HRTs between 85 to 100 hours. TP effluent concentrations were fairly consistent in value, but TSS effluent concentrations varied widely for similar HRTs. Analysis was performed initially using the Madison WP results, and then again without the Madison WP results included.

Generally, there was a lack of data for storm HRTs greater than 40 hrs for metals. This limited the conclusions that could be drawn from the analysis.

4.5.1 Inlet Concentrations for WPs

The inlet concentrations for WPs from the BMP Database are presented in Figure 46 through Figure 49. Standard boxplots were used to show the range of inlet concentrations for each constituent at each WP. Note that TR Cu and TR Zn data were not available at all sites, but TSS and TP data were. Furthermore, some of the boxplots contained very few datapoints. The Shawnee Ridge WP was particularly difficult to interpret since only three data points were available. The Udall WP and Howes St. BMP were not included in the standard boxplot figures because a previous section of this thesis detailed the water quality characteristics of those sites (see section 3.6 for all results, 3.6.1 for median EMC values, and 3.6.6 for standard boxplots). Table 22 shows the median inlet concentrations for the WPs from the BMP Database.

Table 22. Median Inlet Concentration for WPs from the BMP Database

BMP Name	TSS mg/L	TR Zn ug/L	TR Cu ug/L	TP mg/L
Madison WP	166	N/A	N/A	0.45
Shop Creek Pond	103	90.0	23.0	0.44
La Costa	230	360	77.0	0.64
Shawnee Ridge	72.0	40.0	N/A	0.09
Central Park	38.5	111	14.4	3.34
Beltway 8	196	59.2	8.15	0.18
BMP 12	75.6	N/A	N/A	0.20
BMP 13	42.9	N/A	N/A	0.32
BMP 37	58.1	N/A	N/A	0.20
Overall Median	123	110	22.0	0.40

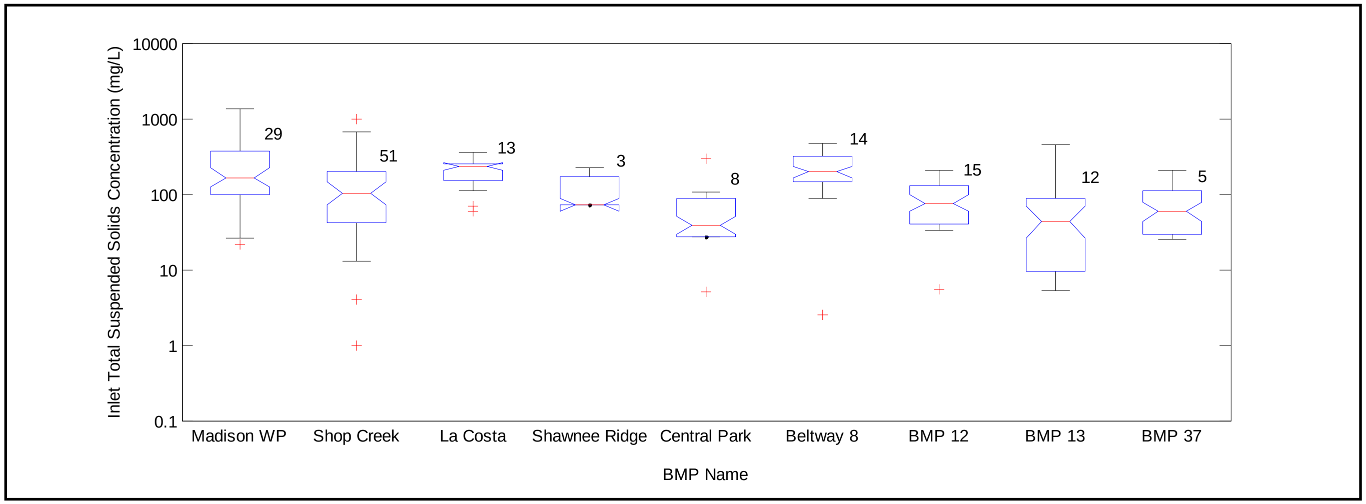


Figure 46. Boxplots of Inlet TSS Concentration for WPs

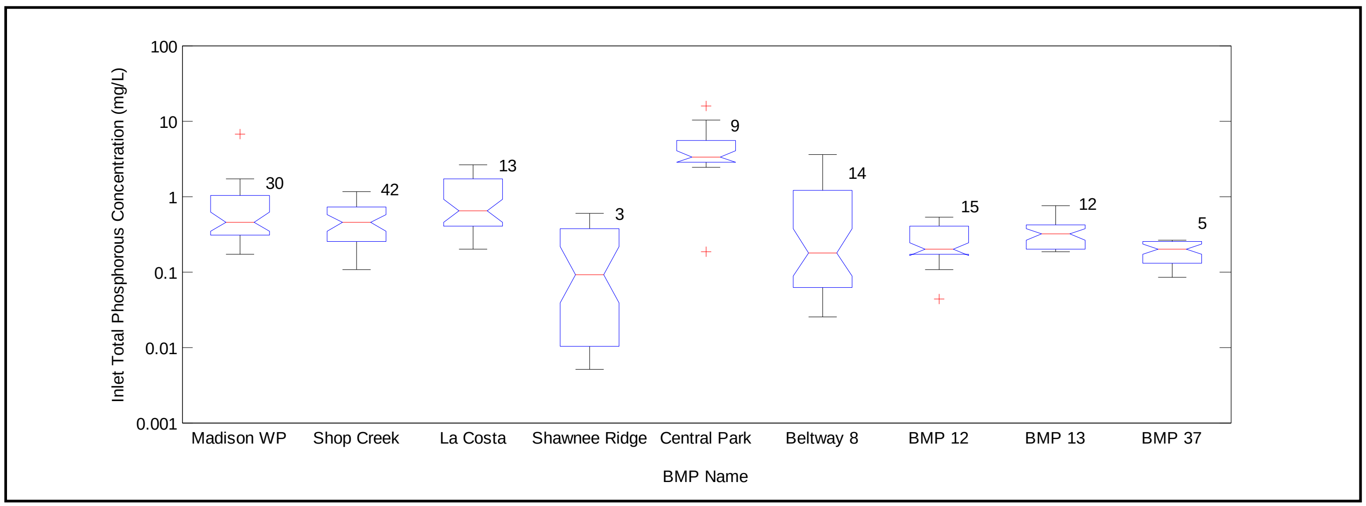


Figure 47. Boxplots of Inlet TP Concentration for WPs

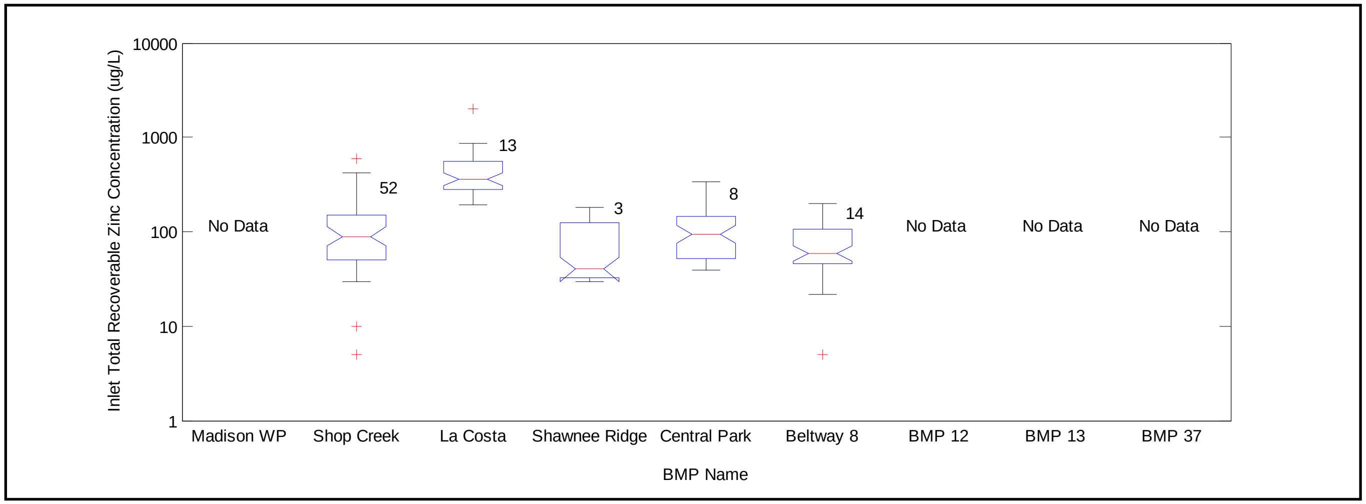


Figure 48. Boxplots of Inlet TR Zn Concentration for WPs

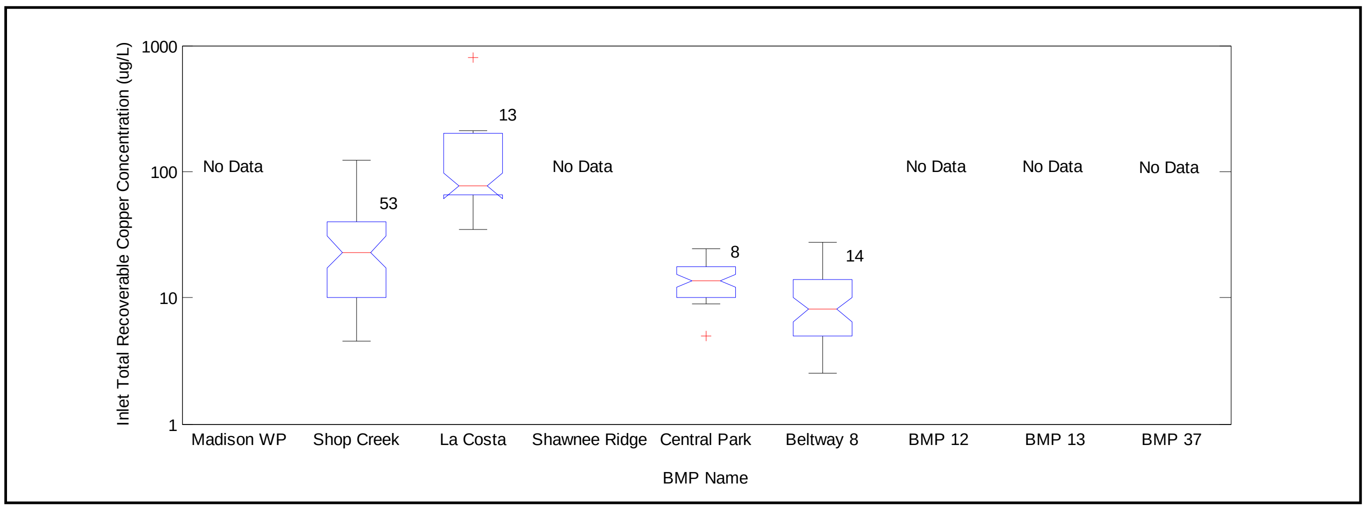


Figure 49. Boxplots of Inlet TR Cu Concentration for WPs

The Central Park WP had much higher TP inlet concentrations than any other WP. Correspondingly, several of the outlet TP concentrations at the Central Park WP were exceptionally high. The dataset used for statistical analysis was sorted according to HRT and outliers were removed without regard to the corresponding BMP. However, three of the four TP effluent values that were classified as outliers and removed from the dataset came from the Central Park WP.

The La Costa WP had much higher TR Zn and TR Cu inlet concentrations than the other WPs. However, this BMP achieved excellent removal of these two pollutants. There were two outliers removed from the TR Zn dataset and one removed from the TR Cu dataset. All three of these effluent values were from the Beltway 8 WP, which did not have higher influent TR Zn or TR Cu values.

4.5.2 Total Suspended Solids for WPs

Figure 54 shows the results of the statistical analysis when unequal bin sizes were used and the Madison WP results were included. There was a clustering of results with HRTs between 85 and 100 hours from the Madison WP, which is shown best by the scatterplot in the figure. The effluent EMC values for TSS varied widely for these events. It was hypothesized that calculated average storm HRTs for the Madison WP might be inappropriate because most of the water displaced during events would drain in a very short time and did not receive treatment. The EMC values from the Madison WP were removed from the dataset and a new statistical analysis was performed.

Figure 55 shows the results of the statistical analysis when unequal bin sizes were used and Figure 56 shows the results when equal bin sizes were used for the revised dataset. Interestingly, the same general trends were present once the Madison WP results were removed from the dataset. Figure 55 shows that there was no consistent lowering of median values as longer HRTs were provided. Furthermore, there was no statistically significant reduction in TSS median values when data was grouped with different bins. Figure 56 shows that the median effluent values were not significantly lower when a longer HRT was provided. The upper prediction level and upper confidence level did not vary considerably. The figures suggest that the effluent from short HRTs were statistically similar to effluent from longer HRTs for WPs.

Influent TSS had a median value of 123 mg/L, as shown in Table 22, and the effluent from WPs was usually between 15 to 30 mg/L. Overall, the WPs removed between 76 to 88% of influent TSS, which was very substantial. WPs do not require as long of a retention time as EDBs because a large portion of the water displaced from runoff has been stored in the pond since a previous event allowing additional pollutant removal. Figure 55 shows with 80.4% confidence that when HRTs from 12 to 24 hours were provided, the effluent median was less than when 12 hours or less was provided. The lower median was 15.4 mg/L, which was half of the 28.5 mg/L median when less than 12 hours were provided. Dissimilarly, Figure 56 shows no significant reduction in medians when less than 15.6 hours were provided compared to 15.6 to 26 hours. Using results from both figures, it is clear that the binning procedure for unequal bin sizes grouped the data in such a way as to suggest a stronger difference in medians than when equally sized bins were used. Overall, the results showed that longer HRTs do not coincide with reduced effluent TSS concentrations for WPs.

4.5.3 Total Recoverable Zinc for WPs

Figure 57 shows the results of the statistical analysis when unequal bin sizes were used and Figure 58 shows the results when equal bin sizes were used. No TR Zn data was included in the Madison WP study, so it did not have to be removed from the subset. Influent TR Zn concentrations had a median value of 110 ug/L for WPs as shown in Table 22, and the median of each effluent bin was between 30 to 40 ug/L regardless of how the bin boundaries were set. Between 63 and 73% of influent TR Zn was removed by the WPs using the median inlet and outlet values. There was no significant difference between median effluent values as the HRT increased. Figure 58 indicates that there was slight narrowing of the prediction interval as the storm HRT was longer. However, extreme variability in effluent concentrations existed for TR Zn and at a 90% confidence level an effluent TR Zn value up to 250 or 300 ug/L would be expected.

One important observation was the lack of EMC values for storm HRTs greater than 40 hours. The WPs that included TR Zn results in the BMP Database provided shorter storm HRTs. There was a small clustering of results at HRTs greater than 72 hours from the Udall WP of the Fort Collins stormwater sampling project. These results were grouped tightly and may indicate that TR Zn was removed to more constant concentrations when a very long HRT was provided. The Udall WP was constructed as a series of two WPs that each provided extended detention. Consequently, effluent TR Zn concentrations from the facility should be representative of a “best-case” scenario.

WPs have been shown to remove TR Zn at statistically significant levels from the inlet to the outlet (Geosyntec and WWE 2008). However, there was no significant lowering of median effluent values when HRTs of 24 hours or 40 hours were provided instead of 12 hours. Results from the Udall WP indicated that effluent variability decreased when a substantially longer HRT was provided. However, with few data points it was difficult to determine how practical it would be to design future WPs with retention times as long as the Udall WP provides.

4.5.4 Total Recoverable Copper for WPs

Figure 59 shows the results of the statistical analysis when unequal bin sizes were used and Figure 60 shows the results when equal bin sizes were used. TR Cu values from the Madison WP were omitted from analysis because of high MDL and identical results for numerous storms. Influent TR Cu concentrations had a median value of 22 ug/L for WPs from the BMP Database, as shown in Table 22. The median of each effluent bin was between 6.0 and 10.0 ug/L regardless of how the bin boundaries were established. Figure 59 displays a slight, insignificant increase in median effluent values as longer storm HRTs were provided. In Figure 60, the equal sample bins show a significant increase in median from bin 2 to bin 3. The scatterplot reveals that the binning process grouped three of the six highest EMC values into bin 3 which shifted the median up. The upper prediction interval and upper confidence interval did not lower as the storm HRT increased according to either binning procedure. Similar variability in effluent concentration was observed regardless of the HRT provided, and a single effluent EMC up to 30 to 35 ug/L would be expected at a 90% confidence level.

Similarly to the TR Zn results, a lack of EMC values for storm HRTs greater than 40 hours limited the utility of the statistical analysis. A small clustering of results from the Fort Collins stormwater sampling project had HRTs longer than 72 hours. Unlike the

TR Zn results, these results were not grouped tightly and indicated that variability in effluent TR Cu concentrations still existed when long HRTs were provided.

WPs have been shown to remove TR Cu at statistically significant levels from inlet to outlet (Geosyntec and WWE 2008). However, there was no additional removal when HRTs of 24 hours or 40 hours were provided instead of 12 hours. Results from the Udall WP indicated that no additional treatment occurred from longer HRTs.

4.5.5 Total Phosphorous for WPs

Figure 61 shows the results of the statistical analysis when unequal bin sizes were used and the Madison WP results were included. A clustering of results with HRTs between 85 and 100 hours from the Madison WP is shown best by the scatterplot in the figure and interestingly, unlike other pollutants, the effluent EMC values for TP were very consistent for these events. It was hypothesized that calculated average storm HRTs for the Madison WP might be inappropriate because most of the water displaced during events would drain in a very short time and not receive treatment. The EMC values from the Madison WP were removed from the dataset and a new statistical analysis was performed.

Figure 62 shows the results of the statistical analysis when unequal bin sizes were used and Figure 63 shows the results when equal bin sizes were used for the revised dataset. The median value of each bin was significantly lower when HRTs longer than 24 hours were provided by the WPs. The median value of TP was between 0.16 and 0.23 mg/L when HRTs less than 24 hours were provided. However, when greater than 24 hours was provided the median TP values ranged between 0.08 to 0.13 mg/L. The median influent concentration for TP in WPs was 0.40 mg/L, as shown in Table 22. Around half of the phosphorous coming into the ponds was removed by the WPs according to the median influent and effluent values when less than 24 hours was provided, but 70 to 85% of the TP was removed when longer HRTs were provided.

The upper confidence level and the upper prediction level lowered substantially as the HRT increased, according to Figure 62. When a storm HRT between 24 hours and 40 hours was provided, there was little chance of effluent TP values from a single event being greater than 1.06 mg/L. When greater than 40 hours was provided, there was little chance of effluent TP values from a single event being greater than 0.60 mg/L. These values were substantially lower than when HRTs less than 12 hours were provided, which had a corresponding upper prediction level of 3.32 mg/L, or when 12 to 24 hours were provided, which had a corresponding upper prediction level of 1.88 mg/L.

The upper prediction interval dropped significantly when equal bin sizes were used as well, which is shown in Figure 63. A very pronounced narrowing of the upper prediction limit occurred when storm HRTs longer than 11.5 hours were provided. There was also some indication that the upper prediction limit was lower when more than 24.2 hours were provided.

WPs have been shown to remove TP at statistically significant levels from inlet to outlet (Geosyntec and WWE 2008). The median value was lower for bins of HRTs longer than 24 hours. Additionally, there was an indication that additional TP removal occurred with greater HRTs because the prediction interval and upper confidence interval decreased with longer HRTs. Communities might consider increasing the HRT that a

WP provides (which may require a larger pond) if stringent TP removal goals are established.

4.6 Results of HRT Analysis for EDBs

Effluent data from the BMP Database contained an irregularity in the overall dataset that created some interesting results. The Lexington Hills EDB (called the Lex Hills Pond in the BMP Database) was substantially different from the other BMPs included in the analysis for two reasons. Primarily, the design drawdown time for the Lexington Hills EDB was 24 hours while all other EDBs had a design drawdown time greater than or equal to 72 hours. When storm HRTs were calculated and results were binned according to common design times, the initial bin of less than 24 hours was comprised almost entirely of results from the Lexington Hills study. Furthermore, the Lexington Hills EDB was located in a medium density residential neighborhood while the other EDBs were from highways or office retail space. Inlet concentrations of TR Zn, TR Cu, and TP were much lower for the Lexington Hills EDB than for the other BMPs included in the analysis. The net effect of the short drawdown time and "clean" influent was a grouping of storm HRTs less than 24 hours that had substantially lower effluent concentrations for TR Zn, TR Cu, and TP than other bins of longer HRTs. When equal bin sizes were used and the Lexington Hills EDB was included in the analysis, the first group of results was heavily influenced by the low effluent EMCs from the Lexington Hills EDB. The median, confidence interval, and prediction interval were weighed down in the first bin and treatment processes were dwarfed by the "clean" water that entered and exited the Lexington Hills EDB.

A figure was created for the statistical analysis using unequal bin sizes with the Lexington Hills EDB results included. Then, the Lexington Hills EDB study results were removed from the dataset and it was reanalyzed for TR Zn, TR Cu, and TP. Influent TSS at the Lexington Hills EDB was not substantially lower than the other study sites, so a separate analysis excluding the Lexington Hills EDB results was not performed for TSS. The equal bin analysis did not include the Lexington Hills EDB results for TR Zn, TR Cu, and TP. Numerous figures were created and appear at the end of this chapter instead of appearing embedded in the text.

4.6.1 Inlet Concentrations for EDBs

Table 23 shows the median inlet concentrations for the EDBs from the BMP Database. Figure 50 through Figure 53 display the inlet EMC concentrations for each EDB. Note that standard boxplots were used to display the influent concentrations instead of Interval Boxplots. Figure 50 shows the inlet TSS concentrations for various BMPs and there was not an appreciable difference between the inlet TSS concentrations at the Lexington Hills EDB and the rest of the sites. Figure 51 shows that the Lexington Hills EDB had much lower inlet TP concentrations, Figure 52 shows that the Lexington Hills EDB had much lower inlet TR Zn concentrations, and Figure 53 shows that the Lexington Hills EDB had much lower inlet TR Cu concentrations than the other EDBs. These figures show that the median of the Lexington Hills EDB was less than the lower extreme value for many of the other EDBs in the dataset for TR Zn, TR Cu, and TP. Therefore, separate analysis was conducted excluding the Lexington Hills EDB from the dataset.

Table 23. Median Inlet Concentrations for EDBs from the BMP Database

BMP Name	TSS mg/L	TR Zn ug/L	TR Cu ug/L	TP mg/L
15/78	130	350	51	0.66
5/56	86	130	31	0.28
605/91 EDB	74	288	36	0.24
Manchester	180	545	84	0.66
5/605 EDB	71	119	21	0.38
Greenville	99	163	14	0.35
Lex Hills Pond	61	35	6.7	0.15
Overall Median	98	230	32	0.33
Overall Median (Excluding Lex Hills Pond)	100	265	38	0.36

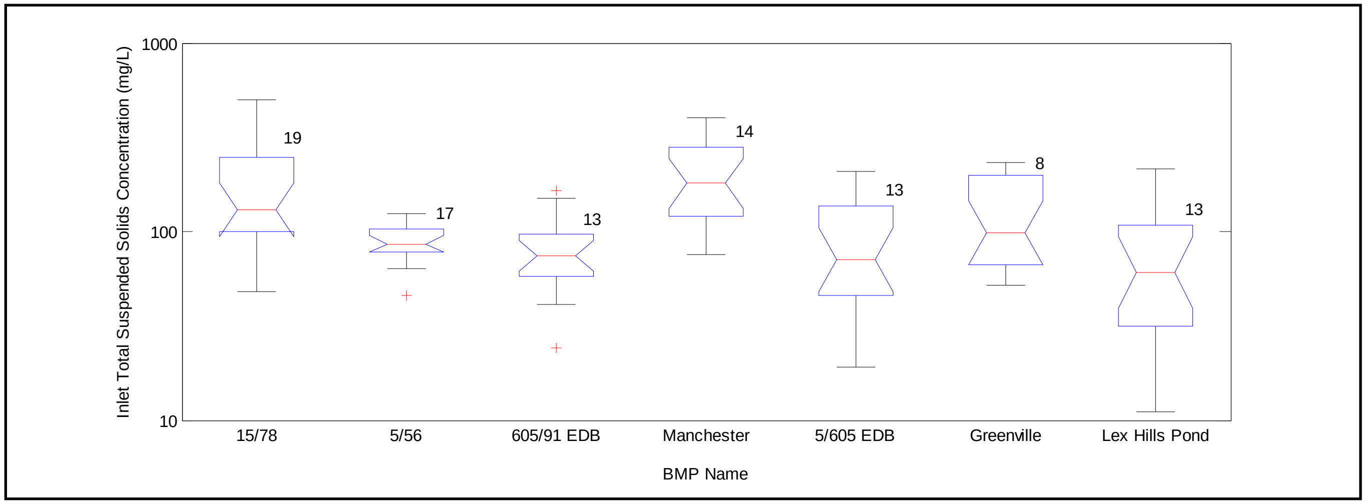


Figure 50. Boxplots of Inlet TSS Concentration for EDBs

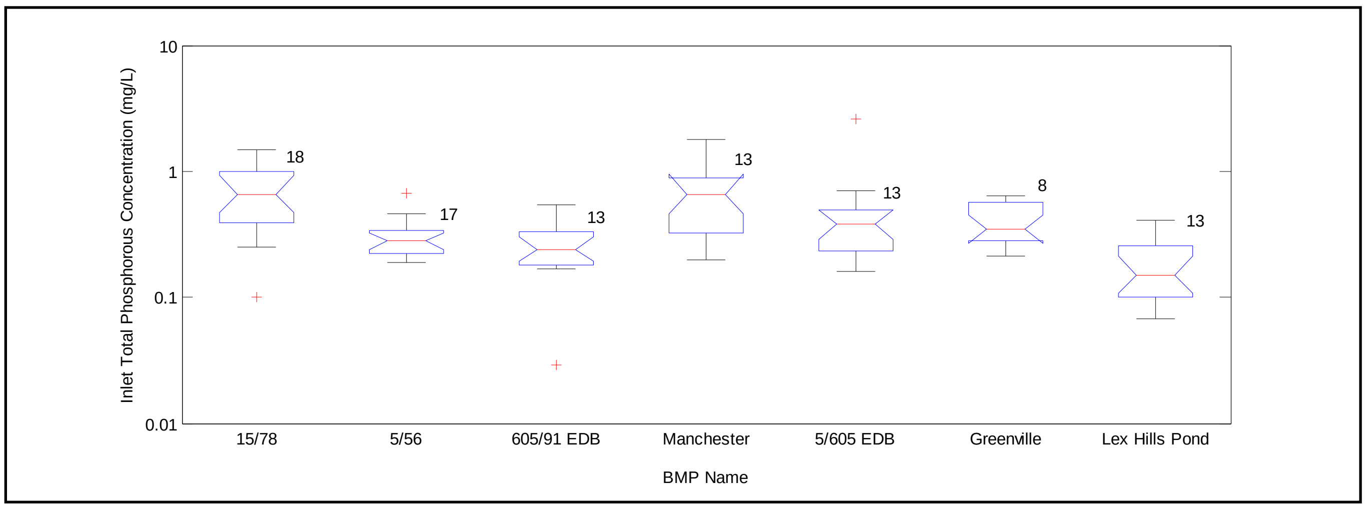


Figure 51. Boxplots of Inlet TP Concentration for EDBs

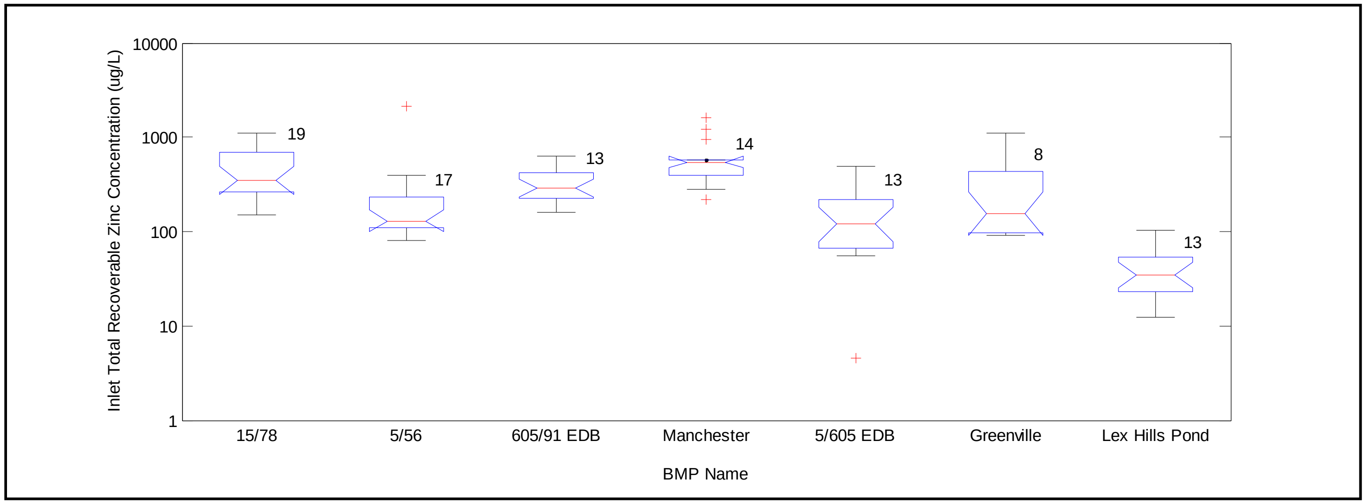


Figure 52. Boxplots of Inlet TR Zn Concentration for EDBs

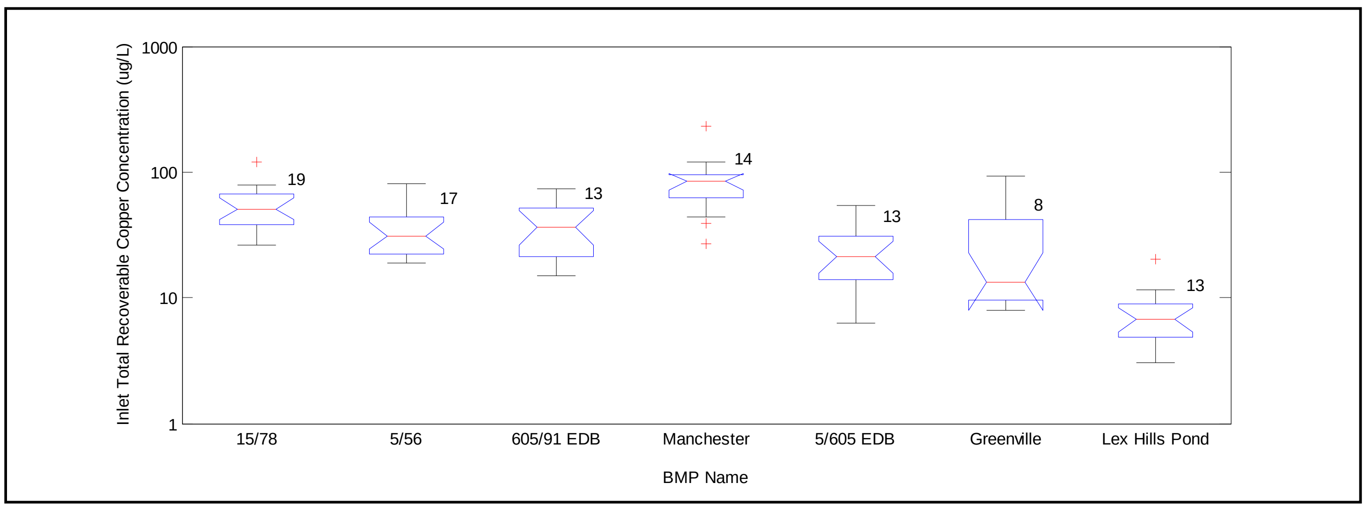


Figure 53. Boxplots of Inlet TR Cu Concentration for EDBs

4.6.2 Total Suspended Solids for EDBs

Figure 64 shows the results of the statistical analysis when unequal bin sizes were used and Figure 65 shows the results when equal bin sizes were used. As longer storm HRTs were provided, the median effluent concentration of TSS decreased substantially. The influent median value was 98 mg/L for all sites, according to Table 23. Upon initial inspection of the median values in Figure 64, which shows binned data using unequal bin sizes, it would appear that even shorter HRTs were capable of achieving nearly 50% TSS removal since the median was 53 mg/L for HRTs less than 24 hours. However, the data in that bin was almost entirely (9 of 11 values) comprised of results from the Lexington Hills EDB. The Lex Hills EDB has a design drawdown time of 24 hours, which was much lower than the other EDBs in the dataset. The median influent value from the Lex Hills EDB was 61 mg/L, which means that the typical TSS removal from that BMP was not good, only 13%. The poor removal rate can likely be attributed to the small HRTs that were provided by the Lex Hills EDB.

The Ranksum results showed that there was a significant lowering of median values in TSS effluent when greater than 24 hours detention was provided and unequal bin sizes were used, according to Figure 64. The same figure also shows a significant median decrease when an HRT greater than 60 hours was provided. At greater than 60 hours, the EDBs treated effluent to TSS concentrations of 30 mg/L, but the scatterplot shows that some values were even less than 20 mg/L. Results from the equal sample bins, as shown in Figure 65, demonstrate a similar finding when longer HRTs were provided. Specifically, storm HRTs that were greater than 59 hours had a median of 32 mg/L, which was significantly lower than when HRTs between 44 and 59 hours occurred. The unequal sample bins, shown in Figure 64, displayed a significant reduction in effluent TSS concentration when more than 40 hours detention was provided. This result was dwarfed in Figure 65 because the two lower bins from the unequal size analysis were combined into a single group because of the binning process. From inspection of both figures, it seems reasonable to conclude that BMPs providing more than 24 hours HRT had lower TSS effluent values. Furthermore, additional treatment from long HRTs was also demonstrated because effluent values were lower when more than 60 hours HRT was provided.

Thus, the results suggest two breaking points where BMP designs should take place. Primarily, an EDB should be designed with a brimfull drawdown time that is more than 24 hours. This is agreeable with previous literature stating that a 40-hour brimfull drawdown time is appropriate for the majority of TSS removal (UDFCD 2010, Grizzard et al. 1986). The design drawdown time of 40 hours for a brimfull EDB corresponds to an average drawdown time of approximately 24 hours. If extensive TSS reduction is required, a much longer HRT should provide additional treatment at a significant level. Storm HRTs that were greater than 59 hours had lower effluent TSS than storm HRTs that were 44 hours or less, and the result was significant according to the Ranksum results shown in Figure 65. When EDBs provided an average HRT between 40 and 60 hours the effluent TSS concentration was no better than when an average HRT between 24 to 40 hours was provided.

Another important finding was the decrease in the upper prediction interval as the storm HRT increased. This result is best illustrated in Figure 65, which shows the equal bin size analysis. Short HRTs of less than 44 hours had more variability for any single event. Effluent TSS values as high as 106 mg/L would be expected at a 90% confidence level. When HRTs greater than 59 hours were provided, a single event would only be expected to have a value up to 59 mg/L at a 90% confidence level. BMPs that provided a longer HRT reduced the variability of effluent TSS concentrations.

4.6.3 Total Recoverable Zinc for EDBs

Figure 66 shows the results of the statistical analysis when unequal bin sizes were used including the Lexington Hills EDB. The Lexington Hills EDB had a brimfull drawdown time of 24 hours, which was three times less than the other BMPs included in the dataset. This resulted in the lower bin being almost entirely (9 of 11 points) comprised of Lexington Hills study data. Influent TR Zn concentrations were exceptionally low for the Lexington Hills EDB compared to the other study BMPs. The "clean" effluent displayed in bin 1 of the Interval Boxplot in Figure 66 was a result of low influent concentrations, not treatment from the BMP. Therefore, the Lexington Hills study data was removed from the TR Zn dataset and the analysis procedure was performed on the revised dataset.

Figure 67 shows the results of the statistical analysis when unequal bin sizes were used and Figure 68 shows the results when equal bin sizes were used to assess the revised dataset. The unequal bin sizes shown in Figure 67 display median effluent concentrations that decreased when longer storm HRTs were provided. Statistically significant differences between median values were not particularly strong, although the difference between less than 40 hours and greater than 60 hours was 83.5%. When equal bin sizes were used, shown in Figure 68, there was a stronger indication that median TR Zn levels decreased when greater storm HRTs were provided. It can be said with 91% confidence that storm HRTs greater than 61 hours had cleaner effluent than HRTs up to 49 hours. Influent TR Zn concentrations had an overall median of 265 ug/L for the EDBs as shown in Table 23 (median excluding Lexington Hills EDB). Approximately 70% of the influent TR Zn was removed when 61 hours or longer were provided compared to 55% when 49 hours or less were provided. The results show that the optimal detention time for TR Zn removal in an EDB was longer than 40 hours, and perhaps even longer than 50 hours.

Another interesting result was that the upper 90% prediction interval did not change as the HRT increased. In fact, a single new event would be 90% likely to have TR Zn effluent concentrations up to around 250 to 260 ug/L regardless of the HRT provided. Single events with high loads of zinc occurred even when long HRTs were provided by EDBs.

4.6.4 Total Recoverable Copper for EDBs

Figure 69 shows the results of the statistical analysis when unequal bin sizes were used and the Lexington Hills EDB was included. Similarly to the results from the TR Zn analysis, there were abnormally low TR Cu values when HRTs less than 24 hours were provided because of the Lexington Hills EDB. The “clean” effluent displayed in Figure 69 was a result of low influent concentrations, not treatment from the BMP. Therefore, the Lexington Hills study data was removed from the TR Cu dataset and analysis was performed on the revised dataset.

Figure 70 shows the results of the statistical analysis when unequal bin sizes were used and Figure 71 shows the results when equal bin sizes were used to assess the revised dataset. The unequal bin sizes shown in Figure 70 display median effluent concentrations that decreased when longer storm HRTs were provided. A statistically significant decrease occurred when the storm HRT was greater than 60 hours compared to HRTs between 40 and 60 hours. The equal bin analysis, shown in Figure 71, also displays a statistically significant improvement in median effluent when greater than 60.3 hours was provided. Results from both binning procedures were very similar. The median TR Cu inlet concentration for the EDBs was 38 ug/L, as shown in Table 23. Storm HRTs up to 49 hours had a corresponding effluent median of 26 ug/L signifying that the BMPs removed approximately 32% of the TR Cu. However, when HRTs were more than 60 hours approximately 70% of the TR Cu was removed. The results indicated that optimal effluent concentrations were obtained when HRTs greater than 60 hours were provided since a statistically significant difference occurred in median values and the magnitude of that difference was substantial.

The upper confidence interval and upper prediction interval were also lower as the storm HRT increased. A single new event would be 90% likely to produce an effluent EMC up to about 64 ug/L if the storm HRT was less than 49 hours. Contrastingly, a storm HRT greater than 60 hours was 90% likely to be 37 ug/L or less.

4.6.5 Total Phosphorous for EDBs

Figure 72 shows the results of the statistical analysis when unequal bin sizes were used and the Lexington Hills EDB results were included. Again, the results from the

Lexington Hills EDB were primarily clustered into the first bin, which had HRTs of 24 hours or less. Influent TP concentrations at the Lexington Hills EDB had a median of 0.15 mg/L. This was less than half of the other sites that had a median of 0.36 mg/L according to Table 23. The Lexington Hills EDB results were omitted from the analysis because of the low influent concentrations, and the statistical analysis was performed on the revised dataset.

Figure 73 shows the results of the statistical analysis when unequal bin sizes were used and Figure 74 shows the results when equal bin sizes were used to assess the revised dataset. In Figure 73, the lowest bin contains results from storm HRTs of 22 to 40 hours. The median value of the bin was 0.37 mg/L, which was very close to the influent median of 0.36 mg/L. This result should be interpreted as a negligible treatment of TP when HRTs less than 40 hours were provided. Along the same lines, Figure 74 shows the median value of 0.34 mg/L from HRTs less than 49 hours. In both figures, the upper limit of the confidence interval was equal or above 0.5 mg/L, which was higher than the median influent value of the overall dataset. When EDBs provided storm HRTs less than 40 hours they were ineffective at TP removal.

Figure 73 does show that a substantial difference in medians resulted when HRTs of 40 to 60 hours were provided, instead of less than 40. This result was complemented by the equal sample analysis, shown in Figure 74, where a statistically lower median was achieved when HRTs of 49 to 60.3 hours occurred compared to HRTs less than 49 hours. Furthermore, when storm HRTs were greater than 60 hours, there was not a significant improvement in effluent quality. The results indicate that optimal TP removal in EDBs occurred when storm HRTs between 50 and 60 hours were provided. This result is problematic because it splits the difference between two common design drawdown times of 40 and 72 hours.

It is important to recognize that median influent value for TP was low, so providing optimal HRTs between 50 and 60 hours still only removed around one third of the influent TP. Furthermore, the upper limit of the confidence interval was 0.35 mg/L (see Figure 74). Strictly speaking, there was little certainty that the results showed any TP removal from inlet to outlet. EDBs from the BMP Database have not been shown to be statistically effective at treating TP in stormwater from inlet to outlet (Geosyntec and WWE 2009). The results presented here show that a distinction in effluent quality might be present when storm HRTs longer than 50-60 hours were provided compared to effluent that was detained for less than 50 hours. The prediction interval, however, did not decrease as the storm HRT increased which means that effluent TP values were highly variable. Optimizing an EDB's drawdown time for TP removal may be impossible since they are not very effective at removing TP.

4.7 Summary of Results and Conclusions

In general, median effluent water quality values for WPs were not reduced when longer HRTs were provided, except for TP. Furthermore, the variability of individual constituents did not decrease when longer HRTs were provided, with the exception of TP, which was consistently lower in median and variability for longer HRTs. There was evidence that exceptionally long HRTs reduced the variability of TR Zn and TR Cu, but limited observations from a single study was the only source of data. The Udall WP provided uncharacteristically long HRTs to treat stormwater runoff, and the low median effluent values could be considered the “best-case scenario” for pollutant removal. The results suggest that it may be more practical to design WPs with short drawdown times because the median was lowered substantially regardless of the HRT provided. Constraints like land availability and construction cost will likely prohibit most communities from being able to build a facility as large as the Udall WP.

Effluent water quality for EDBs was improved when longer storm HRTs were provided. The median effluent value was lower for all constituents when longer HRTs were provided. Variability among effluent values decreased for TR Cu and TSS, but not for TP and TR Zn. The results suggest that longer HRTs were optimal for EDBs because significant reductions in median values resulted when long HRTs were provided. For TP, there was negligible reduction from inlet to outlet when HRTs less than 50 hours were provided. TP was not easily removed by EDBs and previous studies have not been able to determine that statistically significant treatment had occurred from inlet to outlet (Geosyntec and WWE 2009). The results from this analysis suggest that significant reductions in TP may have occurred for EDBs when an HRT greater than 50 hours was provided. However, the magnitude of the TP reduction was still minimal relative to the influent concentration.

Clearly, the WPs were more efficient than the EDBs at consistently removing pollutants from stormwater runoff. The permanent pool of water in a WP is not fully displaced during most storms (UDFCD 2010). This implies that a significant portion of the effluent leaving a WP during an event is comprised of water that has been stored in the pond since the last event. Additional treatment from adsorption, settling, and biological uptake occurs between events so the ponds do not need to detain stormwater as long as EDBs. Additionally, incoming stormwater runoff encounters stored water and the change in momentum encourages pollutants to settle out of the water column.

TSS, TR Zn, and TR Cu are all primarily removed through adsorption and settling. EDB results showed substantial lowering in median effluent values from longer HRTs. These results were not shown by the WP results because the permanent pool of water was displaced during events, and substantial settling of TSS, TR Zn, and TR Cu had occurred between events. Rarely, events with higher effluent concentrations would occur at WPs, but the influence of longer storm HRTs was generally trumped by the longer interevent times. Variability among extreme events was consistent for WPs regardless of the HRT provided exemplifying the importance of the interevent treatment relative to the treatment provided during the drawdown period.

The notable exception was the TP results for WPs. TP is difficult to remove through adsorption and settling alone, but biological uptake from plants and algae has been shown to reduce TP loads to receiving waters (Kantrowitz and Woodham 1995). Larger WPs provided a greater average storm HRT, but also required larger storms to displace the stored volume, and were less influenced by continuous baseflow. The TP results from ponds that provided a longer HRT reflect the effects of longer interevent times where TP was reduced by biological uptake from plants and algae. Longer interevent storage times promote settling and adsorption which also remove some of the TP from stormwater runoff.

The results of the EDB analysis may not be broadly applicable because the dataset was overwhelmingly comprised of California highway BMPs. The Greenville EDB serves an office commercial site in North Carolina, and the Lexington Hill EDB was omitted from most analysis due to low influent concentrations. All other EDBs in the dataset were from California highway studies.

Table 24 shows a summary of the major findings of the HRT analysis for each constituent analyzed for quick reference.

Table 24. Summary of Major Findings from the HRT Analysis

Wet Retention Ponds (WPs)	
TSS	HRTs less than 12 hours provided the same effluent median as longer HRTs. Variability was not reduced when longer HRTs were provided. If TSS reduction is a main concern, a short HRT should provide adequate treatment.
TP	HRTs greater than 24 hours corresponded with significantly lower median TP effluent values. Variability was substantially reduced when longer HRTs were provided. Longer HRTs should reduce the occurrence of storms with high effluent TP concentrations.
TR Zn	HRTs less than 12 hours provided the same effluent median as longer HRTs. Evidence of reduced variability was suggested when extremely long HRTs were provided, but it may not be practical to provide long HRTs for TR Zn removal.
TR Cu	HRTs less than 12 hours provided the same effluent median as longer HRTs. Evidence of reduced variability was suggested when extremely long HRTs were provided, but it may not be practical to provide long HRTs for TR Cu removal.
Extended Detention Basins (EDBs)	
TSS	HRTs greater than 24 hours should be provided under all circumstances. If possible, HRTs greater than 60 hours can be provided for additional pollutant removal at a significant level.
TP	HRTs between 40 and 60 hours provided optimal removal. TP removal has not been shown to be statistically significant from inlet to outlet of EDBs, so TP removal should not be used as the governing design criteria for required HRT.
TR Zn	HRTs greater than 60 hours significantly lowered the TR Zn median. Variability for single events was not reduced.
TR Cu	HRTs greater than 60 hours significantly lowered the TR Cu median. Variability for single events was not reduced.

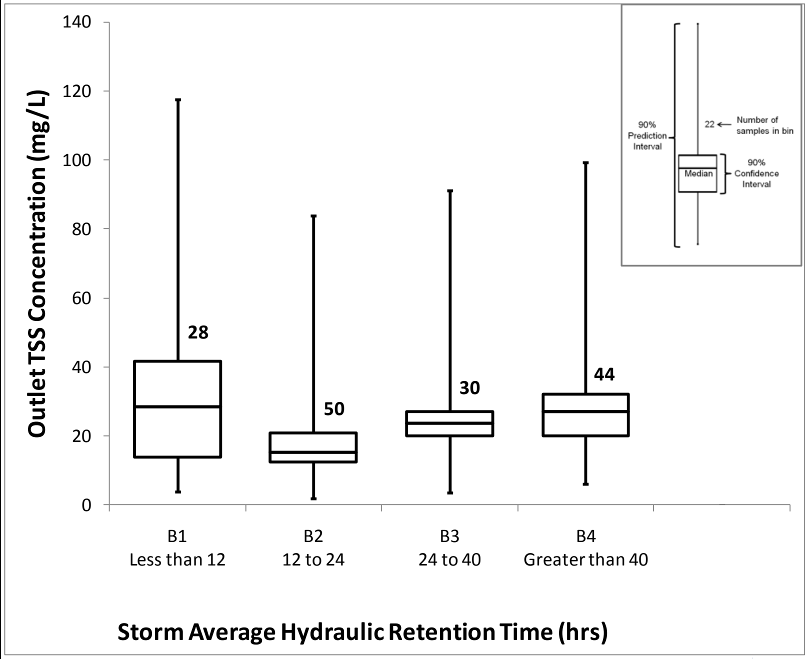
4.8 Recommendations for Further Research

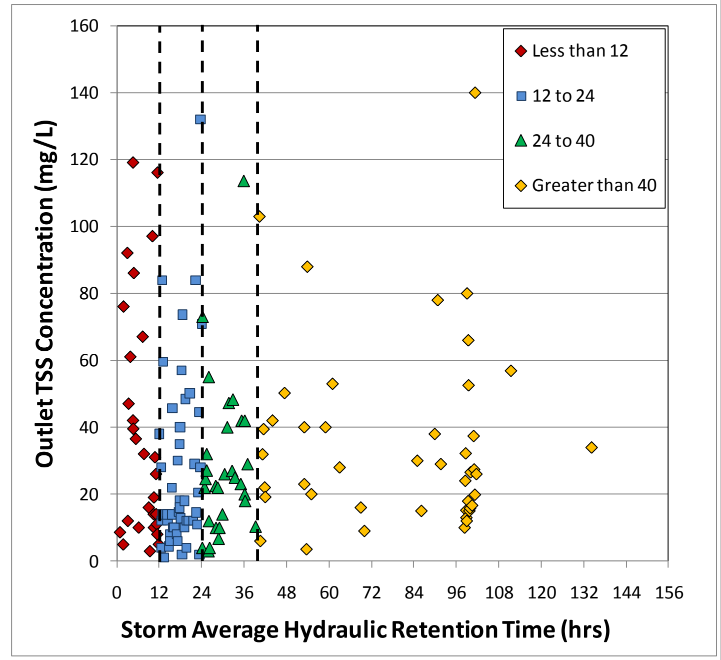
Two major recommendations for future research are listed below:

- A new version of the BMP Database has been released (July 2011) and some new EDB and WP studies were added. Data points from the new studies could be paired to HRT estimates if flow volume was provided with water quality results. The analysis presented in this thesis could be performed again with the new stormwater studies included.

- For WPs, the interevent time is important for pollutant removal because of the additional treatment that occurs in the ponds. This study focused on sizing a BMP based on the HRT that is provided during storms, but an investigation could be conducted to determine how effluent quality was related to interevent time between storms.

Total Suspended Solids for WPs – Unequal Bin Sizes





Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4
Count	28	50	30	44
Median	28.5	15.4	23.8	27.0
Low Confidence Interval	14.0	12.6	20.0	20.1
High Confidence Interval	41.6	21.0	27.1	32.2
Low Prediction Interval	3.86	1.95	3.55	6.00
High Prediction Interval	118	84	91.3	99

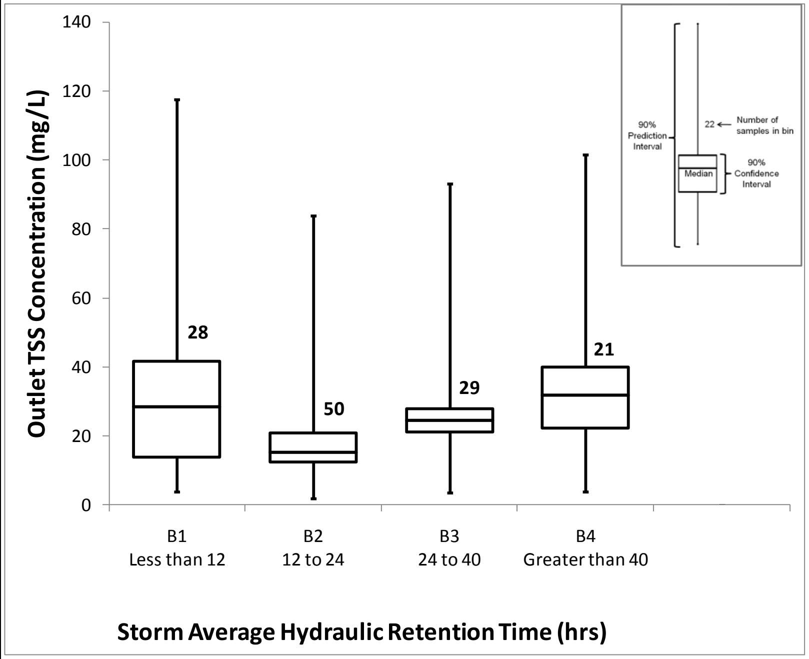
Intervals are at a 90% confidence level unless otherwise specified

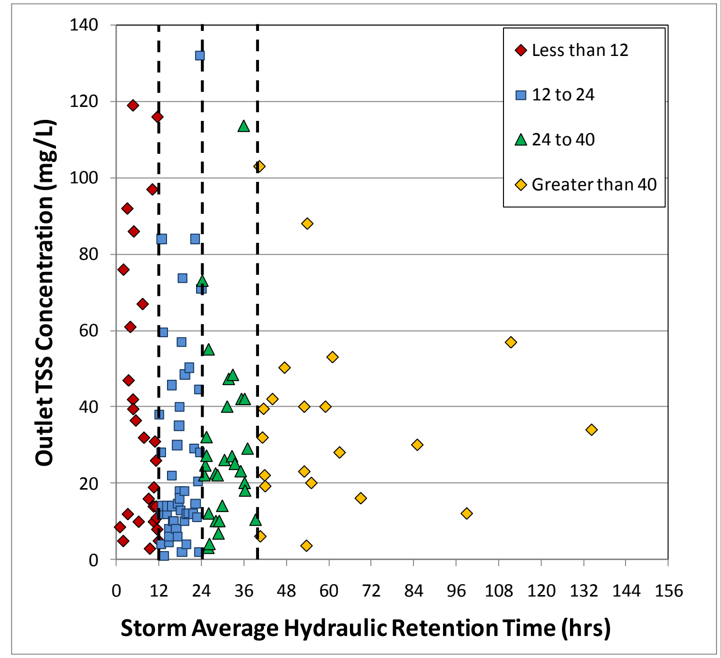
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.1963	80.4
B2-B3	0.3551	64.5
B3-B4	0.3579	64.2
B1-B3	0.5438	45.6
B1-B4	0.8038	19.6
B2-B4	0.0261	97.4

Figure 54. Analysis of TSS for WPs using Unequal Bin Sizes, Includes Madison WP

Total Suspended Solids for WPs – Unequal Bin Sizes, Madison WP Removed





Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4
Count	28	50	29	21
Median	28.5	15.4	24.6	31.9
Low Confidence Interval	14.0	12.6	21.1	22.2
High Confidence Interval	41.6	21.0	27.9	40.0
Low Prediction Interval	3.86	1.95	3.50	3.79
High Prediction Interval	118	84	93.3	102

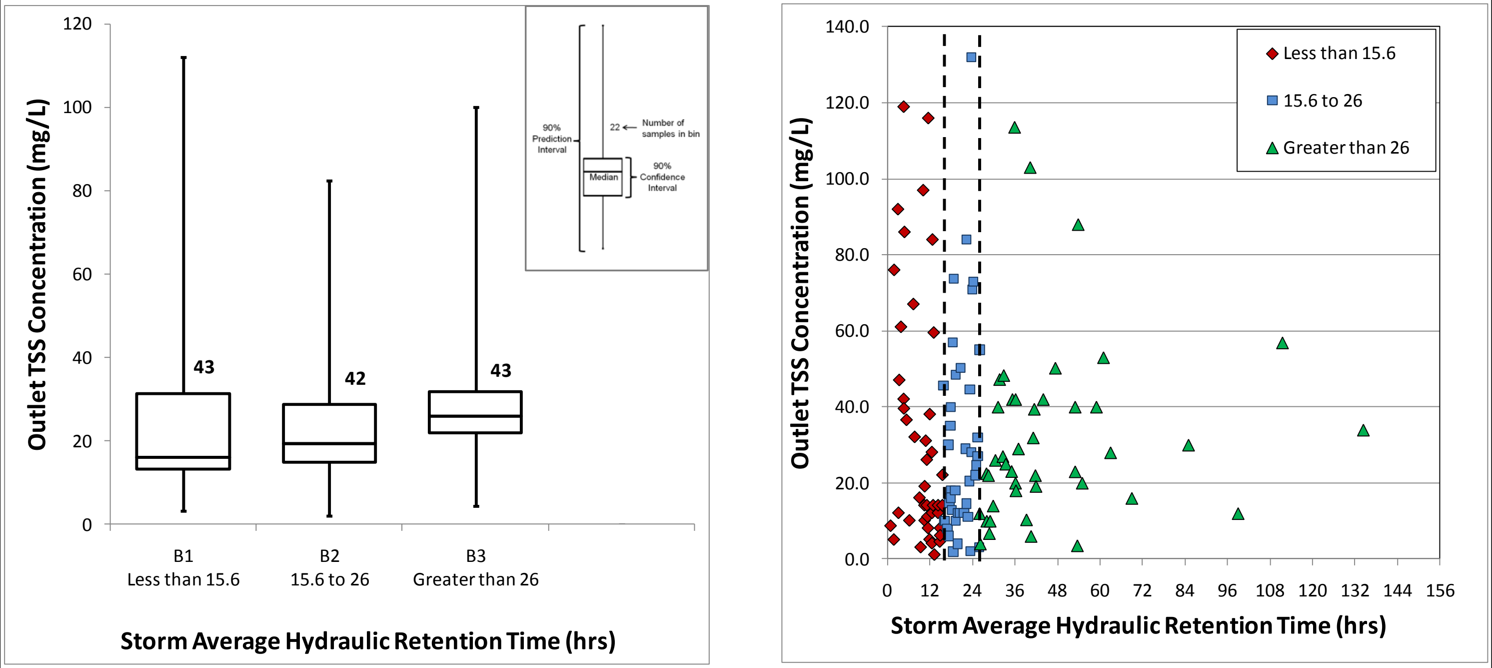
Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.1963	80.4
B2-B3	0.246	75.4
B3-B4	0.2624	73.8
B1-B3	0.678	32.2
B1-B4	0.6567	34.3
B2-B4	0.0321	96.8

Figure 55. Analysis of TSS for WPs using Unequal Bin Sizes, Excludes Madison WP

Total Suspended Solids for WPs – Equal Bin Sizes, Madison WP Removed



Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3
Count	43	42	43
Median	16.0	19.3	26.0
Low Confidence Interval	13.2	14.9	22.0
High Confidence Interval	31.4	28.8	31.9
Low Prediction Interval	3.17	2.15	4.40
High Prediction Interval	112	82	100

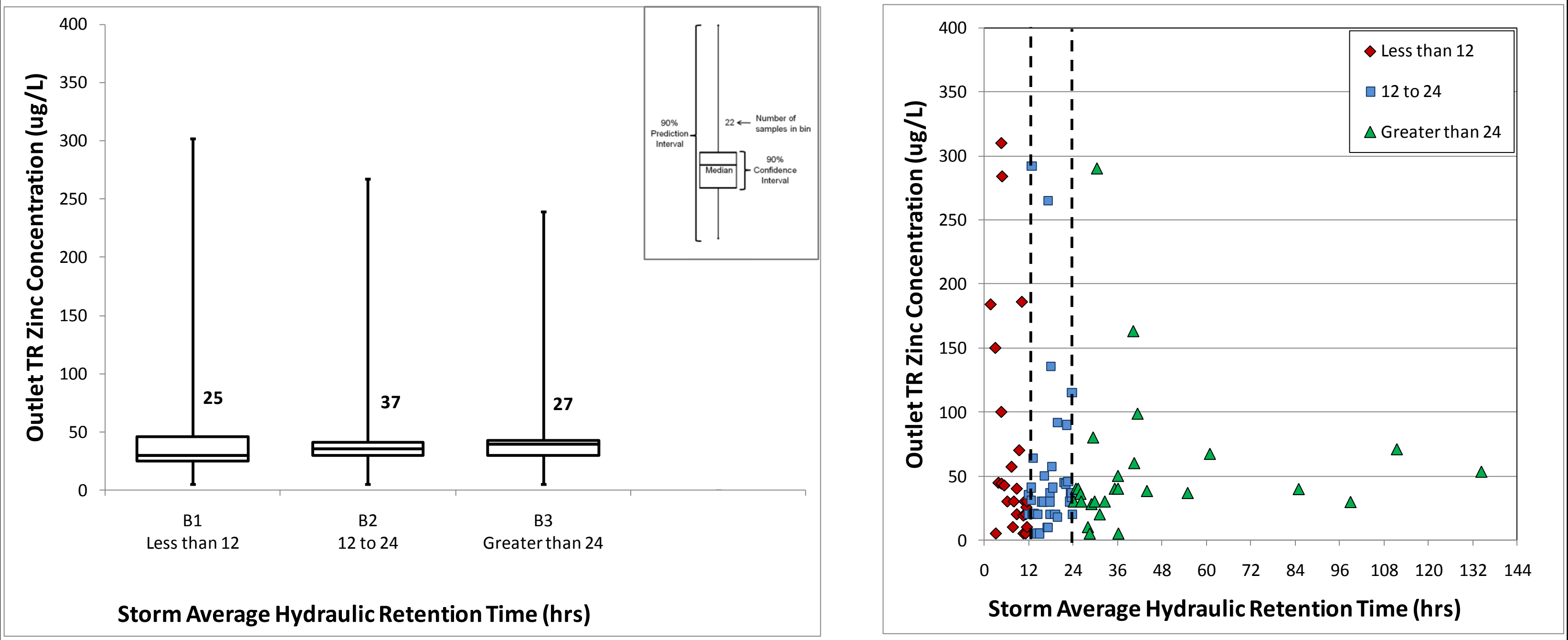
Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.857	14.3
B2-B3	0.3769	62.3
B1-B3	0.3246	67.5

Figure 56. Analysis of TSS for WPs using Equal Bin Sizes, Excludes Madison WP

Total Recoverable Zinc for WPs – Unequal Bin Sizes



Interval Boxplot Values (ug/L)

Statistic	B1	B2	B3
Count	25	37	27
Median	30.0	35.3	39.7
Low Confidence Interval	24.9	30.0	30.0
High Confidence Interval	46.0	41.0	42.7
Low Prediction Interval	5.00	5.00	5.00
High Prediction Interval	302	268	239

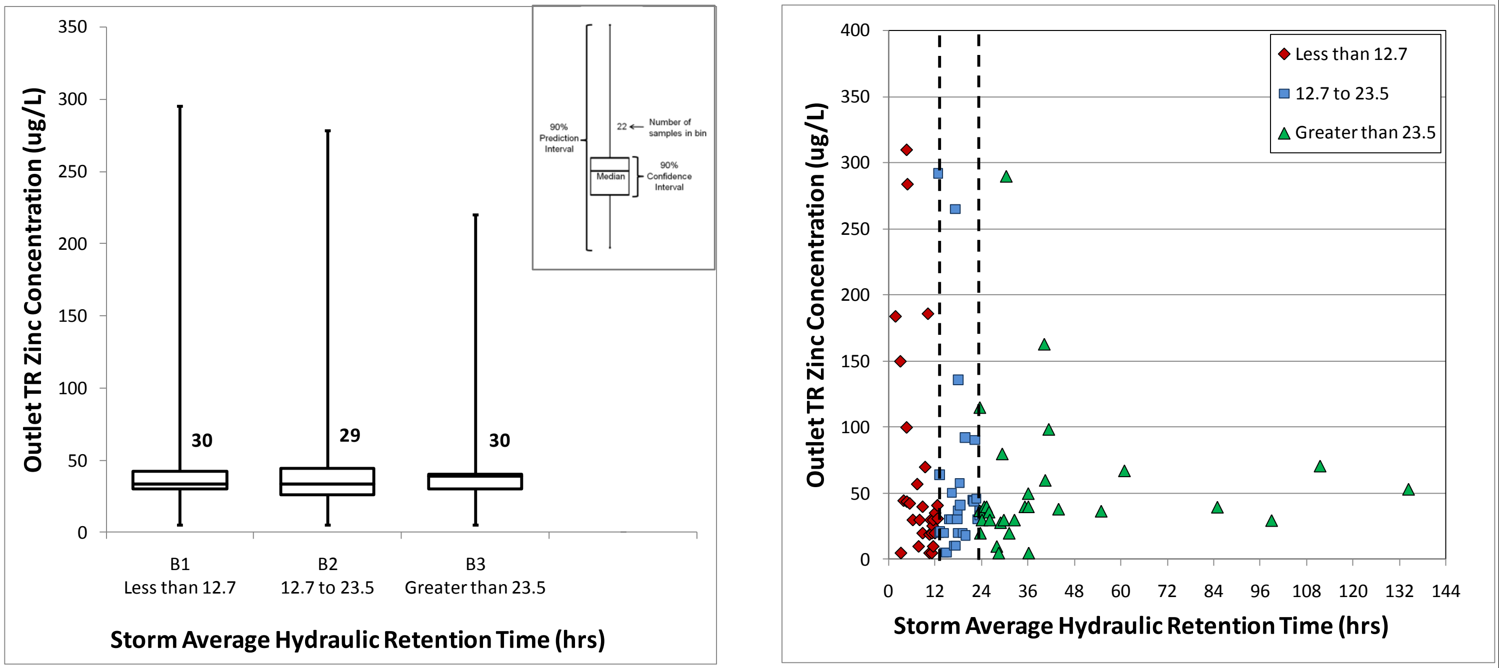
Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.954	4.6
B2-B3	0.5176	48.2
B1-B3	0.769	23.1

Figure 57. Analysis of TR Zn for WPs using Unequal Bin Sizes

Total Recoverable Zinc for WPs – Equal Bin Sizes



Interval Boxplot Values (ug/L)

Statistic	B1	B2	B3
Count	30	29	30
Median	33.1	33.2	39.0
Low Confidence Interval	30.0	26.1	30.0
High Confidence Interval	42.5	44.4	40.0
Low Prediction Interval	5.00	5.00	5.00
High Prediction Interval	296	279	220

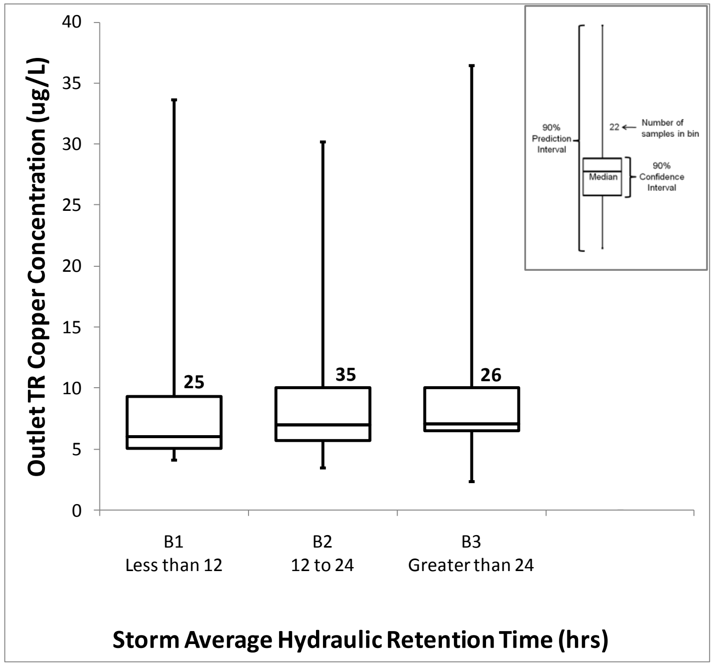
Intervals are at a 90% confidence level unless otherwise specified

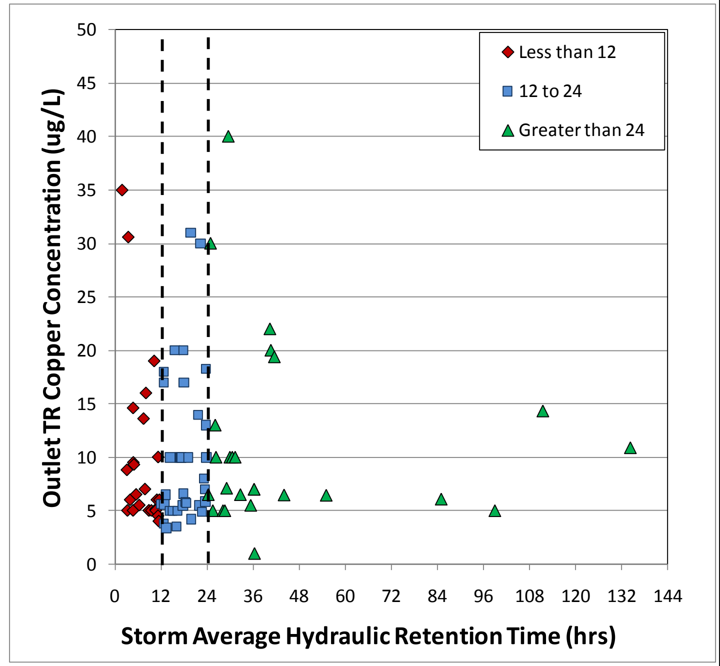
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.958	4.2
B2-B3	0.4941	50.6
B1-B3	0.684	31.6

Figure 58. Analysis of TR Zn for WPs using Equal Bin Sizes

Total Recoverable Copper for WPs – Unequal Bin Sizes





Interval Boxplot Values (ug/L)

Statistic	B1	B2	B3
Count	25	35	26
Median	6.00	7.00	7.05
Low Confidence Interval	5.09	5.71	6.48
High Confidence Interval	9.32	10.00	10.00
Low Prediction Interval	4.15	3.48	2.40
High Prediction Interval	33.7	30.2	36.5

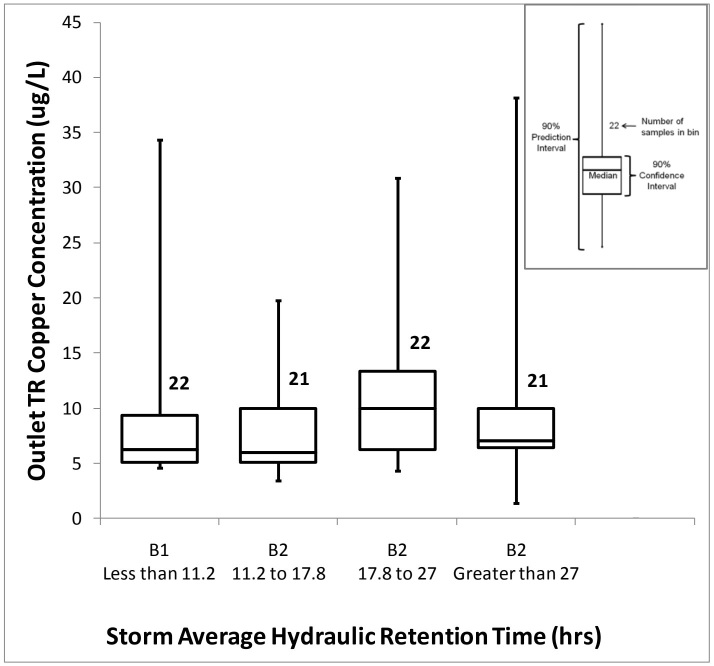
Intervals are at a 90% confidence level unless otherwise specified

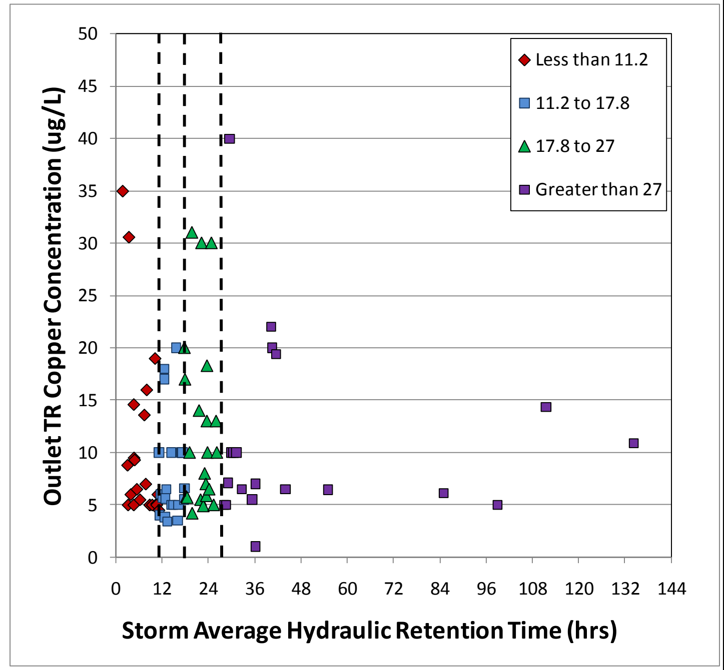
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.578	42.2
B2-B3	0.5733	42.7
B1-B3	0.233	76.7

Figure 59. Analysis of TR Cu for WPs using Unequal Bin Sizes

Total Recoverable Copper for WPs – Equal Bin Sizes





Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4
Count	22	21	22	21
Median	6.25	6.00	10.00	7.00
Low Confidence Interval	5.06	5.12	6.27	6.45
High Confidence Interval	9.37	10.00	13.36	10.00
Low Prediction Interval	4.58	3.41	4.30	1.40
High Prediction Interval	34.34	19.80	30.85	38.20

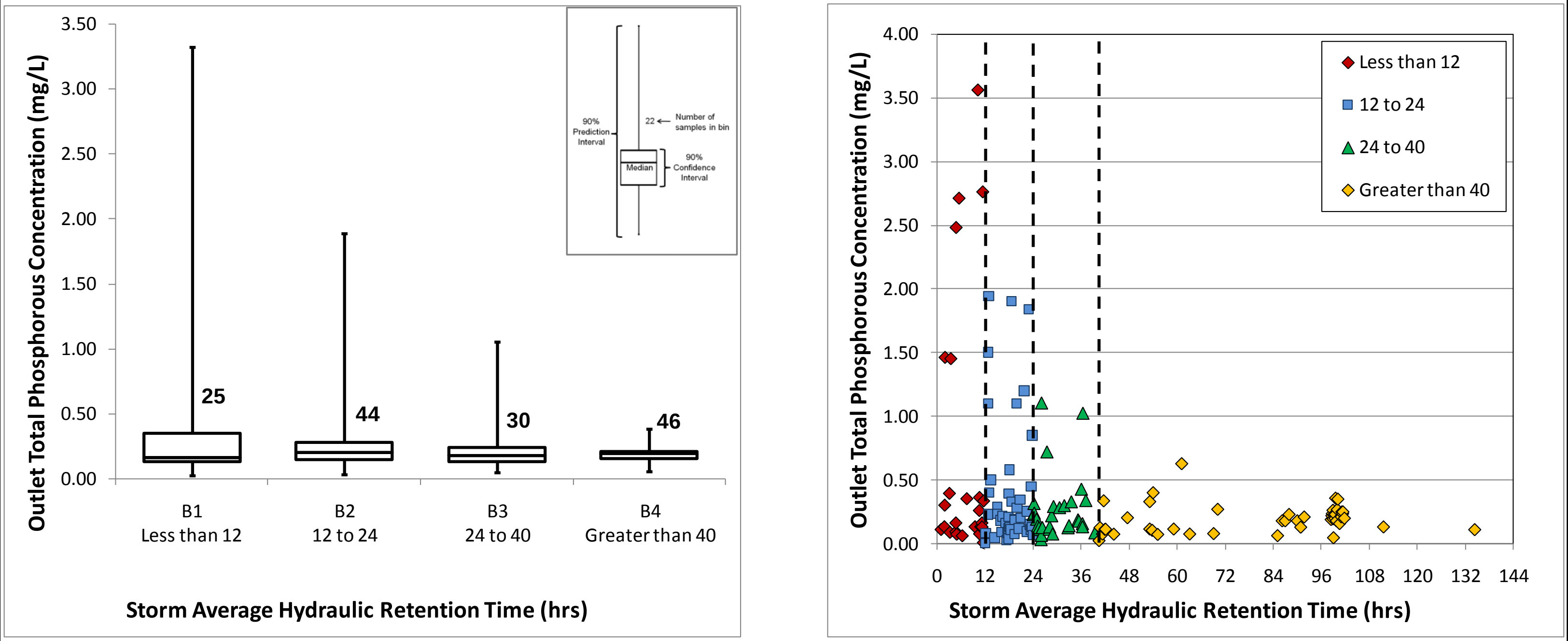
Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.617	38.4
B2-B3	0.054	94.6
B3-B4	0.559	44.1
B1-B3	0.2302	77.0
B1-B4	0.3996	60.0
B2-B4	0.1929	80.7

Figure 60. Analysis of TR Cu for WPs using Equal Bin Sizes

Total Phosphorous for WPs – Unequal Bin Sizes



Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4
Count	25	44	30	46
Median	0.16	0.21	0.18	0.19
Low Confidence Interval	0.13	0.15	0.13	0.16
High Confidence Interval	0.35	0.28	0.24	0.21
Low Prediction Interval	0.02	0.03	0.05	0.05
High Prediction Interval	3.32	1.88	1.06	0.39

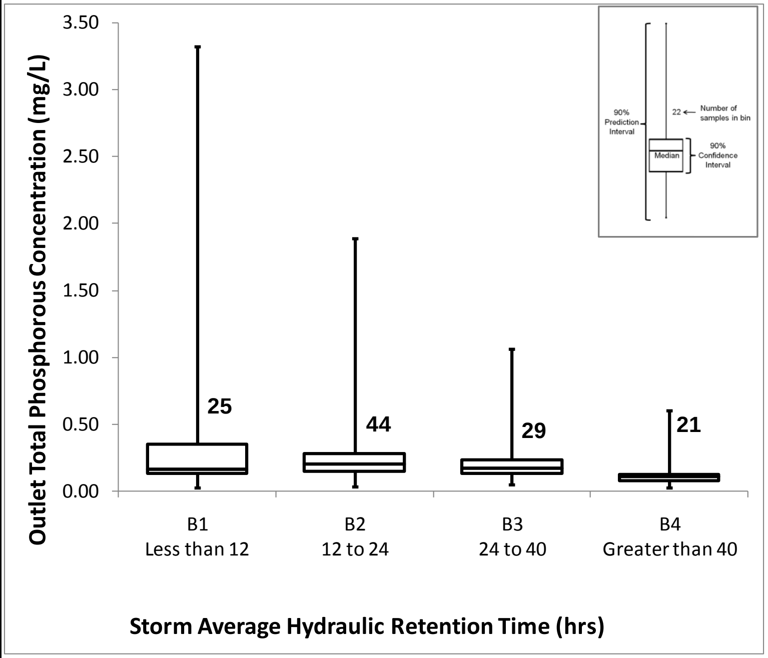
Intervals are at a 90% confidence level unless otherwise specified

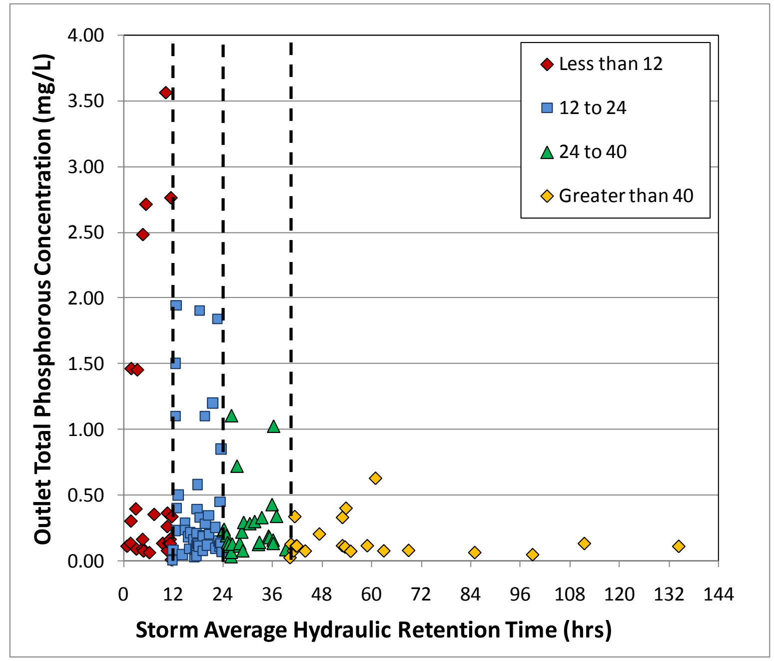
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.827	17.3
B2-B3	0.567	43.3
B3-B4	0.5915	40.9
B1-B3	0.5769	42.3
B1-B4	0.3205	68.0
B2-B4	0.2198	78.0

Figure 61. Analysis of TP for WPs using Unequal Bin Sizes, Includes Madison WP

Total Phosphorous for WPs – Unequal Bin Sizes, Madison WP Removed





Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4
Count	25	44	29	21
Median	0.16	0.21	0.17	0.11
Low Confidence Interval	0.13	0.15	0.13	0.08
High Confidence Interval	0.35	0.28	0.23	0.12
Low Prediction Interval	0.02	0.03	0.05	0.03
High Prediction Interval	3.32	1.88	1.06	0.60

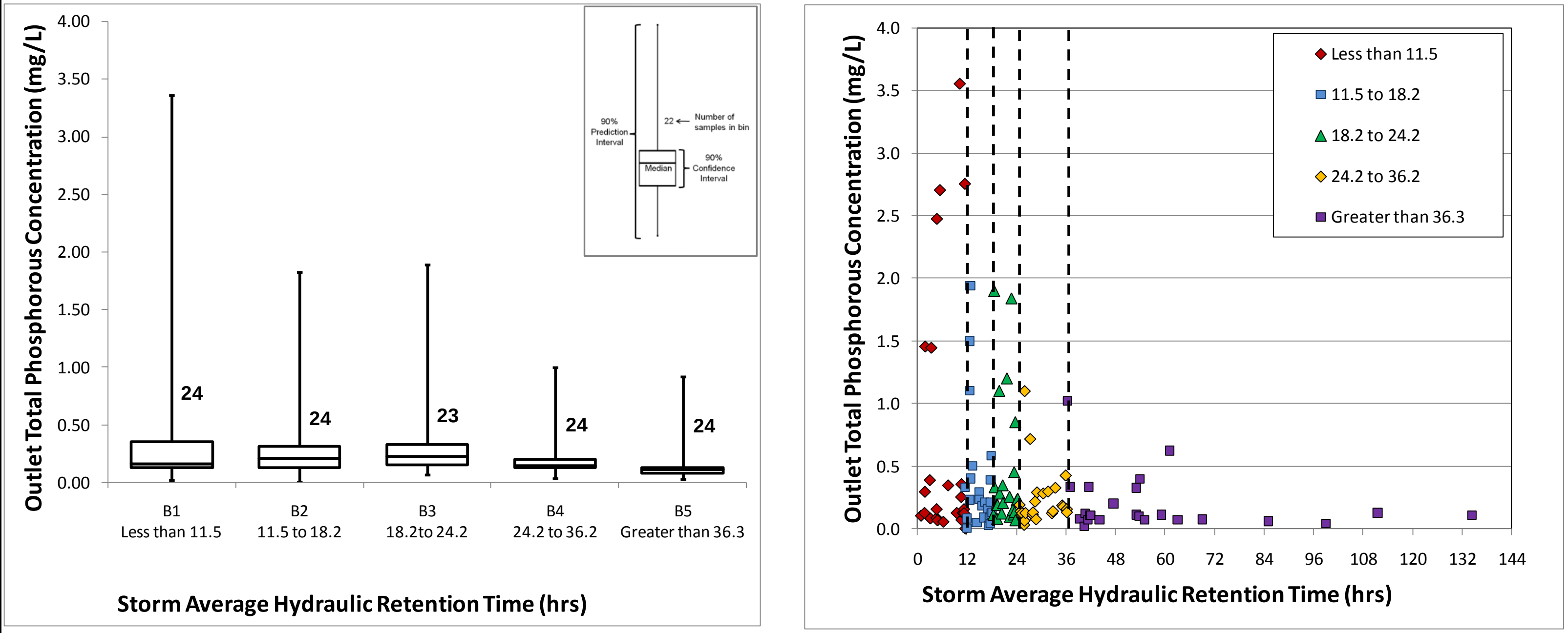
Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.827	17.3
B2-B3	0.5059	49.4
B3-B4	0.0215	97.9
B1-B3	0.5379	46.2
B1-B4	0.031	96.9
B2-B4	0.013	98.7

Figure 62. Analysis of TP for WPs using Unequal Bin Sizes, Excludes Madison WP

Total Phosphorous for WPs – Equal Bin Sizes, Madison WP Removed



Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3	B4	B5
Count	24	24	23	24	24
Median	0.16	0.21	0.23	0.15	0.11
Low Confidence Interval	0.13	0.13	0.15	0.13	0.08
High Confidence Interval	0.36	0.31	0.33	0.20	0.13
Low Prediction Interval	0.02	0.01	0.07	0.04	0.03
High Prediction Interval	3.36	1.83	1.89	1.00	0.92

Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

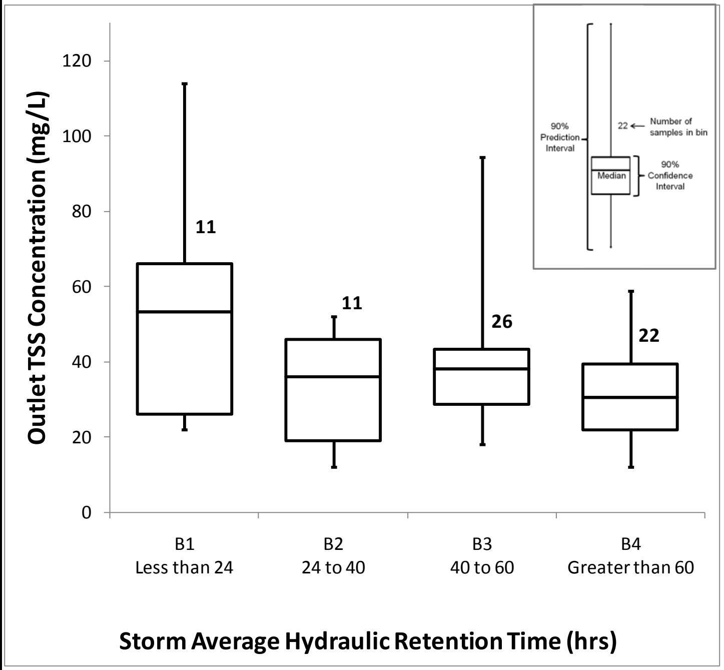
Bins Compared	Test Result	Significance Level (%)
B1-B2	0.7181	28.2
B2-B3	0.5094	49.1
B3-B4	0.1732	82.7
B4-B5	0.1077	89.2
B1-B3	0.7902	21.0

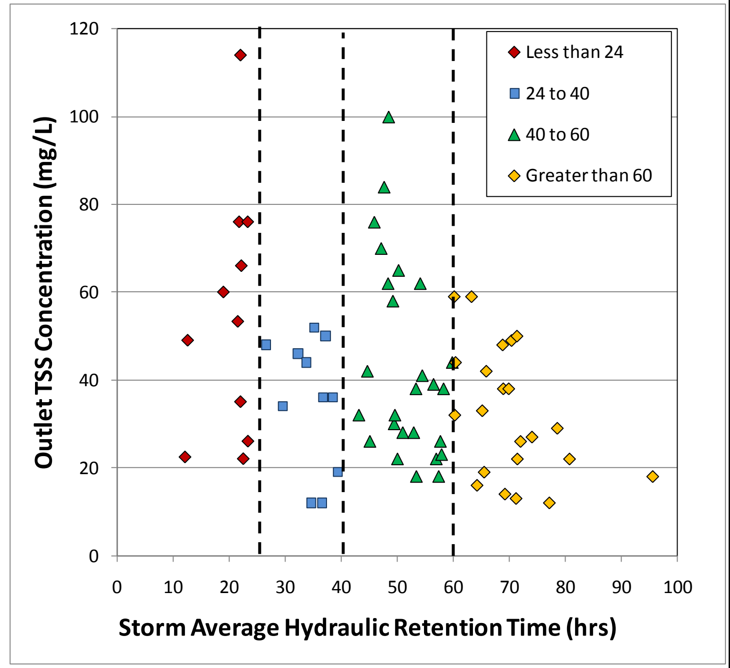
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B2-B4	0.5707	42.9
B3-B5	0.0148	98.5
B1-B4	0.5497	45.0
B2-B5	0.1296	87.0
B1-B5	0.0649	93.5

Figure 63. Analysis of TP for WPs using Equal Bin Sizes, Excludes Madison WP

Total Suspended Solids for EDBs – Unequal Bin Sizes





Interval Boxplot Values (mg/L)

Statistic	B1*	B2*	B3	B4
Count	11	11	26	22
Median	53.3	36.0	38.0	30.5
Low Confidence Interval	26.0	19.0	28.6	22.0
High Confidence Interval	66.0	46.0	43.4	39.4
Low Prediction Interval	22.0	12.0	18.0	12.2
High Prediction Interval	114	52.0	94.4	59.0

Intervals are at a 90% confidence level unless otherwise specified

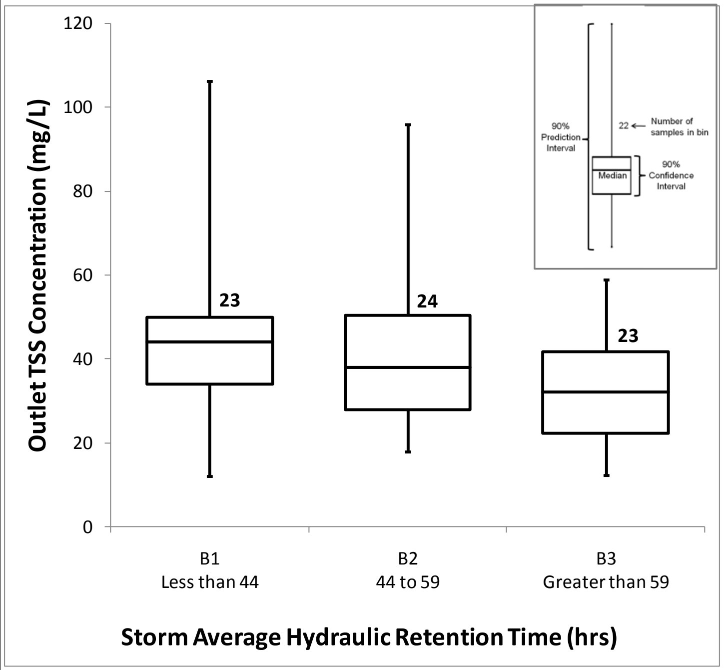
* B1 and B2 show 85.4% confidence interval due to low sample size

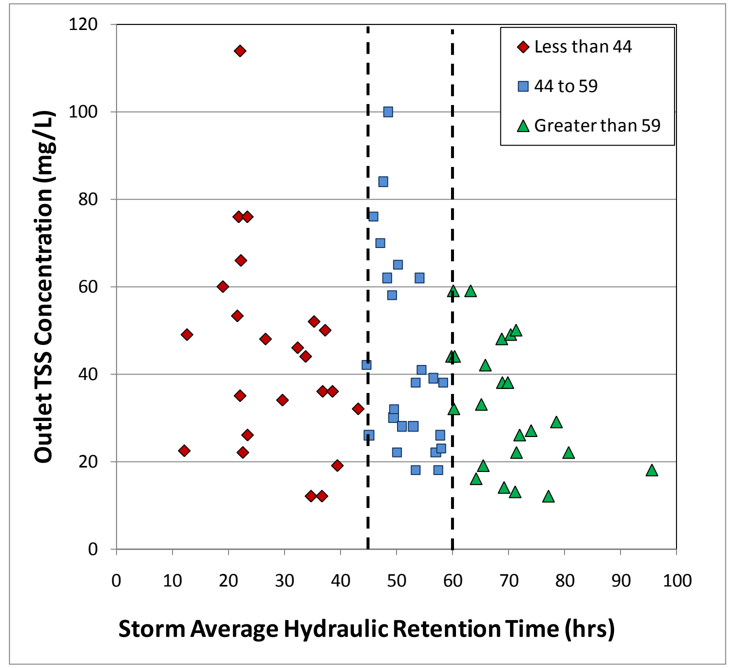
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.076	92.4
B2-B3	0.618	38.2
B3-B4	0.0996	90.0
B1-B3	0.2947	70.5
B1-B4	0.0152	98.5
B2-B4	0.5794	42.1

Figure 64. Analysis of TSS for EDBs using Unequal Bin Sizes

Total Suspended Solids for EDBs – Equal Bin Sizes





Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3
Count	23	24	23
Median	44.0	38.0	32.0
Low Confidence Interval	34.1	28.0	22.2
High Confidence Interval	49.9	50.5	41.8
Low Prediction Interval	12.0	18.0	12.2
High Prediction Interval	106	96.0	59.0

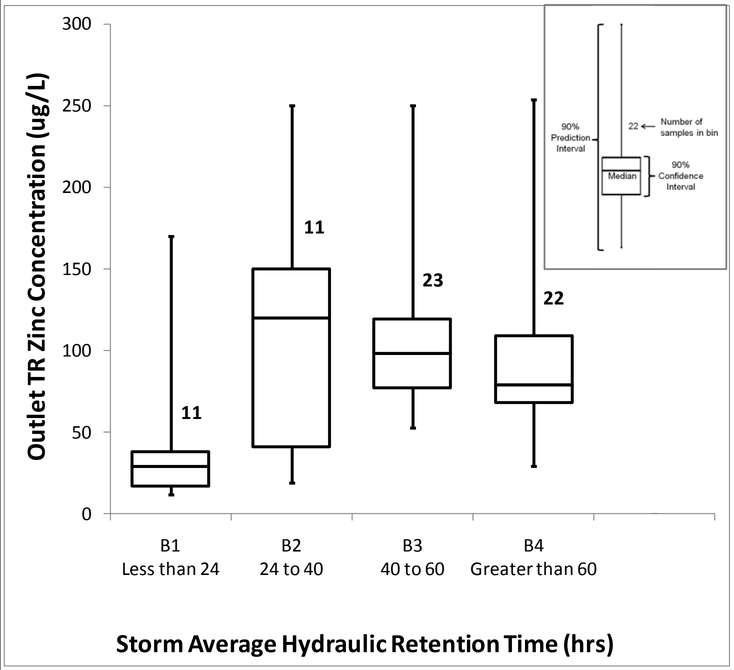
Intervals are at a 90% confidence level unless otherwise specified

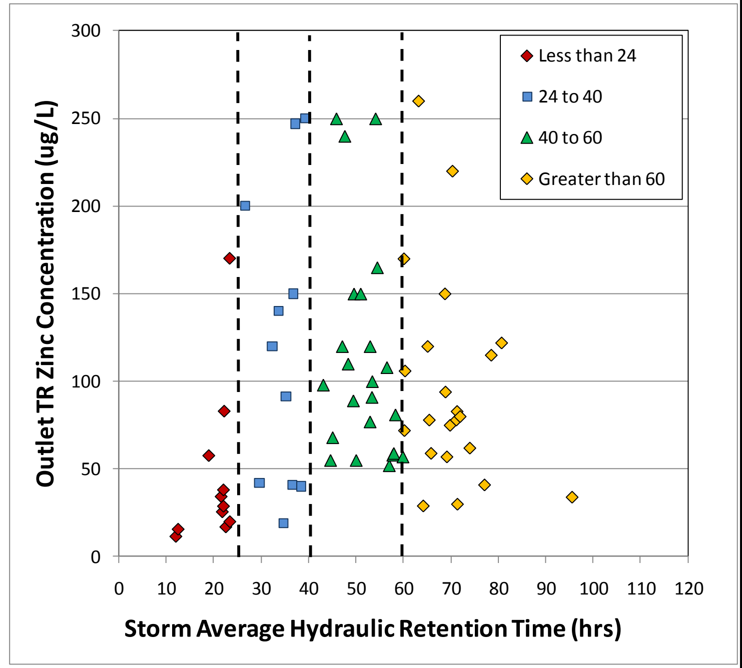
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.848	15.2
B2-B3	0.1387	86.1
B1-B3	0.0824	91.8

Figure 65. Analysis of TSS for EDBs using Equal Bin Sizes

Total Recoverable Zinc for EDBs – Unequal Bin Sizes





Interval Boxplot Values (ug/L)

Statistic	B1*	B2*	B3	B4
Count	11	11	23	22
Median	28.9	120	98.0	79.0
Low Confidence Interval	17.1	41.0	77.2	68.4
High Confidence Interval	38.2	150	119	109
Low Prediction Interval	11.7	19.1	52.6	29.2
High Prediction Interval	170	250	250	254

Intervals are at a 90% confidence level unless otherwise specified

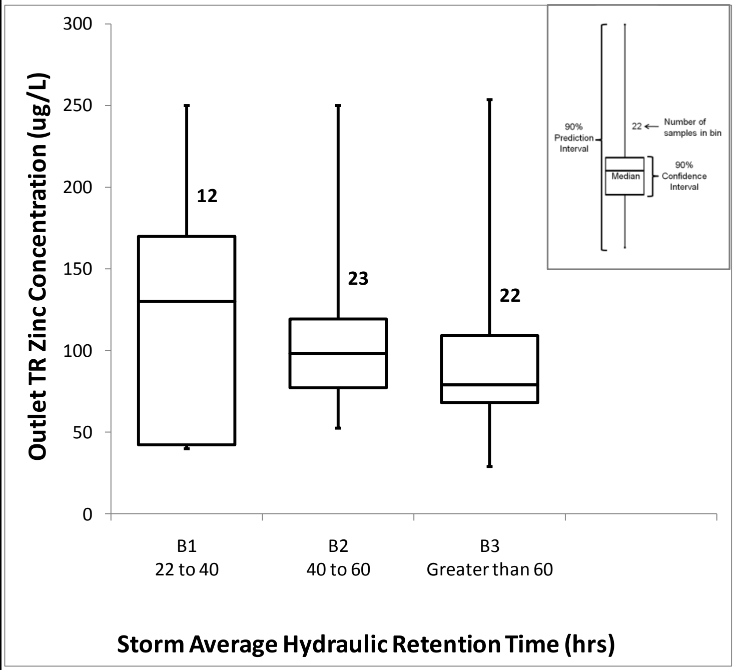
* B1 and B2 show 85.4% confidence interval due to low sample size

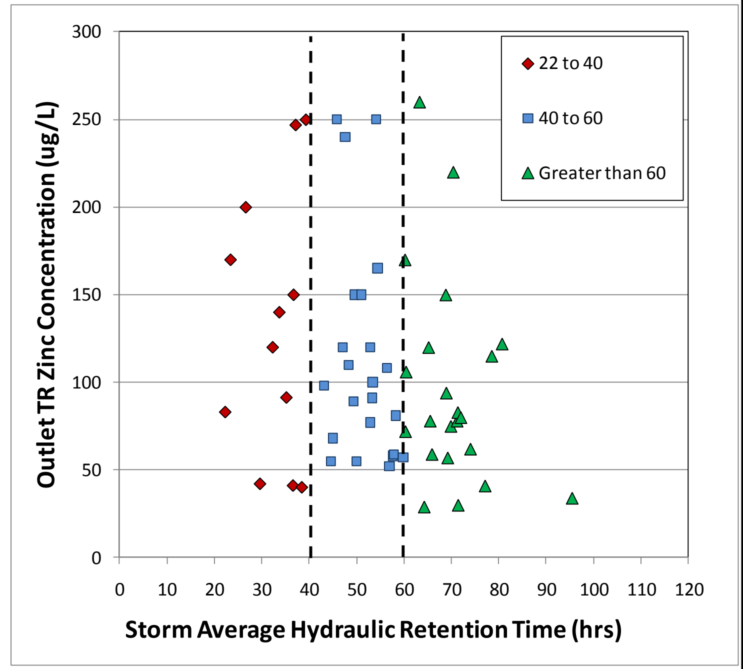
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.0104	99.0
B2-B3	0.9706	2.9
B3-B4	0.3943	60.6
B1-B3	0.0006	99.9
B1-B4	0.0033	99.7
B2-B4	0.5161	48.4

Figure 66. Analysis of TR Zn for EDBs using Unequal Bin Sizes, Includes Lexington Hills EDB

Total Recoverable Zinc for EDBs – Unequal Bin Sizes, Lexington Hills EDB Removed





Interval Boxplot Values (ug/L)

Statistic	B1*	B2	B3
Count	12	23	22
Median	130.0	98.0	79.0
Low Confidence Interval	42.0	77.2	68.4
High Confidence Interval	170.0	119.4	109.2
Low Prediction Interval	40.0	52.6	29.2
High Prediction Interval	250.0	250.0	254.0

Intervals are at a 90% confidence level unless otherwise specified

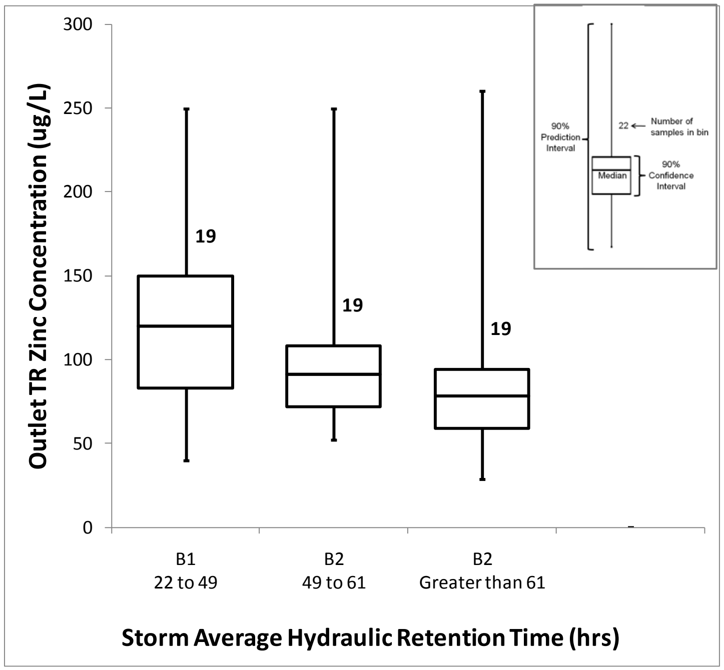
* B1 shows a 90.8% confidence interval due to low sample size

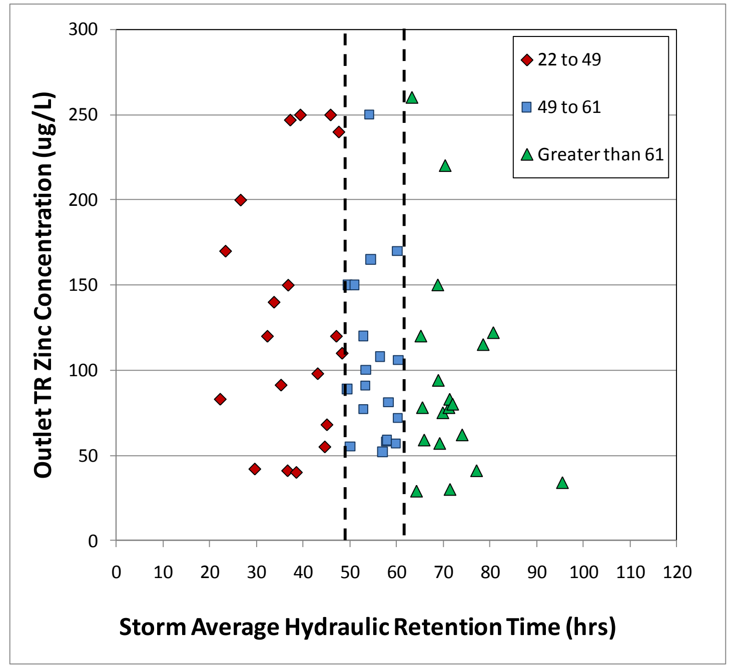
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.5898	41.0
B2-B3	0.3943	60.6
B1-B3	0.1651	83.5

Figure 67. Analysis of TR Zn for EDBs using Unequal Bin Sizes, Excludes Lexington Hills EDB

Total Recoverable Zinc for EDBs – Equal Bin Sizes, Lexington Hills EDB Removed





Interval Boxplot Values (ug/L)

Statistic	B1*	B2*	B3*
Count	19	19	19
Median	120.0	91.0	78.0
Low Confidence Interval	83.0	72.0	59.0
High Confidence Interval	150.0	108.0	94.0
Low Prediction Interval	40.0	52.0	29.0
High Prediction Interval	250.0	250.0	260.0

Intervals are at a 90% confidence level unless otherwise specified

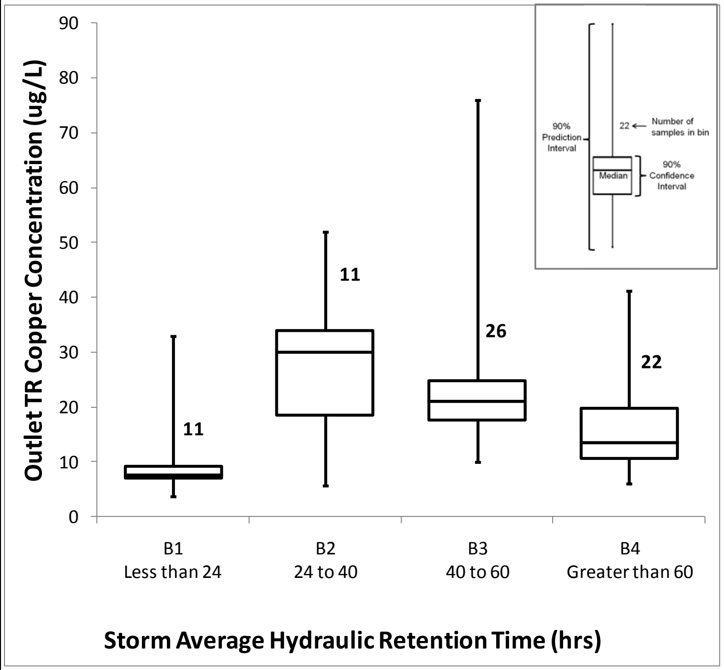
* B1, B2, and B3 show an 88.5% confidence interval due to low sample size

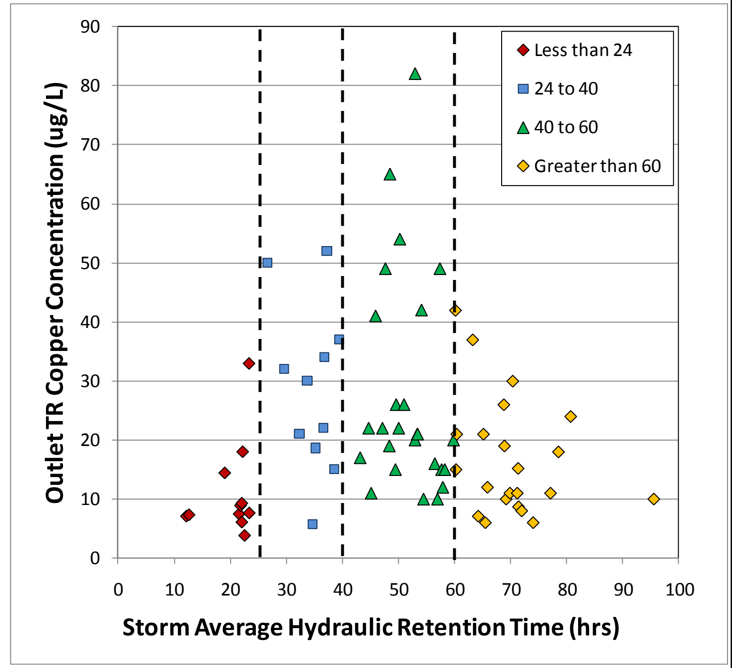
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.365	63.5
B2-B3	0.373	62.7
B1-B3	0.090	91.0

Figure 68. Analysis of TR Zn for EDBs using Equal Bin Sizes, Excludes Lexington Hills EDB

Total Recoverable Copper for EDBs – Unequal Bin Sizes





Interval Boxplot Values (ug/L)

Statistic	B1*	B2*	B3	B4
Count	11	11	26	22
Median	7.59	30.0	21.0	13.5
Low Confidence Interval	7.05	18.6	17.6	10.6
High Confidence Interval	9.25	34.0	24.8	19.7
Low Prediction Interval	3.77	5.73	10.0	6.00
High Prediction Interval	33.0	52.0	76.1	41.3

Intervals are at a 90% confidence level unless otherwise specified

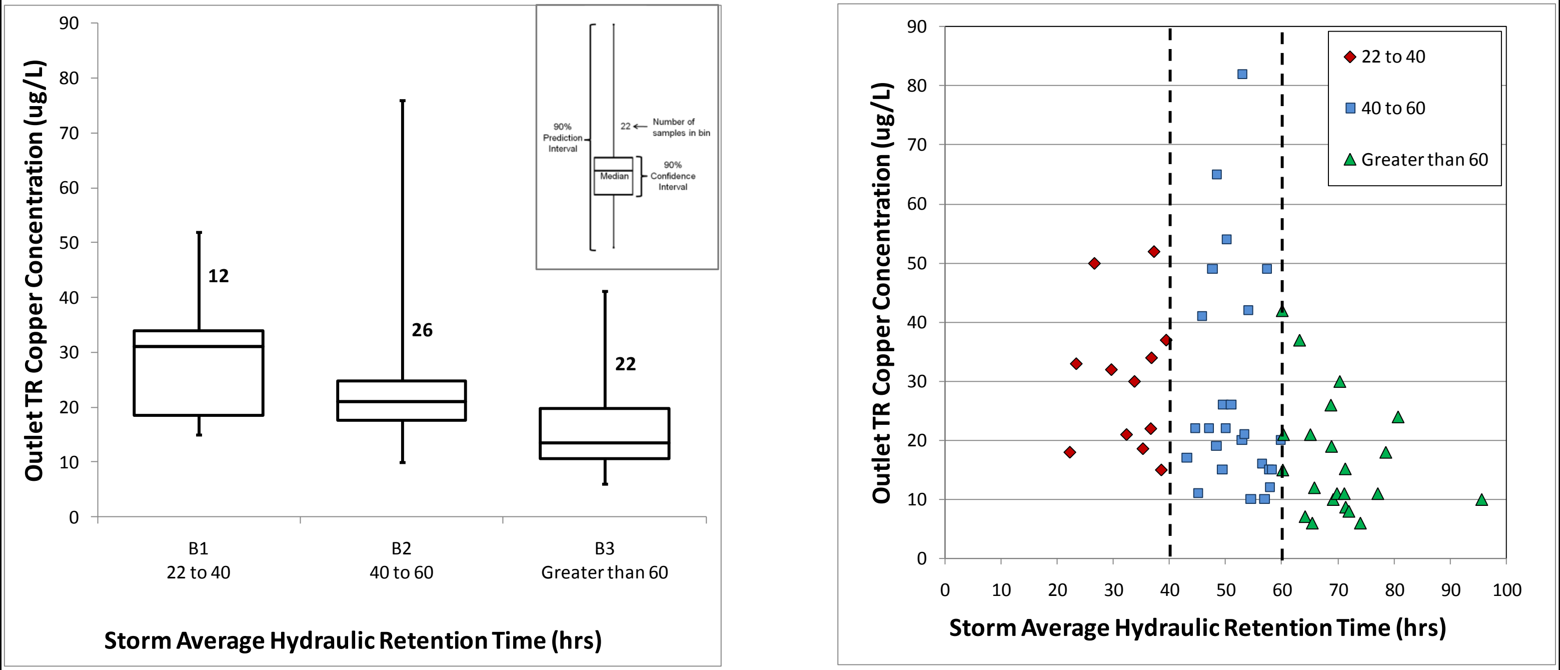
* B1 and B2 show 85.4% confidence interval due to low sample size

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.0047	99.5
B2-B3	0.4742	52.6
B3-B4	0.0115	98.9
B1-B3	0.000283	100.0
B1-B4	0.0428	95.7
B2-B4	0.0197	98.0

Figure 69. Analysis of TR Cu for EDBs using Unequal Bin Sizes, Includes Lexington Hills EDB

Total Recoverable Copper for EDBs – Unequal Bin Sizes, Lexington Hills EDB Removed



Interval Boxplot Values (ug/L)

Statistic	B1*	B2	B3
Count	12	26	22
Median	31.0	21.0	13.5
Low Confidence Interval	18.6	17.6	10.6
High Confidence Interval	34.0	24.8	19.7
Low Prediction Interval	15.0	10.0	6.0
High Prediction Interval	52.0	76.1	41.3

Intervals are at a 90% confidence level unless otherwise specified

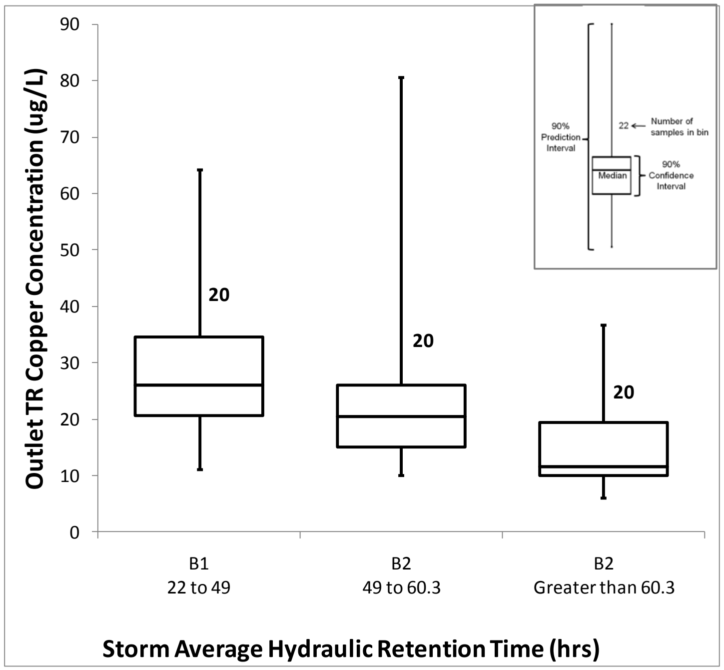
* B1 shows a 90.8% confidence interval due to low sample size

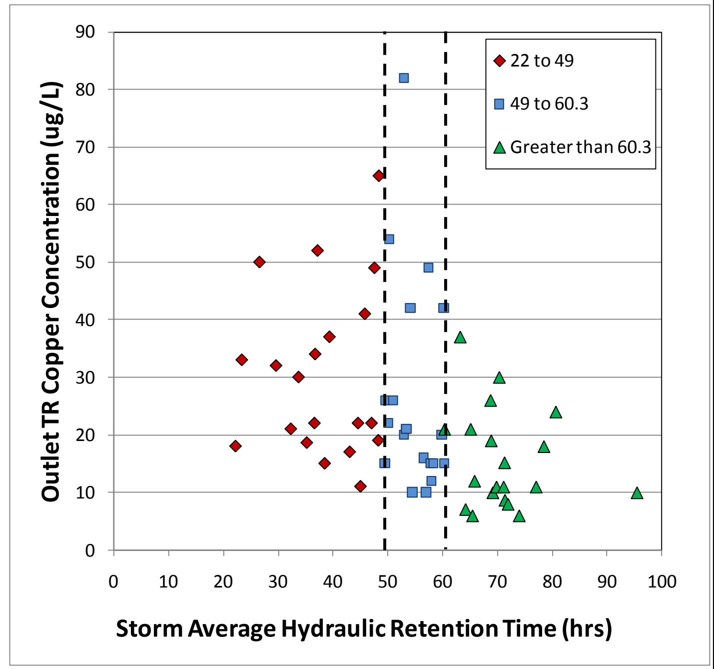
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.251	74.9
B2-B3	0.0115	98.9
B1-B3	0.0026	99.7

Figure 70. Analysis of TR Cu for EDBs using Unequal Bin Sizes, Excludes Lexington Hills EDB

Total Recoverable Copper for EDBs – Equal Bin Sizes, Lexington Hills EDB Removed





Interval Boxplot Values (ug/L)

Statistic	B1	B2	B3
Count	20	20	20
Median	26.0	20.5	11.5
Low Confidence Interval	20.6	15.0	10.0
High Confidence Interval	34.5	26.0	19.4
Low Prediction Interval	11.2	10.0	6.0
High Prediction Interval	64.4	80.6	36.7

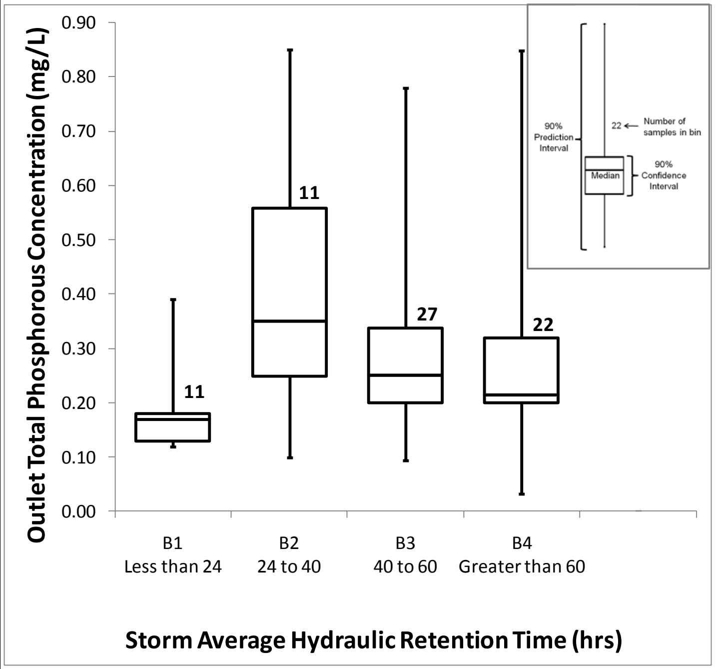
Intervals are at a 90% confidence level unless otherwise specified

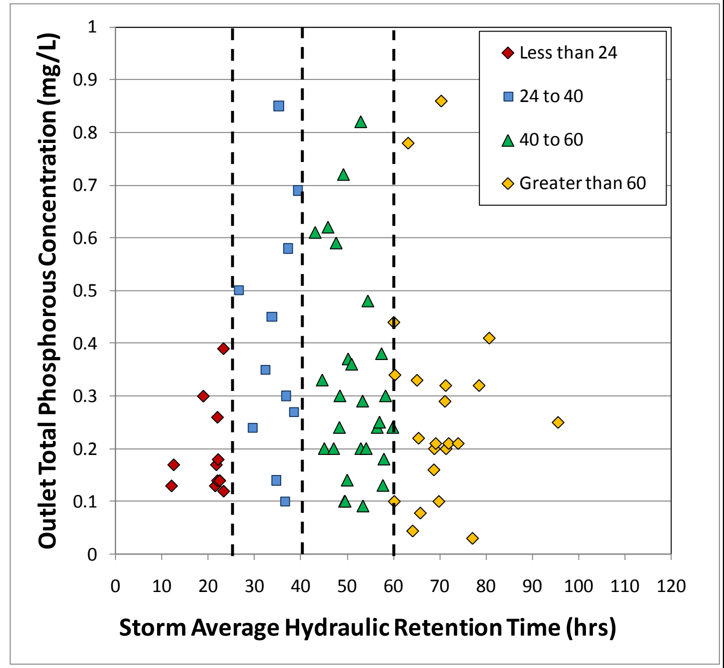
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.1798	82.0
B2-B3	0.0184	98.2
B1-B3	0.001	99.9

Figure 71. Analysis of TR Cu for EDBs using Equal Bin Sizes, Excludes Lexington Hills EDB

Total Phosphorous for EDBs – Unequal Bin Sizes





Interval Boxplot Values (mg/L)

Statistic	B1*	B2*	B3	B4
Count	11	11	27	22
Median	0.17	0.35	0.25	0.21
Low Confidence Interval	0.13	0.25	0.20	0.20
High Confidence Interval	0.18	0.56	0.34	0.32
Low Prediction Interval	0.12	0.10	0.09	0.03
High Prediction Interval	0.39	0.85	0.78	0.85

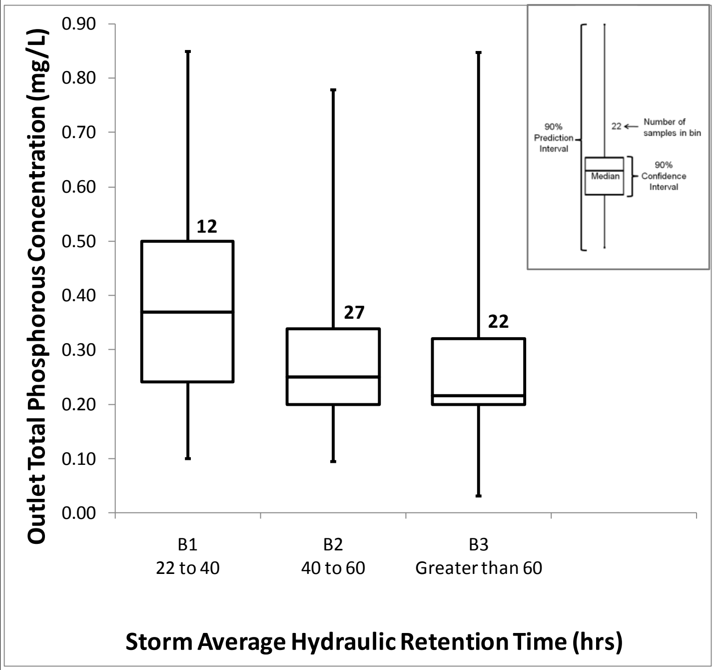
Intervals are at a 90% confidence level unless otherwise specified
* B1 and B2 show 85.4% confidence interval due to low sample size

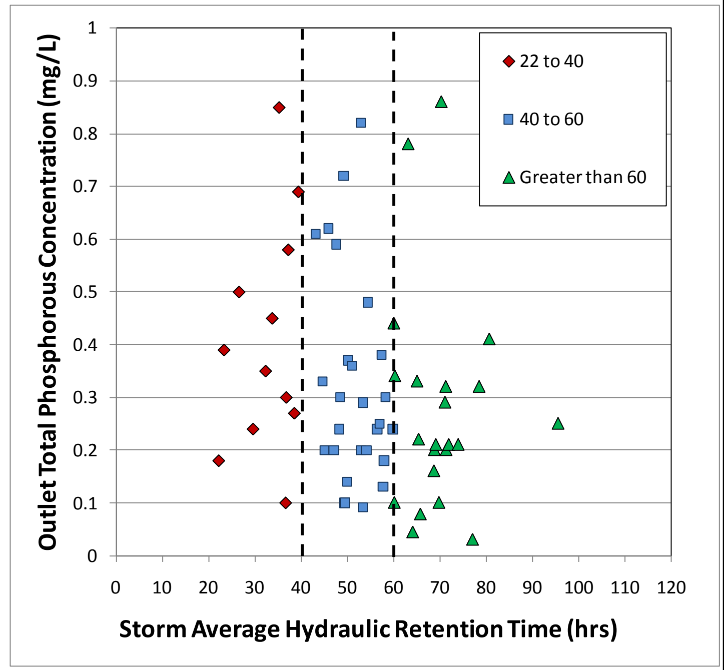
Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.0232	97.7
B2-B3	0.273	72.7
B3-B4	0.4324	56.8
B1-B3	0.0439	95.6
B1-B4	0.2142	78.6
B2-B4	0.082	91.8

Figure 72. Analysis of TP for EDBs using Unequal Bin Sizes, Includes Lexington Hills EDB

Total Phosphorous for EDBs – Unequal Bin Sizes, Lexington Hills EDB Removed





Interval Boxplot Values (mg/L)

Statistic	B1*	B2	B3
Count	12	27	22
Median	0.37	0.25	0.21
Low Confidence Interval	0.24	0.20	0.20
High Confidence Interval	0.50	0.34	0.32
Low Prediction Interval	0.10	0.09	0.03
High Prediction Interval	0.85	0.78	0.85

Intervals are at a 90% confidence level unless otherwise specified

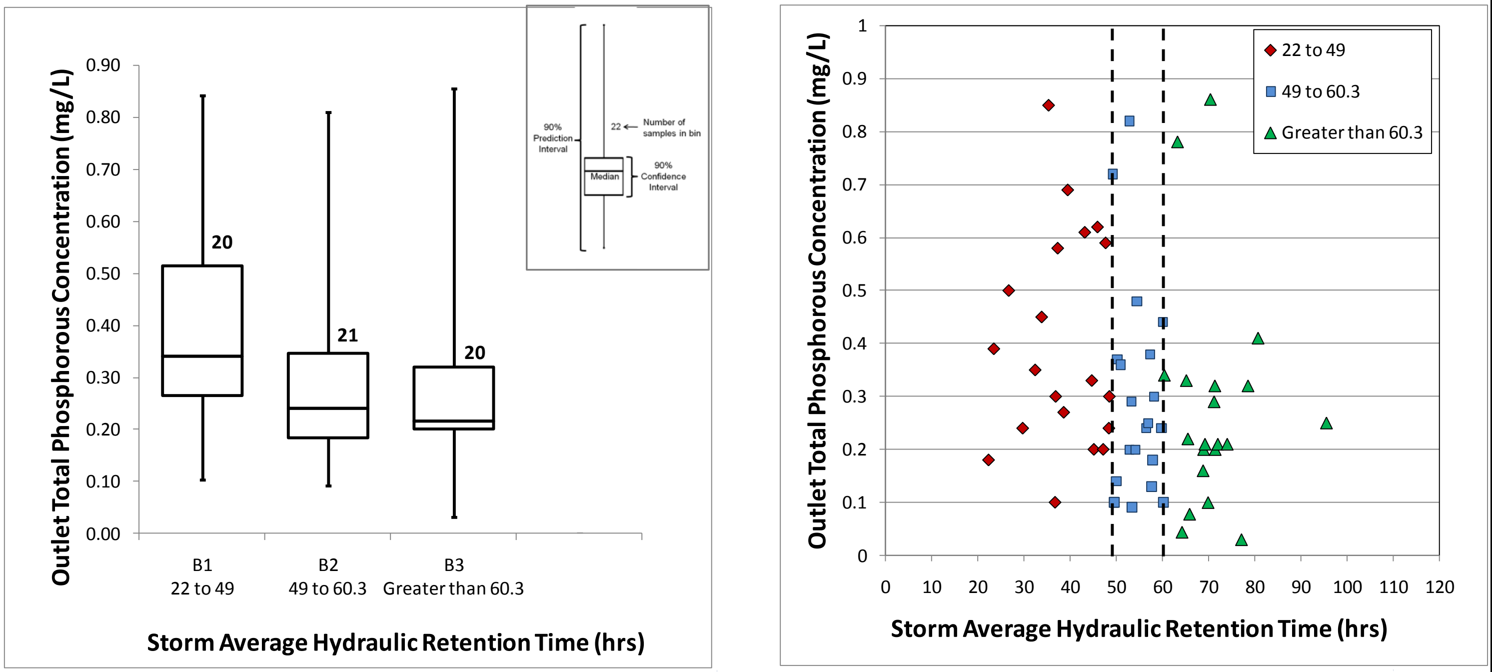
* B1 shows a 90.8% confidence interval due to low sample size

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.1953	80.5
B2-B3	0.4324	56.8
B1-B3	0.0537	94.6

Figure 73. Analysis of TP for EDBs using Unequal Bin Sizes, Excludes Lexington Hills EDB

Total Phosphorous for EDBs – Equal Bin Sizes, Lexington Hills EDB Removed



Interval Boxplot Values (mg/L)

Statistic	B1	B2	B3
Count	20	21	20
Median	0.34	0.24	0.21
Low Confidence Interval	0.26	0.18	0.20
High Confidence Interval	0.51	0.35	0.32
Low Prediction Interval	0.10	0.09	0.03
High Prediction Interval	0.84	0.81	0.86

Intervals are at a 90% confidence level unless otherwise specified

Matlab Ranksum Results

Bins Compared	Test Result	Significance Level (%)
B1-B2	0.062	93.8
B2-B3	0.7739	22.6
B1-B3	0.0437	95.6

Figure 74. Analysis of TP for EDBs using Equal Bin Sizes, Excludes Lexington Hills EDB

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APPENDIX A: RATING CURVES AND ASSUMPTIONS

Udall WP Inlet

The inlet to the Udall WP consists of a 96-inch reinforced concrete pipe where water free falls into a forebay. Depth measurements with a double-bubbler system were taken approximately 15 ft upstream of where the pipe daylights. Figure A-1 shows an overhead view of runoff entering the Udall WP through the pipe.

Figure A-1. Overhead View of Runoff Entering the Udall WP through the Inlet Pipe

Uniform flow was assumed since the effects of the outlet drop would be minimal where the depth readings were taken. Manning's open channel flow equation was used to generate the rating curves at the inlet and is shown as Equation A-1.

$$Q = \frac{1.49}{n} R^{2/3} S^{1/2}$$

Equation A-1

Where: Q = flow in cfs

n = Manning's roughness coefficient = 0.013

R = Hydraulic radius (ft)

S = Slope = 0.0078 (ft/ft) (Rocky Mountain Consultants 2001)

Flow was calculated for the range of depths that would be expected in the pipe using SWMM. The CR10 datalogger at the site required the rating curve to be in the form of a polynomial equation for depth to flow conversion. Two polynomial equations were used to accurately convert depth to flow. Low flows were more accurately represented with a refined curve from 0.0 to 1.1 ft. Higher flows occurring at depths greater than 1.1 ft were better estimated with an overall polynomial curve that was fit from 0.0 to 8.0 ft. Figure A-2 displays the Udall inlet overall rating curve for all depths and shows the two polynomial best-fit lines.

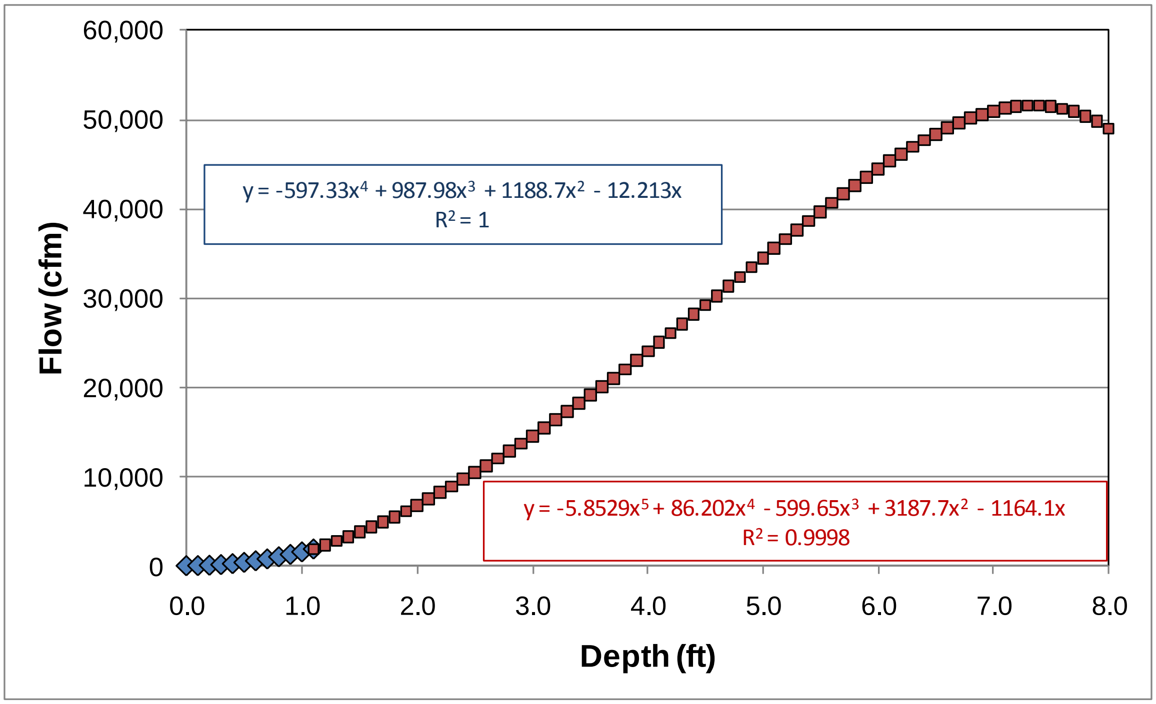

Figure A-2. Udall Inlet Overall Rating Curve for all Depths

Udall WP Pond 1 and Pond 2 Outlets

Similar outlet structures were constructed at both Pond 1 and Pond 2 of the Udall WP. A plate consisting of three columns of 1 ¾ in. diameter circular orifices, spaced 4 inches apart on center vertically, allowed water to slowly drain through to a culvert. Figure A-3 shows water flowing through one of the orifice plates at Pond 2. Above the water quality orifices is horizontal trash rack that was modeled as a weir. An example of water flowing through the outlet structure trash grate is shown in Figure A-4. The total height of the orifice plate was different between the ponds. At Pond 1, the trash rack was located 4.3 ft above the culvert invert; the trash rack was 3.75 ft above the culvert invert at Pond 2.

Figure A-3. Water Flowing through Orifice Plate at Pond 2

Figure A-4. Water Flowing through the Trash Grate at the Pond 1 Outlet Structure

Both ponds were modeled using UD_Detention (v2.2) from the UDFCD website. A two-part rating curve was developed for each pond outlet by fitting separate polynomial equations to the orifice plate portion of the outlet structure and the trash rack portion of the structure, respectively. When the orifice plate contribution was modeled, it was assumed that 50% blockage was occurring based on observations of frequent clogging at the sites. The UD_Detention output was multiplied by 0.5 at each stage to estimate 50% blocked orifices. Clogging percentages varied between events and adjustments were made for each storm. The Pond 1 outlet rating curve is shown in Figure A-5 with each best-fit polynomial equation. The Pond 2 outlet rating curve is shown in Figure A-6 with each best-fit polynomial equation. Note that the weir portion dominates the orifice contribution resulting in a spike in the stage-discharge curve at both pond outlets when the stage of the pond reaches the trash grate.

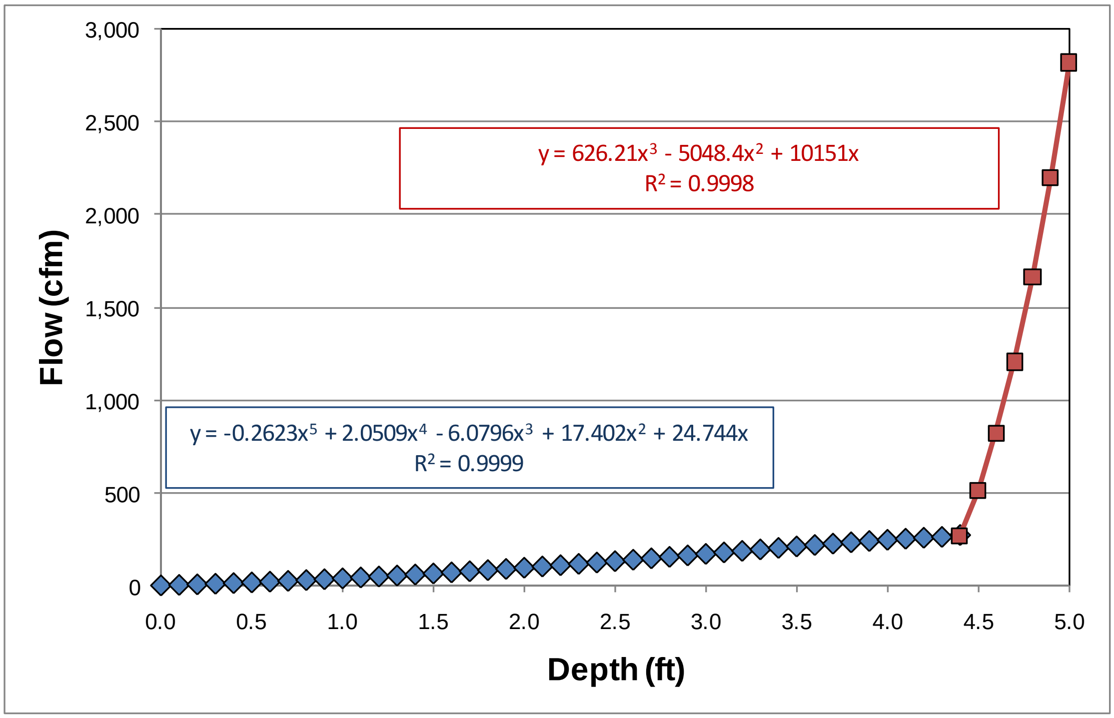

Figure A-5. Udall Pond 1 Outlet Rating Curve for all Depths

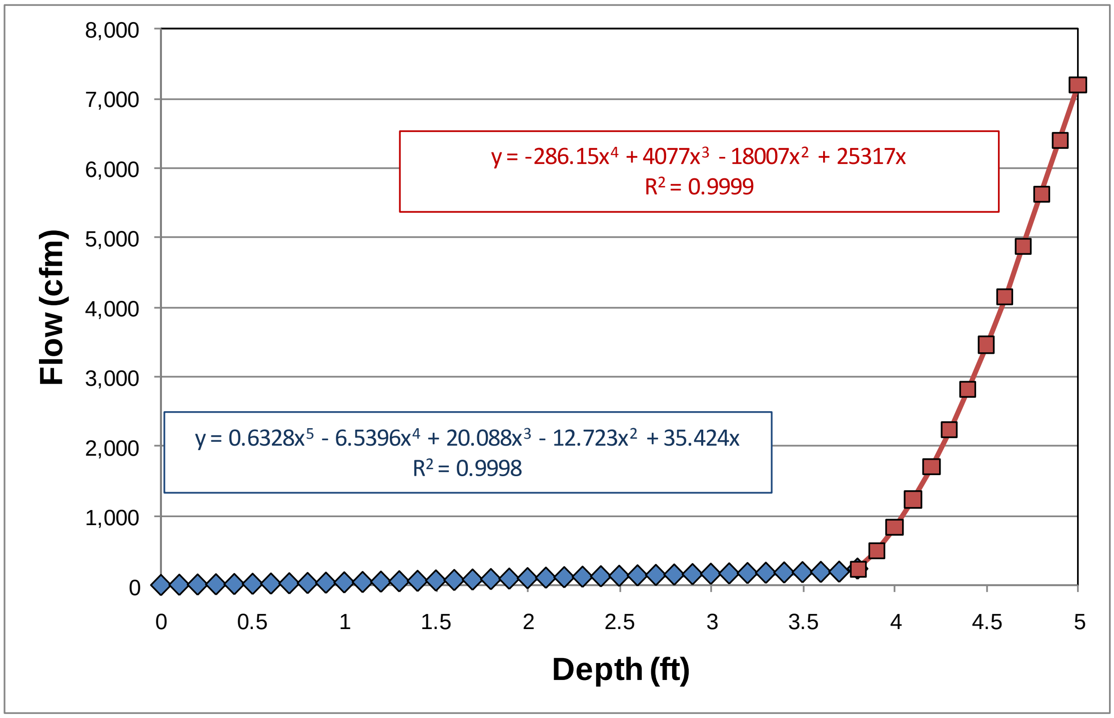

Figure A-6. Udall Pond 2 Outlet Rating Curve for all Depths

Howes St. BMP Inlet

The inlet to the Howes St. BMP is comprised of two connected 10 ft wide rectangular culverts that discharge stormwater into a wetland channel. A concrete wall runs for some distance upstream separating the culverts. During the summer of 2009, a flow monitor was installed in each culvert. It was observed that the west culvert only discharged between 10% to 20% of the flow that the east culvert discharged during storm events, based on a total of three events. Figure A-7 shows the uneven discharge at the Howes St. BMP inlet during a storm event. From the figure, it is evident that the east culvert was discharging more runoff than the west culvert.

Figure A-7. Uneven Discharge for the Howes St. BMP Inlet

Before the start of the water quality sampling in October of 2009, one of the flow monitors became unusable. With only one working flow monitor, the decision was made to record the flow on the east culvert and then to estimate the flow contribution from the west culvert. The west culvert was assumed to contribute 15% of the total measured flow from the east culvert for every storm. Therefore, total storm volumes recorded from the East culvert were multiplied by 1.15 to estimate the incoming flow at the inlet.

Creating a depth-discharge rating curve for the inlet was particularly challenging due to the existence of trash racks in each culvert. Equation A-1 was used for depths of zero to the bottom of the trash-rack under the assumption that free flow conditions would exist. The top-hanging trash racks, shown in Figure A-8, caused the water to back up into the culvert and created pressurized flow once water levels rose above 0.7 ft.

Figure A-8. Howes St. Inlet Configuration

Debris accumulated in the trash racks and it was estimated that roughly 60% of the available area between bars became obstructed during events. To model the flow in the culverts at depths above 0.7 ft, the flow passing under the trash rack was assumed behave similarly to a sluice gate. Flow passing through the trash rack was estimated using a weir equation (with blockage due to the trash). The USBR report R-92-05 (1992) provided guidance and equations for estimating the headloss as water passed through the trash rack. An iterative calculation process was conducted to estimate how upstream flow depth related to the depth of the water downstream of the rack, where the pressure transducer measures flow. Then, the downstream head was related to the total flow of water at that point and a rating curve was generated. The strainer that collects water samples was located on the east culvert, as shown in Figure A-8.

An ISCO 3220 flow monitor was used to record the flow data at the east culvert. It allowed up to 50 data points to be directly entered for a rating curve. Figure A-9 displays the rating curve for the east culvert at the Howes St. BMP inlet.

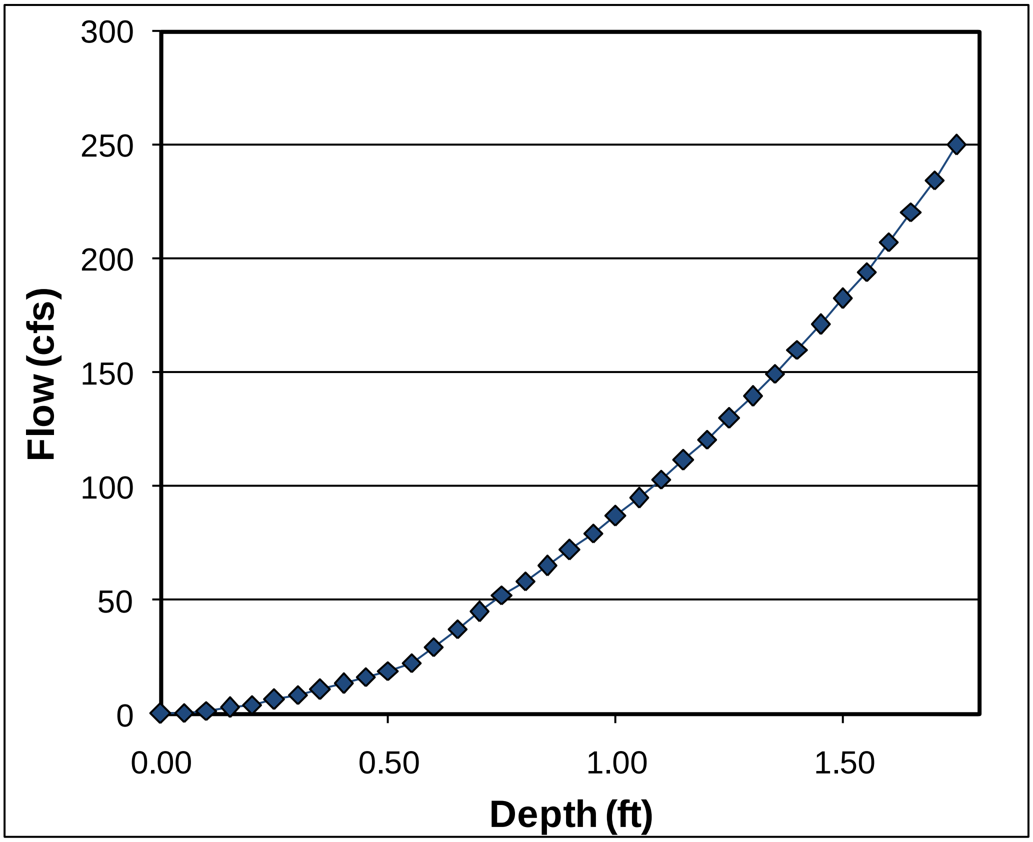

Figure A-9. Rating Curve for East Culvert at the Howes St. BMP Inlet

Efforts were made to verify the flow contribution of the west culvert, estimate the presence of trash on the racks, and to field check the flow depth during each event. However, direct observations were not always performed due to safety considerations and availability of personnel during events. Most of the uncertainty in the rating curve occurs when the flow depth was greater than 0.7 ft and was influenced by the trash rack. Runoff flowing out of the inlet rarely reached the trash rack bottom. Some entire storms were recorded where flow depth was lower than the trash rack. When there was sufficient flow to reach the trash rack, it was not sustained for very long and usually comprised between 5% to 15% of the overall hydrograph. Therefore, most of the recorded flow was estimated using Manning's equation under normal flow conditions.

Howes St. BMP Outlet

The Howes St. BMP wetland channel conveys water to an old oxbow pond where some water is permanently stored. Two concrete pipes discharge stormwater from the wetland pond into to the Cache la Poudre River, as shown in Figure A-9. A 3.5 ft circular concrete pipe and 2.75 ft tall elliptical concrete pipe are situated adjacent to each other at the north end of the pond. The elliptical pipe is offset 0.65 ft above the circular pipe. SWMM was used to model the pipes using parameters including entry and exit loss coefficients, total pipe lengths, pipe inverts at the entrance and exit, and Manning's roughness coefficient for concrete. Rating curves were generated by placing a large storage unit in SWMM and allowing it to drain until empty through the modeled culverts. An ISCO 6712 automated sampler was used to monitor flow and to collect water quality samples on site. Figure A-10 displays the rating curve generated by SWMM. On two occasions, a beaver dam was in place during all or a portion of a sampled event, which required adjustments to the flow record from different rating curves. Since these curves were required for unique circumstances they are not shown here.

Figure A-9. Howes St. BMP Outlet to Cache la Poudre River (looking from River to Pond)

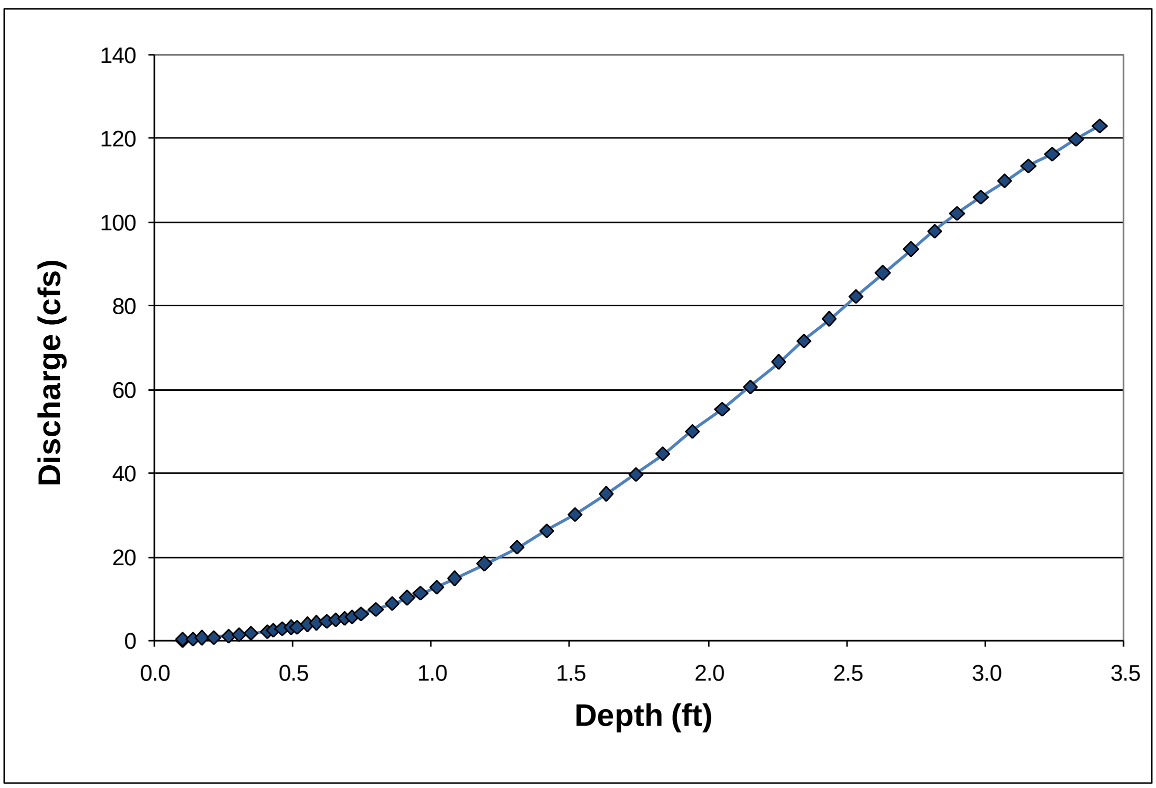

Figure A-10. Howes St. BMP Outlet Rating Curve

APPENDIX B: STORMWATER SAMPLING SUMMARY NOTES

Storm Notes-FTC Sampling 2009-April 2011

This document serves as a quick reference sheet for all storm events that were sampled at the Howes St. BMP and the Udall WP up to April of 2011. Total storm volumes displayed for Howes St. and Udall have had the baseflow contribution subtracted. A 6-hr inter-event time was used to distinguish events. Percent capture (%cap) for an event had to be 60% or greater for EMCs to be used in later analysis. "Results not used" implies that the EMC for a particular site could not be used in later analysis because it did not meet data screening requirements (usually %cap < 60%). One storm only had field values collected (10/10/10) and is not included here, but that data appears in the field value summary spreadsheet.

Event Title: 10/27/09

Christman Precip = 1.32 in
Rain Turning to Snow

Snowmelt observed over the course of a week following the event. Christman field precip record was used since there is a heated raingage. The Howes St. Outlet and Udall sites had two submitted sample sets: one on 10/28/10, another on 11/1/2009. After analysis of the runoff record, it was clear that the 11/1/09 data should be considered as an independent snowmelt runoff event for both the Udall Inlet, and the Howes St. Outlet. The Howes St. Outlet has a small enough permanent pool volume that the initial runoff phase of the storm had emptied out of the pond before the second set of samples were collected. At the Udall ponds, however, the distinction between events was not clear. Thus, the entire period of runoff (snow melted for approx. 7 days) was used to estimate the percent capture at the Udall Ponds.

- Howes St. Inlet: Did not sample, equipment error
- Howes St. Outlet: V = 204,000 cf for EMC 10/28/10, %cap = 62%
- Udall Inlet: V = 96,000 cf for EMC 10/28/10, % cap = 71%
- Udall Pond 1: V = 192,000 cf, lab results combined for EMC values, % cap = 60%
- Udall Pond 2: V = 195,000 cf, % cap = 37% -> **results not used**

NOTE: Dissolved metals were not filtered correctly. They were returned as "Partially Dissolved" in the March 20th sampling results and the same method was used for both of these storms. Thus, no dissolved metal values for this storm were included in EMC analysis.

Event Title: 3/20/10
Composite Precip for Howes St. = 0.31 in
Rain/Snow

Only samples for the Howes St. Outlet were submitted for lab analysis. Samples froze overnight at Udall and were discarded. No E coli samples were taken for this event.

- Howes St. Outlet: V = 82,000 cf, %cap = 93%

NOTE: Dissolved metals were not filtered correctly. They were returned as "Partially Dissolved" and were not included in EMC analysis.

Event Title 4/21/10
Composite Precip for Howes St. = 1.28 in
Composite Precip for Udall = 1.32 in (event 1), 2.09 in (both events)
Rain

This large rain event produced more runoff at the Howes St. site than the ISCOs could collect at the chosen sampling interval. As a result, the EMC values for the event at Howes St. had to be omitted from subsequent EMC analysis. At Udall, the inlet had a higher sample interval and was able to capture enough of the event hydrograph. The two ponds did not draw down for a week and actually accepted runoff from a second rain event. Three sets of samples were submitted to the PCL for EMC analysis at Pond 1 and Pond 2. In addition, Pond 2 reached a level that caused backwater at Pond 1. The pond 1 flow record was replaced with pond 2 flow for the time when constant flow was observed in pond 2 (steady state, inflow = outflow). Depth records at each pond were used to determine when the record needed to be adjusted.

- Howes St. Inlet: V = 602,000 cf, %cap = 35% -> **results not used**
- Howes St. Outlet: V = 826,000 cf, %cap = 28% -> **results not used**
- Udall Inlet: V = 647,000 cf, %cap = 73%
- Udall Pond 1: 1,094,000 cf, %cap = 62%, two storms, 3 submitted samples
- Udall Pond 2: 1,033,000 cf, %cap = 71%, two storms, 3 submitted samples

Event Title 4/28/10
Composite Precip for Howes St. = 0.68 in
Composite Precip for Udall = 0.71 in
Rain

All sites were sampled for this event.

- Howes St. Inlet: V = 177,500 cf, %cap = 92%
- Howes St. Outlet: V = 327,400 cf, %cap = 68%
- Udall Inlet: V = 261,800 cf, %cap = 96%
- Udall Pond 1: 271,800 cf, %cap = 79%
- Udall Pond 2: 258,300 cf, %cap = 85%

Event Title 5/11/10
Composite Precip for Howes St. = 1.54 in
Composite Precip for Udall = 1.53 in
Rain/Snow

This event produced a large amount of runoff. The Christman Field gage was not functioning correctly for this event so it was not used to estimate the total precipitation. The Howes St. outlet had a sampling interval that was set too low and most of the storm was not sampled. Also, a beaver dam in the outlet pipes washed out during the middle of the storm, and the flow record was adjusted to account for this. The Udall ponds were tampered with during the event by City crews who removed the orifice plates. Samples were not submitted at the Udall ponds since the flow record was no longer valid.

- Howes St. Inlet: V = 468,000 cf, %cap = 62%
- Howes St. Outlet: V = 787,000 cf, %cap = 40% -> **results not used**
- Udall Inlet: V = 493,000 cf, %cap = 96%
- Udall Pond 1: Orifice plate removed, no samples collected
- Udall Pond 2: Orifice plate removed, no samples collected

Event Title 5/26/10
Composite Precip for Howes St. = 0.27 in
Composite Precip for Udall = 0.17 in
Rain

The Poudre River was high enough to prevent sampling at the Howes St. Outlet. This event had a very uneven rainfall distribution; more runoff occurred at Howes St. than at Udall. Maintenance was occurring at the Udall ponds and the sluice gate was open prior to the event. Pond 1 was empty at the beginning of the event, and a lot of the runoff bypassed the pond completely and went directly to Pond 2. Due to the flow routing complications and relatively low runoff produced, no samples were submitted for the Udall Ponds.

- Howes St. Inlet: V = 180,000 cf, %cap = 100%
- Howes St. Outlet: Poudre River backwater prevented sampling
- Udall Inlet: V = 82,700 cf, %cap = 95%
- Udall Pond 1: Sluice gate open, no samples collected
- Udall Pond 2: Sluice gate open, no samples collected

Event Title 6/11/10
Composite Precip for Howes St. = 1.93 in
Composite Precip for Udall = 1.77 in
Rain

Moderate rainfall occurred throughout an entire weekend. The Poudre River was high enough to prevent sampling at the Howes St. Outlet, and also was observed flowing **into** Pond 2 at Udall. Thus, sampling was not possible at those locations.

Due to budget restrictions, no samples were submitted to the PCL for this event. Sampling was done at CSU and included Alk, TSS, TP, TN, TOC, TDS, TC, IC.

- Howes St. Inlet: V = 962,000 cf, %cap = 87%
- Howes St. Outlet: Poudre River backwater prevented sampling
- Udall Inlet: V = 654,000 cf, %cap = 74%
- Udall Pond 1: Poudre River backwater prevented sampling
- Udall Pond 2: Poudre River backwater prevented sampling

Event Title 7/4/10
Composite Precip for Howes St. = 0.49 in
Composite Precip for Udall = 0.61 in
Rain

An intense but short storm occurred after 3-4 weeks of no precipitation. Samples were collected at all sites. A small, separate event occurred the night before samples were collected at Pond 1 and Pond 2. The effects of the second storm were negligible at pond 2. There was evidence of increased flow at Pond 1 by the time samples were collected. Three of the 22 individual ISCO samples that were composited for an EMC occurred after the effects of the second event. Since approx. 87% of the bottles did not include the 2^{nd} event the EMC was considered to be representative of the first event only.

- Howes St. Inlet: V = 236,000 cf, %cap = 100%
- Howes St. Outlet: V = 261,100 cf, %cap = 95%
- Udall Inlet: V = 197,200 cf, %cap = 96%
- Udall Pond 1: 208,700 cf, % cap = 84%
- Udall Pond 2: 200,400 cf, %cap 71%

Event Title 8/8/10
Composite Precip for Howes St. = 0.13 in
Composite Precip for Udall = 0.28 in
Rain

Uneven rainfall distribution over the City with more rain at the CCC station and at CTL. Samples were analyzed at the CSU lab and nothing was submitted to the PCL. There was some confusion in acquiring the results from CSU. After careful inspection it is believed that the results were analyzed within holding times and the data was entered incorrectly into a spreadsheet. This error was fixed and the storm summary spreadsheet shows the correct values.

- Howes St. Inlet: V = 75,700 cf, %cap = 71%
- Howes St. Outlet: V = 114,800 cf, %cap = 95%
- Udall Inlet: V = 77,000 cf, %cap = 81%
- Udall Pond 1: 75,800 cf, % cap = 80%
- Udall Pond 2: 79,400 cf, %cap 84%

Event Title 10/22/10
Composite Precip for Howes St. = 0.29 in
Composite Precip for Udall = 0.33 in
Rain

A low intensity rain did not produce enough runoff at the Howes St. Inlet or Udall Inlet for sampling. The Howes St. Outlet did not collect samples due to an equipment malfunction. Samples were submitted for Pond 1 and Pond 2 at Udall. The sampling interval was changed during sample collection at Pond 2. In order to maintain a representative EMC, volumes of each aliquot were adjusted during the compositing process.

- Howes St. Inlet: Sample not submitted
- Howes St. Outlet: Sample not submitted
- Udall Inlet: Sample not submitted
- Udall Pond 1: 89,900 cf, % cap = 69%
- Udall Pond 2: 88,800 cf, %cap 90%

Event Title 11/9/10
Composite Precip for Howes St. = 0.20 in
Composite Precip for Udall = 0.20 in
Rain

The sluice gate was open at Udall which had caused Pond 1 to be empty at the beginning of the event. Samples were collected at the Udall Inlet and at Pond 2, but Pond 1 was not submitted. There was an error with the pressure transducer at the Howes St. Outlet. Oscillations were observed and it is unknown if a true volume based EMC was collected. Due to the low intensity of the storm and evenly spaced aliquot samples, the value was included in EMC analysis.

- Howes St. Inlet: 53,300 cf, %cap = 93%
- Howes St. Outlet: 74,700 cf, %cap = 59%
- Udall Inlet: 101,100 cf, %cap = 94%
- Udall Pond 1: Sample not collected due to sluice gate
- Udall Pond 2: 104,900 cf, % cap = 76%

Event Title 4/13/11
Composite rainfall records were not available at the time the Thesis was written
CCC total rainfall: 0.95 in
Rain/slushy snow

At the Howes St. Outlet the pond level was below the rating curve because an beaver pond was assumed to be present. This resulted in a discharge of 0 cfs during baseflow. The sampler had not sampled any bottles at 0:30 on 4/14/11 and the elliptical beaver dam had apparently washed out. The sampling routine was amended to sample every hour, so there was no flow-weighting for the sample. The event had rained at a consistent intensity so it is believed that there was not much change in the flow magnitude at the outlet. It is believed that the aliquot samples were a good representation of the EMC. At Pond 2 of Udall, the pond level was not high enough to trigger the sampling routine until approximately 70% of the runoff response had already exited the facility. The trigger depth was lowered during the drawdown period but an EMC could not be collected.

- Howes St. Inlet: 216,000 cf, %cap = 94%
- Howes St. Outlet: **equal time samples, believed to have good EMC approximation**
- Udall Inlet: 211,00 cf, %cap = 99%
- Udall Pond 1: 243,500 cf, %cap = 60%
- Udall Pond 2: V = 121,500 cf, %cap = 30% -> **results not used**

<u>Event Title 4/24/11</u>
Composite rainfall records were not available at the time the Thesis was written
CCC total rainfall: 0.49 in
Rain

The depth probe at the Howes St. Outlet was not functioning properly for this event. Each recorded depth was too low, but it is believed that the depths were consistently low throughout the storm. An observable hydrograph was recorded and equal volume samples were collected. It is believed that a representative EMC was collected through the aliquot samples even though the readings were incorrect.

- Howes St. Inlet: 117,000 cf, %cap = 85%
- Howes St. Outlet: **depth probe problems but believed to have representative EMC**
- Udall Inlet: 83,000 cf, %cap = 83%
- Udall Pond 1: 90,000 cf, %cap = 94%
- Udall Pond 2: 82,800 cf, %cap = 68%

APPENDIC C: STORMWATER SAMPLING RESULTS

Table C-1a. Howes St. BMP Inlet EMC Concentrations

	Storm Hydrology		**Storm Date**	10/27/2009	3/20/2010	4/21/2010	4/28/2010	5/11/2010	5/26/2010	6/11/2010
			Rainfall Depth (in)			1.28	0.68	1.54	0.27	1.93
			Total Storm Volume (cf)			601,500	177,500	468,000	180,000	962,000
			Sampled Volume (cf)			209,000	163,000	289,500	180,000	837,500
			% Hydrograph Captured			35	92	62	100	87
			Notes	Not Sampled	Not Sampled	**Results Not Used**				
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**10/27/2009**	**3/20/2010**	**4/21/2010**	**4/28/2010**	**5/11/2010**	**5/26/2010**	**6/11/2010**
Alkalinity	ALK_2320B	mg/L		-	-	-	30.95	30.4	58.02	34
Calcium (dissolved)	CA_D_215.1	mg/L		-	-	-	8.66	8.06	12.38	-
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	0.25	0.25	0.25	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	0.25	0.25	1.2	-
Chloride	CL_300.0	mg/L		-	-	-	6.6	5	-	-
Chemical Oxygen Demand	COD_5220D	mg/L		-	-	-	45	74	341	-
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	2.5	2.5	2.5	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	2.5	2.5	7.31	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	-	-	-	2.5	2.5	9.23	-
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	6.59	10.61	38.87	-
Hardness	HARD_130.1	mg/L		-	-	-	32	34	84	-
Potassium (disolved)	K_D_258.1	mg/L		-	-	-	3.142	4.145	10.793	-
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	-	-	-	1.884	1.506	2.059	-
Sodium (dissolved)	NA_D_273.1	mg/L		-	-	-	4.49	3.21	4.9	-
Ammonia (as N)	NH3_350.1	mg/L	0.1	-	-	-	0.52	0.65	1.54	-
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	-	-	0.025	0.025	0.09	-
Nitrate (as N)	NO3_353.2	mg/L	0.05	-	-	-	0.61	0.31	0.71	-
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	2.5	2.5	2.5	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	2.5	7.17	42.22	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	-	-	-
Suspended Solids	SS_2540D	mg/L	1	-	-	-	49	103	648	57
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	-	-	-	1.359	2.643	9.615	-
Total Organic Carbon	TOC_5310B	mg/L		-	-	-	13	16.8	23	23.79
Total Phosphorous (as P)	TPO4_365.1	mg/L		-	-	-	0.110	0.130	0.482	0.601
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	-	-	-	10.1	15.2	35.5	-
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	32.8	62.8	247.2	-
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		-	-	-	0.839	1.993	8.075	-
Nitrate + Nitrite	**NO2 + NO3**	mg/L		-	-	-	0.635	0.335	0.8	-
Total Nitrogen	**NO2+3 + TKN**	mg/L		-	-	-	1.994	2.978	10.415	2.207
CSU Lab										
Total Dissolved Solids		mg/L		-	-	-	-	-	-	60
Total Carbon		mg/L		-	-	-	-	-	-	30.31
Inorganic Carbon		mg/L		-	-	-	-	-	-	6.515

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

- Signifies that constituent analysis was not requested or was removed for QA/QC

Dark blue highlights signify items that were submitted for analysis but results were never returned from the Fort Collins PCL

Table C-1b. Howes St. BMP Inlet EMC Concentrations

	Storm Hydrology		Storm Date	7/4/2010	8/8/2010	10/22/2010	11/9/2010	4/13/2011	4/20/2011	4/24/2011
			Rainfall Depth (in)	0.49	0.13		0.2	0.95		0.49
			Total Storm Volume (cf)	236,000	76,000		53,000	216,000		117,000
			Sampled Volume (cf)	236,000	54,000		50,000	204,000		99,000
			% Hydrograph Captured	100	71		94	94		85
			Notes			Not Sampled		Rain to snow	Not Sampled	
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**7/4/2010**	**8/8/2010**	**10/22/2010**	**11/9/2010**	**4/13/2011**	**4/20/2011**	**4/24/2011**
Alkalinity	ALK_2320B	mg/L		41.72	48	-	41.59	44.58	-	34.69
Calcium (dissolved)	CA_D_215.1	mg/L		14.49	-	-	-	9.59	-	9.6
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	-	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	-	-	-	-
Chloride	CL_300.0	mg/L		8.02	-	-	-	15.7	-	7.3
Chemical Oxygen Demand	COD_5220D	mg/L		289	-	-	-	128	-	47
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	-	6.48	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	9.07	-	-	-	7.82	-	4.39
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	-	-	-	5.88
Hardness	HARD_130.1	mg/L		74	-	-	125	61	-	61
Potassium (disolved)	K_D_258.1	mg/L		7.522	-	-	-	6.54	-	3.94
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	2.313	-	-	-	3.46	-	2.96
Sodium (dissolved)	NA_D_273.1	mg/L		4.38	-	-	-	10.92	-	7.51
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.88	-	-	1.26	1.14	-	0.71
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	-	-	0.14	0.07	-	0.02
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.75	-	-	7.23	0.31	-	2.03
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Sulfate	SO4_300.0	mg/L	5	5.61	-	-	-	6.1	-	5.01
Suspended Solids	SS_2540D	mg/L	1	525	677	-	98	140	-	56
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	3.28	-	-	6.31	4.932	-	2.025
Total Organic Carbon	TOC_5310B	mg/L		41	30.89	-	30.4	24.7	-	15.2
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.363	1.439	-	0.549	0.245	-	0.114
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	24.9	-	-	-	39.52	-	22.57
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	-	110.65	-	34
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		2.4	-	-	5.05	3.792	-	1.315
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.75	-	-	7.37	0.38	-	2.05
Total Nitrogen	**NO2+3 + TKN**	mg/L		4.03	1.597	-	13.68	5.312	-	4.075
CSU Lab										
Total Dissolved Solids		mg/L		-	153	-	-	-	-	-
Total Carbon		mg/L		-	40.06	-	-	-	-	-
Inorganic Carbon		mg/L		-	9.171	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Dark blue highlights signify items that were submitted for analysis but results were never returned from the Fort Collins PCL

Table C-2a. Howes St. BMP Outlet EMC Concentrations

	Storm Hydrology		**Storm Date**	10/27/2009	3/20/2010	4/21/2010	4/28/2010	5/11/2010	5/26/2010	6/11/2010
			Rainfall Depth (in)	1.32	0.31	1.28	0.68	1.55		
			Total Storm Volume (cf)	204,000	82,000	825,500	327,500	787,000		
			Sampled Volume (cf)	127,000	76,000	230,000	223,000	313,500		
			% Hydrograph Captured	62	93	28	68	40		
			Notes	Diss. Metals Removed		Results Not Used		Results Not Used	Not Sampled	Not Sampled
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**10/27/2009**	**3/20/2010**	**4/21/2010**	**4/28/2010**	**5/11/2010**	**5/26/2010**	**6/11/2010**
Alkalinity	ALK_2320B	mg/L		-	133.96	-	33.74	-	-	-
Calcium (dissolved)	CA_D_215.1	mg/L		43.72	45.82	-	10.4	-	-	-
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	0.25	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	0.25	0.25	-	0.25	-	-	-
Chloride	CL_300.0	mg/L		103	134	-	6.8	-	-	-
Chemical Oxygen Demand	COD_5220D	mg/L		554	139	-	57	-	-	-
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	2.5	7.74	-	2.5	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	-	-	-	2.5	-	-	-
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	16.98	18.28	-	5.87	-	-	-
Hardness	HARD_130.1	mg/L		198	174	-	34	-	-	-
Potassium (disolved)	K_D_258.1	mg/L		31.347	-	-	3.46	-	-	-
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	18.919	39.006	-	2.213	-	-	-
Sodium (dissolved)	NA_D_273.1	mg/L		50.6	-	-	4.6	-	-	-
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.74	0.37	-	0.48	-	-	-
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	0.05	-	0.025	-	-	-
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.73	0.38	-	0.43	-	-	-
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	2.5	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	2.5	14.34	-	2.5	-	-	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	-	-	-
Suspended Solids	SS_2540D	mg/L	1	40	132	-	-	-	-	-
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	5.253	0.991	-	1.229	-	-	-
Total Organic Carbon	TOC_5310B	mg/L		198.7	16.6	-	11.6	-	-	-
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.580	0.066	-	0.131	-	-	-
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	-	-	-	8.4	-	-	-
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	135.8	115.1	-	33.2	-	-	-
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		4.513	0.621	-	0.749	-	-	-
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.73	0.43	-	0.455	-	-	-
Total Nitrogen	**NO2+3 + TKN**	mg/L		5.983	1.421	-	1.684	-	-	-
CSU Lab										
Total Dissolved Solids		mg/L		-	-	-	-	-	-	-
Total Carbon		mg/L		-	-	-	-	-	-	-
Inorganic Carbon		mg/L		-	-	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-2b. Howes St. BMP Outlet EMC Concentrations

	Storm Hydrology		**Storm Date**	7/4/2010	8/8/2010	10/22/2010	11/9/2010	4/13/2011	4/20/2011	4/24/2011
			Rainfall Depth (in)	0.49	0.13		0.2	0.95		0.49
			Total Storm Volume (cf)	261,000	115,000		74,500			
			Sampled Volume (cf)	247,000	109,500		44,000			
			% Hydrograph Captured	95	95		59			
			Notes			Not Sampled		Not EMC	Not Sampled	Approximate EMC
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**7/4/2010**	**8/8/2010**	**10/22/2010**	**11/9/2010**	**4/13/2011**	**4/20/2011**	**4/24/2011**
Alkalinity	ALK_2320B	mg/L		10.86	90	-	206.1	-	-	93.37
Calcium (dissolved)	CA_D_215.1	mg/L		21.07	-	-	-	-	-	29.65
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	-	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	-	-	-	-
Chloride	CL_300.0	mg/L		-	-	-	-	39.1	-	16.4
Chemical Oxygen Demand	COD_5220D	mg/L		182	-	-	-	-	-	42
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	7.07	-	-	-	-	-	5.19
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	-	-	-	5.62
Hardness	HARD_130.1	mg/L		86	-	-	251	-	-	111
Potassium (disolved)	K_D_258.1	mg/L		15.779	-	-	-	-	-	3.77
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	1.86	-	-	-	-	-	8.35
Sodium (dissolved)	NA_D_273.1	mg/L		8.78	-	-	-	-	-	15.71
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.74	-	-	0.47	0.45	-	0.35
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	0.2	-	-	0.12	0.05	-	0.02
Nitrate (as N)	NO3_353.2	mg/L	0.05	-	-	-	2.05	0.76	-	0.54
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	22.4	-	13.5
Suspended Solids	SS_2540D	mg/L	1	116	25	-	14	55	-	38
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	3.519	-	-	2.931	0.855	-	1.158
Total Organic Carbon	TOC_5310B	mg/L		43.4	21.43	-	38.5	-	-	13.4
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.333	0.327	-	0.257	0.064	-	0.083
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	30.6	-	-	-	-	-	12.85
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	-	-	-	35.27
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		2.779	-	-	2.461	0.405	-	0.808
Nitrate + Nitrite	**NO2 + NO3**	mg/L		-	-	-	2.17	0.81	-	0.56
Total Nitrogen	**NO2+3 + TKN**	mg/L		-	1.32	-	5.101	1.665	-	1.718
CSU Lab										
Total Dissolved Solids		mg/L		-	160	-	-	-	-	-
Total Carbon		mg/L		-	38.87	-	-	-	-	-
Inorganic Carbon		mg/L		-	17.44	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-3a. Udall Inlet EMC Concentrations

	Storm Hydrology		**Storm Date**	10/27/2009	3/20/2010	4/21/2010	4/28/2010	5/11/2010	5/26/2010	6/11/2010
			Rainfall Depth (in)	1.32		1.35	0.71	1.53	0.17	1.77
			Total Storm Volume (cf)	96,500		646,500	262,000	492,500	82,500	653,500
			Sampled Volume (cf)	68,000		474,803	252,000	472,500	78,500	484,500
			% Hydrograph Captured	71		73	96	96	95	74
			Notes		Not Sampled					
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**10/27/2009**	**3/20/2010**	**4/21/2010**	**4/28/2010**	**5/11/2010**	**5/26/2010**	**6/11/2010**
Alkalinity	ALK_2320B	mg/L		-	-	35.57	32.95	29.56	46.07	36
Calcium (dissolved)	CA_D_215.1	mg/L		28.98	-	8.33	9.84	8.71	10.8	-
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	0.25	0.25	0.25	0.25	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	0.25	-	0.25	0.25	-	1.29	-
Chloride	CL_300.0	mg/L		101	-	8.3	9.1	15.6	-	-
Chemical Oxygen Demand	COD_5220D	mg/L		548	-	151	20	43	337	-
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	2.5	2.5	2.5	2.5	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	5.66	-	5.81	2.5	-	7.98	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	-	-	8.39	6.52	2.5	12.33	-
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	39.55	-	25.85	7.72	-	36.78	-
Hardness	HARD_130.1	mg/L		198	-	51	36	34	70	-
Potassium (disolved)	K_D_258.1	mg/L		28.831	-	5.54	2.609	2.42	8.859	-
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	15.888	-	2.093	2.561	2.113	2.086	-
Sodium (dissolved)	NA_D_273.1	mg/L		31.68	-	5.68	5.39	9.23	5.04	-
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.9	-	1.19	0.05	0.45	1.63	-
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	-	0.025	0.025	0.025	0.11	-
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.74	-	0.48	0.35	0.58	0.85	-
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	2.5	2.5	2.5	2.5	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	9.45	-	17.42	2.5	-	38.69	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	-	-	-
Suspended Solids	SS_2540D	mg/L	1	90	-	146	49	72	534	71
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	4.889	-	4.382	0.25	1.681	15.078	-
Total Organic Carbon	TOC_5310B	mg/L		110.8	-	24.5	11.4	9.2	22.6	27.12
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.663	-	0.233	0.023	0.254	0.503	0.611
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	-	-	27	43.6	17	39.9	-
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	170.2	-	149.3	47.5	-	244.1	-
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		3.989	-	3.192	0.2	1.231	13.448	-
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.74	-	0.505	0.375	0.605	0.96	-
Total Nitrogen	**NO2+3 + TKN**	mg/L		5.629	-	4.887	0.625	2.286	16.038	2.228
CSU Lab										
Total Dissolved Solids		mg/L		-	-	-	-	-	-	42
Total Carbon		mg/L		-	-	-	-	-	-	33.42
Inorganic Carbon		mg/L		-	-	-	-	-	-	6.298

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-3b. Udall Inlet EMC Concentrations

	Storm Hydrology		**Storm Date**	7/4/2010	8/8/2010	10/22/2010	11/9/2010	4/13/2011	4/20/2011	4/24/2011
			Rainfall Depth (in)	0.61	0.28		0.24	0.95		0.49
			Total Storm Volume (cf)	197,500	77,000		101,000	211,500		83,000
			Sampled Volume (cf)	190,000	62,500		95,500	210,000		69,000
			% Hydrograph Captured	96	81		94	99		83
			Notes			Not Sampled			Not Sampled	
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**7/4/2010**	**8/8/2010**	**10/22/2010**	**11/9/2010**	**4/13/2011**	**4/20/2011**	**4/24/2011**
Alkalinity	ALK_2320B	mg/L		26.4	36	-	53.5	43.88	-	36.22
Calcium (dissolved)	CA_D_215.1	mg/L		10.84	-	-	-	12.05	-	11
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	-	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	-	-	-	-
Chloride	CL_300.0	mg/L		6.21	-	-	-	19.3	-	8.3
Chemical Oxygen Demand	COD_5220D	mg/L		245	-	-	-	106	-	67
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	9.43	-	-	18.253	6.29	-	10.03
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	-	17.58	-	10.38
Hardness	HARD_130.1	mg/L		48	-	-	92	74	-	67
Potassium (disolved)	K_D_258.1	mg/L		5.29	-	-	21.363	4.09	-	3.09
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	1.821	-	-	6.094	4.06	-	3.4
Sodium (dissolved)	NA_D_273.1	mg/L		3.83	-	-	-	12.39	-	8.45
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.84	-	-	1.25	1	-	0.91
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	0.025	-	-	0.13	0.02	-	0.02
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.025	-	-	1.06	0.7	-	1.13
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Sulfate	SO4_300.0	mg/L	5	5.04	-	-	-	2.5	-	5.4
Suspended Solids	SS_2540D	mg/L	1	240	434	-	100	132	-	28
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	2.525	-	-	4.721	2.792	-	1.558
Total Organic Carbon	TOC_5310B	mg/L		29.4	30.76	-	32.9	15.3	-	15
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.216	0.924	-	0.368	0.116	-	0.092
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	41.9	-	-	113.15	28.86	-	22.95
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	-	103.78	-	53
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		1.685	-	-	3.471	1.792	-	0.648
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.05	-	-	1.19	0.72	-	1.15
Total Nitrogen	**NO2+3 + TKN**	mg/L		2.575	1.455	-	5.911	3.512	-	2.708
CSU Lab										
Total Dissolved Solids		mg/L		-	129	-	-	-	-	-
Total Carbon		mg/L		-	38.23	-	-	-	-	-
Inorganic Carbon		mg/L		-	7.469	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

- Signifies that constituent analysis was not requested or was removed for QA/QC

Dark blue highlights signify items that were submitted for analysis but results were never returned from the Fort Collins PCL

Table C-4a. Udall Pond 1 Outlet EMC Concentrations

	Storm Hydrology		Storm Date	10/27/2009	3/20/2010	4/21/2010	4/28/2010	5/11/2010	5/26/2010	6/11/2010
			Rainfall Depth (in)	1.32		2.09	0.71			
			Total Storm Volume (cf)	192,000		1,094,000	272,000			
			Sampled Volume (cf)	113,500		675,500	216,000			
			% Hydrograph Captured	59		62	79			
			Notes	3 Lab Sets Combined	Not Sampled	3 Lab Sets Combined		Not Sampled	Not Sampled	Not Sampled
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**10/27/2009**	**3/20/2010**	**4/21/2010**	**4/28/2010**	**5/11/2010**	**5/26/2010**	**6/11/2010**
Alkalinity	ALK_2320B	mg/L		-	-	54.28	55.35	-	-	-
Calcium (dissolved)	CA_D_215.1	mg/L		32.3	-	16.95	17.15	-	-	-
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	0.25	0.25	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	0.25	-	0.25	0.25	-	-	-
Chloride	CL_300.0	mg/L		130.2	-	15.60	14.9	-	-	-
Chemical Oxygen Demand	COD_5220D	mg/L		325.4	-	78.63	22	-	-	-
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	2.50	2.5	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	2.5	-	3.36	2.5	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	-	-	5.87	2.5	-	-	-
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	19.38	-	14.32	6.08	-	-	-
Hardness	HARD_130.1	mg/L		181.24	-	67.36	64	-	-	-
Potassium (disolved)	K_D_258.1	mg/L		19.43	-	4.25	2.847	-	-	-
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	21.66	-	4.89	4.944	-	-	-
Sodium (dissolved)	NA_D_273.1	mg/L		55.48	-	8.75	7.69	-	-	-
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.66	-	0.65	0.4	-	-	-
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	-	0.04	0.025	-	-	-
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.59	-	1.83	1.06	-	-	-
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	2.50	2.5	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	2.5	-	6.63	2.5	-	-	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	-	-	-
Suspended Solids	SS_2540D	mg/L	1	39.44	-	56.88	30	-	-	-
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	3.51	-	2.65	1.11	-	-	-
Total Organic Carbon	TOC_5310B	mg/L		109.02	-	15.35	10.6	-	-	-
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.335	-	0.133	0.064	-	-	-
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	-	-	21.84	15.5	-	-	-
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	98.57	-	70.82	39.7	-	-	-
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		2.84	-	1.99	0.71	-	-	-
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.59	-	1.87	1.09	-	-	-
Total Nitrogen	**NO2+3 + TKN**	mg/L		4.10	-	4.52	2.195	-	-	-
CSU Lab										
Total Dissolved Solids		mg/L		-	-	-	-	-	-	-
Total Carbon		mg/L		-	-	-	-	-	-	-
Inorganic Carbon		mg/L		-	-	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-4b. Udall Pond 1 Outlet EMC Concentrations

	Storm Hydrology		**Storm Date**	7/4/2010	8/8/2010	10/22/2010	11/9/2010	4/13/2011	4/20/2011	4/24/2011
			Rainfall Depth (in)	0.92	0.28	0.33		0.95		0.49
			Total Storm Volume (cf)	250,500	76,000	90,000		243,500		90,000
			Sampled Volume (cf)	175,500	60,500	62,500		145,000		84,500
			% Hydrograph Captured	70	80	69		60		94
			Notes				Not Sampled		Not Sampled	
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**7/4/2010**	**8/8/2010**	**10/22/2010**	**11/9/2010**	**4/13/2011**	**4/20/2011**	**4/24/2011**
Alkalinity	ALK_2320B	mg/L		84.02	70	121.04	-	45.86	-	71.13
Calcium (dissolved)	CA_D_215.1	mg/L		26.37	-	-	-	14.64	-	22.41
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	-	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	-	-	-	-
Chloride	CL_300.0	mg/L		201	-	-	-	20	-	12.8
Chemical Oxygen Demand	COD_5220D	mg/L		67	-	-	-	64	-	42
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	2.5	-	6.84	-	6.14	-	8.13
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	-	-	-	6.47
Hardness	HARD_130.1	mg/L		114	-	144	-	67	-	91
Potassium (disolved)	K_D_258.1	mg/L		5.017	-	-	-	4.4	-	2.89
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	7.597	-	11.301	-	4.45	-	7.53
Sodium (dissolved)	NA_D_273.1	mg/L		9.02	-	-	-	13.08	-	11.67
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.05	-	0.05	-	1.06	-	0.6
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	0.025	-	-	-	0.02	-	0.02
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.025	-	-	-	0.65	-	1.36
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Sulfate	SO4_300.0	mg/L	5	15.1	-	-	-	7.6	-	10.6
Suspended Solids	SS_2540D	mg/L	1	40	23	40	-	53	-	42
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	1.844	-	1.01	-	2.375	-	1.431
Total Organic Carbon	TOC_5310B	mg/L		21.4	34.56	30	-	20.5	-	13
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.102	0.33	0.115	-	0.627	-	0.075
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	38.9	-	38.92	-	31.47	-	22.31
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	-	67.21	-	38.21
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		1.794	-	0.96	-	1.315	-	0.831
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.05	-	0.00	-	0.67	-	1.38
Total Nitrogen	**NO2+3 + TKN**	mg/L		1.894	1.559	0.96	-	3.045	-	2.811
CSU Lab										
Total Dissolved Solids		mg/L		-	141	-	-	-	-	-
Total Carbon		mg/L		-	48.95	-	-	-	-	-
Inorganic Carbon		mg/L		-	14.39	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-5a. Udall Pond 2 Outlet EMC Concentrations

	Storm Hydrology		Storm Date	10/27/2009	3/20/2010	4/21/2010	4/28/2010	5/11/2010	5/26/2010	6/11/2010
			Rainfall Depth (in)	1.32		2.09	0.71			
			Total Storm Volume (cf)	195,500		1,033,000	258,500			
			Sampled Volume (cf)	72,000		736,500	220,500			
			% Hydrograph Captured	37		71	85			
			Notes	Results Not Used	Not Sampled	3 Lab Sets Combined		Not Sampled	Not Sampled	Not Sampled
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**10/27/2009**	**3/20/2010**	**4/21/2010**	**4/28/2010**	**5/11/2010**	**5/26/2010**	**6/11/2010**
Alkalinity	ALK_2320B	mg/L		-	-	59.12	74.49	-	-	-
Calcium (dissolved)	CA_D_215.1	mg/L		-	-	16.82	23.44	-	-	-
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	0.25	0.25	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	0.25	0.25	-	-	-
Chloride	CL_300.0	mg/L		-	-	15.52	22	-	-	-
Chemical Oxygen Demand	COD_5220D	mg/L		-	-	59.92	37	-	-	-
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	2.50	2.5	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	2.50	2.5	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	-	-	5.15	2.5	-	-	-
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	10.88	5	-	-	-
Hardness	HARD_130.1	mg/L		-	-	64.98	95	-	-	-
Potassium (disolved)	K_D_258.1	mg/L		-	-	3.87	2.524	-	-	-
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	-	-	5.06	7.528	-	-	-
Sodium (dissolved)	NA_D_273.1	mg/L		-	-	9.09	10.58	-	-	-
Ammonia (as N)	NH3_350.1	mg/L	0.1	-	-	0.54	0.13	-	-	-
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	-	-	0.03	0.025	-	-	-
Nitrate (as N)	NO3_353.2	mg/L	0.05	-	-	0.80	0.87	-	-	-
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	2.50	2.5	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	3.83	2.5	-	-	-
Sulfate	SO4_300.0	mg/L	5	-	-	-	-	-	-	-
Suspended Solids	SS_2540D	mg/L	1	-	-	33.95	12	-	-	-
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	-	-	2.32	0.934	-	-	-
Total Organic Carbon	TOC_5310B	mg/L		-	-	14.64	9.5	-	-	-
Total Phosphorous (as P)	TPO4_365.1	mg/L		-	-	0.111	0.048	-	-	-
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	-	-	19.15	11.9	-	-	-
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	53.26	29.6	-	-	-
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		-	-	1.78	0.804	-	-	-
Nitrate + Nitrite	**NO2 + NO3**	mg/L		-	-	0.83	0.895	-	-	-
Total Nitrogen	**NO2+3 + TKN**	mg/L		-	-	3.15	1.83	-	-	-
CSU Lab										
Total Dissolved Solids		mg/L		-	-	-	-	-	-	-
Total Carbon		mg/L		-	-	-	-	-	-	-
Inorganic Carbon		mg/L		-	-	-	-	-	-	-

Values lower than the detection limit were assigned a value of 1/2 of the detection limit; some detection limits changed over the course of sampling when new methods were used and are shown in red

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Table C-5b. Udall Pond 2 Outlet EMC Concentrations

	Storm Hydrology		**Storm Date**	7/4/2010	8/8/2010	10/22/2010	11/9/2010	4/13/2011	4/20/2011	4/24/2011
			Rainfall Depth (in)	0.92	0.28	0.33	0.24	0.95		0.49
			Total Storm Volume (cf)	225,500	79,500	89,000	105,000	121,500		83,000
			Sampled Volume (cf)	160,000	66,500	80,000	80,000	37,000		56,500
			% Hydrograph Captured	71	84	90	76	30		68
			Notes					Not EMC	Not Sampled	
Constituent	**Lab Test Code**	**Units**	**Detection Limit**	**7/4/2010**	**8/8/2010**	**10/22/2010**	**11/9/2010**	**4/13/2011**	**4/20/2011**	**4/24/2011**
Alkalinity	ALK_2320B	mg/L		95.97	126	203.77	204.14	-	-	88.03
Calcium (dissolved)	CA_D_215.1	mg/L		32.22	-	-	-	-	-	28.21
Cadmium (dissolved)	CD_D_200.7	ug/L	0.50	-	-	-	-	-	-	-
Cadmium (total recoverable)	CD_TR_200.7	ug/L	0.50	-	-	-	-	-	-	-
Chloride	CL_300.0	mg/L		23.9	-	-	-	-	-	15
Chemical Oxygen Demand	COD_5220D	mg/L		144	-	-	-	-	-	45
Chromium (dissolved)	CR_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Chromium (total recoverable)	CR_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Copper (dissolved)	CU_D_200.7	ug/L	5.00	7.14	-	3.47	5.49	-	-	4.95
Copper (total recoverable)	CU_TR_200.7	ug/L	5.00	-	-	-	-	-	-	6.44
Hardness	HARD_130.1	mg/L		133	-	236	247	-	-	117
Potassium (disolved)	K_D_258.1	mg/L		5.067	-	-	-	-	-	2.84
Magnesium (dissolved)	MG_D_242.1	mg/L	0.1	8.624	-	21.326	-	-	-	9.63
Sodium (dissolved)	NA_D_273.1	mg/L		9.63	-	-	-	-	-	13.7
Ammonia (as N)	NH3_350.1	mg/L	0.1	0.05	-	0.05	0.54	-	-	0.35
Nitrite (as N)	NO2_353.2	mg/L	0.05, 0.04	0.025	-	-	0.06	-	-	0.04
Nitrate (as N)	NO3_353.2	mg/L	0.05	0.025	-	-	1.53	-	-	1.64
Lead (dissolved)	PB_D_200.7	ug/L	5.00	-	-	-	-	-	-	-
Lead (total recoverable)	PB_TR_200.7	ug/L	5.00	-	-	-	-	-	-	-
Sulfate	SO4_300.0	mg/L	5	16	-	-	-	-	-	13.5
Suspended Solids	SS_2540D	mg/L	1	28	29	16	22	-	-	20
Total Kjeldahl Nitrogen	TKN_351.2	mg/L	0.5	1.815	-	1.395	1.92	-	-	1.481
Total Organic Carbon	TOC_5310B	mg/L		23	53.42	20.6	41.6	-	-	13.3
Total Phosphorous (as P)	TPO4_365.1	mg/L		0.077	0.34	0.080	0.113	-	-	0.073
Zinc (dissolved)	ZN_D_200.7	ug/L	5.00, 11.00	28.2	-	15.37	29.9	-	-	17.19
Zinc (total recoverable	ZN_TR_200.7	ug/L	5.00, 1.00	-	-	-	-	-	-	36.66
Computed										
Organic Nitrogen	**TKN - NH3**	mg/L		1.765	-	1.345	1.38	-	-	1.131
Nitrate + Nitrite	**NO2 + NO3**	mg/L		0.05	-	-	1.59	-	-	1.68
Total Nitrogen	**NO2+3 + TKN**	mg/L		1.87	1.443	1.35	3.51	-	-	3.16
CSU Lab										
Total Dissolved Solids		mg/L		-	261	-	-	-	-	-
Total Carbon		mg/L		-	77.74	-	-	-	-	-
Inorganic Carbon		mg/L		-	24.32	-	-	-	-	-

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APPENDIX D: TABLES FOR BMP DATABASE HRT ANALYSIS

Table D1. BMP Database Values when Average Storm HRT was Estimated using the Fraction Full Method (1 of 5)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
DB	675395640	15/78	1	120	28	150.0	77.0	32.0	20.0	0.25	0.82	1.22	11,680	8,713	39,642	19,821	11,680	29	11,680	72	0	52.9
DB	675395640	15/78	2	98	32	180.0	98.0	31.0	17.0	0.29	0.61	0.39	6,219	5,660	39,642	19,821	6,219	16	6,219	72	0	43.1
DB	675395640	15/78	3	120	36	280.0	150.0	47.0	34.0	0.39	0.30	0.36	4,147	3,271	39,642	19,821	4,147	10	4,147	72	0	36.8
DB	675395640	15/78	4	270	38	350.0	81.0	51.0	15.0	0.65	0.30	0.61	16,451	14,894	39,642	19,821	16,451	41	16,451	72	0	58.3
DB	675395640	15/78	5	82	48	270.0	200.0	63.0	50.0	0.66	0.50	0.30	2,159	371	39,642	19,821	2,159	5	2,159	72	0	26.6
DB	675395640	15/78	6	100	46	440.0	120.0	51.0	21.0	1.20	0.35	0.38	3,117	2,193	39,642	19,821	3,117	8	3,117	72	0	32.3
DB	675395640	15/78	7	48	14	260.0	57.0	28.0	10.0	0.48	0.21	1.99	33,151	28,311	39,642	19,821	33,151	84	33,151	72	0	69.2
DB	675395640	15/78	8	100	22	280.0	52.0	68.0	10.0	0.37	0.25	1.12	15,128	12,404	39,642	19,821	15,128	38	15,128	72	0	57.0
DB	675395640	15/78	9	160	38	300.0	91.0	43.0	21.0	0.48	0.29	0.91	11,983	9,770	39,642	19,821	11,983	30	11,983	72	0	53.3
DB	675395640	15/78	10	500	62	710.0	110.0	75.0	19.0	1.50	0.24	0.69	8,697	7,019	39,642	19,821	8,697	22	8,697	72	0	48.3
DB	675395640	15/78	11	340	76	1000.0	170.0	120.0	33.0	1.30	0.39	0.29	1,754	1,683	39,642	19,821	1,754	4	1,754	72	0	23.4
DB	675395640	15/78	12	200	38	260.0	94.0	37.0	19.0		0.20	1.80	32,524	28,146	39,642	19,821	32,524	82	32,524	72	0	68.9
DB	675395640	15/78	13	68	260	730.0	120.0	78.0	82.0	1.00	0.20	0.86	11,693	9,674	39,642	19,821	11,693	29	11,693	72	0	53.0
DB	675395640	15/78	14	240	66	380.0	83.0	65.0	18.0	0.47	0.18	0.20	1,630	1,543	39,642	19,821	1,630	4	1,630	72	0	22.2
DB	675395640	15/78	15	130	32	620.0	72.0	41.0	15.0	0.70	0.10	1.10	18,681	16,006	39,642	19,821	18,681	47	18,681	72	0	60.3
DB	675395640	15/78	16	370	70	1100.0	120.0	120.0	22.0	1.30	0.20	0.59	8,035	6,600	39,642	19,821	8,035	20	8,035	72	0	47.1
DB	675395640	15/78	17	200	26	510.0	68.0	44.0	11.0	0.90	0.20	0.53	7,057	5,768	39,642	19,821	7,057	18	7,057	72	0	45.1
DB	675395640	15/78	18	250	32	830.0	150.0	64.0	26.0	0.70	0.10	0.74	9,406	7,606	39,642	19,821	9,406	24	9,406	72	0	49.6
DB	675395640	15/78	19	120	30	230.0	89.0	26.0	15.0	0.10	0.10	0.93	9,327	7,308	39,642	19,821	9,327	24	9,327	72	0	49.4
DB	1531148492	5/56	1	96		100.0		25.0		0.28		1.22	18,910	7,788	13,795	6,898	18,910	137	18,910	72	0	98.7
DB	1531148492	5/56	2	86		120.0		20.0		0.20		0.48	8,443	448	13,795	6,898	8,443	61	8,443	72	0	64.3
DB	1531148492	5/56	3	66		81.0		20.0		0.26		0.66	11,880	14,909	13,795	6,898	11,880	86	11,880	72	0	69.7
DB	1531148492	5/56	4	110		130.0		32.0		0.30		0.26	2,973	11,682	13,795	6,898	2,973	22	2,973	72	0	48.1
DB	1531148492	5/56	5	78		110.0		20.0		0.44		0.86	12,378	2,597	13,795	6,898	12,378	90	12,378	72	0	70.3
DB	1531148492	5/56	6	100	34	120.0	42.0	46.0	32.0	0.67	0.24	0.17	912	9,805	13,795	6,898	912	7	912	72	0	29.6
DB	1531148492	5/56	7	82	36	130.0	40.0	28.0	15.0	0.46	0.27	0.20	1,614	362	13,795	6,898	1,614	12	1,614	72	0	38.5
DB	1531148492	5/56	8	125	18	2100.0	34.0	81.0	10.0	0.34	0.25	1.64	18,312	954	13,795	6,898	18,312	133	18,312	72	0	95.6
DB	1531148492	5/56	9	64	22	140.0	30.0	19.0	8.7	0.25	0.20	1.12	13,296	15,776	13,795	6,898	13,296	96	13,296	72	0	71.4
DB	1531148492	5/56	10	46	44	92.0	57.0	23.0	20.0	0.21	0.24		6,329	4,733	13,795	6,898	6,329	46	6,329	72	0	59.8
DB	1531148492	5/56	11	82	42	110.0	55.0	28.0	22.0	0.30	0.33	0.38	2,386	2,193	13,795	6,898	2,386	17	2,386	72	0	44.6
DB	1531148492	5/56	13	110	220	220.0	160.0	43.0	28.0	0.26	0.26	2.84	24,992	21,856	13,795	6,898	24,992	181	#N/A	72	0	#N/A
DB	1531148492	5/56	14	76	42	190.0	59.0	31.0	12.0	0.34	0.08	0.78	9,317	9,172	13,795	6,898	9,317	68	9,317	72	0	65.9
DB	1531148492	5/56	15	110	26	180.0	58.0	33.0	15.0	0.23	0.13	0.52	5,521	4,219	13,795	6,898	5,521	40	5,521	72	0	57.7
DB	1531148492	5/56	16	94	16	260.0	29.0	51.0	7.1	0.35	0.04	0.52	8,383	5,291	13,795	6,898	8,383	61	8,383	72	0	64.2
DB	1531148492	5/56	17	92	22	390.0	55.0	46.0	22.0	0.19	0.14	0.45	3,371	3,059	13,795	6,898	3,371	24	3,371	72	0	50.0
DB	1531148492	5/56	18	86	12	330.0	41.0	36.0	22.0	0.19	0.10	0.22	1,431	13,803	13,795	6,898	1,431	10	1,431	72	0	36.7
DB	1225581126	605/91 edb	1	85	59	390.0	260.0	56.0	37.0	0.33	0.78	0.57	1,402	680	2,457	1,228	1,402	57	1,402	72	0	63.2
DB	1225581126	605/91 edb	2	80	49	310.0	220.0	50.0	30.0	0.17	0.86	0.71	2,216	510	2,457	1,228	2,216	90	2,216	72	0	70.4
DB	1225581126	605/91 edb	3	61	94	240.0	99.0	30.0	19.0	0.03	0.34	1.62	7,160	1,964	2,457	1,228	7,160	291	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	6	110	19	541.0	250.0	39.9	37.0	0.50	0.69	0.16	304	37	2,457	1,228	304	12	304	72	0	39.4
DB	1225581126	605/91 edb	7	41	14	288.0	115.0	33.7	16.3	0.24	0.34	0.83	6,658	1,793	2,457	1,228	6,658	271	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	8	58	13	240.0	110.0	36.0	22.0	0.35	0.62	1.46	7,504	2,427	2,457	1,228	7,504	305	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	10	61	24	161.0	96.0	22.0	18.0	0.54	0.41	1.43	19,121	1,413	2,457	1,228	19,121	778	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	11	150		636.0		73.0		0.30		0.55	1,673		2,457	1,228	1,673	68	1,673	72	0	66.0
DB	1225581126	605/91 edb	12	58		170.0		20.0		0.18		3.47	52,676	26,338	2,457	1,228	52,676	2,144	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	15	74	17	282.0	159.0	20.0	25.0	0.21	0.32	0.57	5,878	1,053	2,457	1,228	5,878	239	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	16	93	22	347.0	122.0	39.0	24.0	0.26	0.41	0.58	2,755	625	2,457	1,228	2,755	112	2,755	72	0	80.7
DB	1225581126	605/91 edb	18	165	36	550.0	166.0	59.0	29.0	0.18	0.36				2,457	1,228	#N/A	#N/A	#N/A	72	0	#N/A
DB	1225581126	605/91 edb	19	24	9	182.0	64.0	15.0	8.1	0.20	0.17				2,457	1,228	#N/A	#N/A	#N/A	72	0	#N/A

Table D1. BMP Database Values when Average Storm HRT was Estimated using the Fraction Full Method (2 of 5)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
DB	327123853	Lex Hills Pond	1	125	35	65.8	28.9	7.8	6.0	0.25	0.14	0.72	8,275	8,075	12,000	6,000	8,275	69	8,275	24	0	22.1
DB	327123853	Lex Hills Pond	2	61	22	24.3	11.7	6.7	7.1	0.12	0.13	0.07	1,225	279	12,000	6,000	1,225	10	1,225	24	0	12.1
DB	327123853	Lex Hills Pond	3	102	49	59.7	15.8	8.3	7.3	0.15	0.17	0.14	1,342	809	12,000	6,000	1,342	11	1,342	24	0	12.6
DB	327123853	Lex Hills Pond	4	68	114	52.4	38.2	11.3	9.3	0.33	0.26	0.62	8,276	6,815	12,000	6,000	8,276	69	8,276	24	0	22.1
DB	327123853	Lex Hills Pond	5	77	53	41.9	34.4	7.9	7.4	0.15	0.13	0.44	7,538	6,217	12,000	6,000	7,538	63	7,538	24	0	21.6
DB	327123853	Lex Hills Pond	6	41	26	23.1	20.1	5.4	7.6	0.11	0.12	0.35	10,685	13,364	12,000	6,000	10,685	89	10,685	24	0	23.4
DB	327123853	Lex Hills Pond	7	179	76	47.8	25.7	11.6	8.9	0.28	0.17	0.19	7,898	8,917	12,000	6,000	7,898	66	7,898	24	0	21.8
DB	327123853	Lex Hills Pond	8	214	60	103.0	57.7	20.2	14.4	0.41	0.30	0.06	4,593	1,501	12,000	6,000	4,593	38	4,593	24	0	19.0
DB	327123853	Lex Hills Pond	9	11	10	12.5	12.9	3.1	2.9	0.07	0.05	0.40	33,668	3,398	12,000	6,000	33,668	281	#N/A	24	0	#N/A
DB	327123853	Lex Hills Pond	10	38	12	31.5	19.1	6.0	5.7	0.12	0.14	0.53	17,353	5,149	12,000	6,000	17,353	145	17,353	24	0	34.7
DB	327123853	Lex Hills Pond	11	53	22	34.6	17.1	5.7	3.8	0.18	0.14	0.21	9,100	1,200	12,000	6,000	9,100	76	9,100	24	0	22.6
DB	327123853	Lex Hills Pond	12	17	10	22.9	9.7	3.0	2.4	0.08	0.07	0.50	28,000	6,000	12,000	6,000	28,000	233	#N/A	24	0	#N/A
DB	327123853	Lex Hills Pond	13	18	10	14.2	8.3	3.4	2.2	0.07	0.06	0.56	32,000	10,000	12,000	6,000	32,000	267	#N/A	24	0	#N/A
DB	-983058634	Manchester	1	330	76	1600.0	250.0	230.0	41.0	1.20	0.62	0.22	1,672	1,174	8,927	4,464	1,672	19	1,672	72	0	45.9
DB	-983058634	Manchester	2	92	18	280.0	94.0	44.0	17.0	0.66	0.24	1.53	19,243	15,995	8,927	4,464	19,243	216	#N/A	72	0	#N/A
DB	-983058634	Manchester	3	400	33	940.0	120.0	97.0	21.0	0.86	0.33	1.19	5,760	4,147	8,927	4,464	5,760	65	5,760	72	0	65.2
DB	-983058634	Manchester	4	190	59	460.0	170.0	86.0	42.0	1.80	0.44	0.81	4,180	3,770	8,927	4,464	4,180	47	4,180	72	0	60.2
DB	-983058634	Manchester	5	300	84	550.0	240.0	96.0	49.0	0.51	0.59	0.59	1,872	1,035	8,927	4,464	1,872	21	1,872	72	0	47.6
DB	-983058634	Manchester	6	170	28	390.0	150.0	71.0	26.0	1.00	0.36	0.39	2,319	1,808	8,927	4,464	2,319	26	2,319	72	0	51.0
DB	-983058634	Manchester	7	270	58	540.0		88.0		0.76	0.72	0.32	2,070	955	8,927	4,464	2,070	23	2,070	72	0	49.2
DB	-983058634	Manchester	8	190	94	550.0	160.0	95.0	28.0		0.23	2.18	17,579	9,900	8,927	4,464	17,579	197	#N/A	72	0	#N/A
DB	-983058634	Manchester	9	170	48	570.0	150.0	82.0	26.0	0.38	0.16	0.95	7,273	4,601	8,927	4,464	7,273	81	7,273	72	0	68.8
DB	-983058634	Manchester	10	94	38	440.0	75.0	62.0	11.0	0.80	0.10	0.94	7,795	4,627	8,927	4,464	7,795	87	7,795	72	0	69.9
DB	-983058634	Manchester	11	120	76	280.0	190.0	39.0	28.0	0.20	0.17	2.26	20,838	12,707	8,927	4,464	20,838	233	#N/A	72	0	#N/A
DB	-983058634	Manchester	12	76	18	220.0	100.0	27.0	21.0	0.20	0.09	0.43	2,711	1,873	8,927	4,464	2,711	30	2,711	72	0	53.4
DB	-983058634	Manchester	13	280	100	1200.0	390.0	120.0	65.0	0.60	0.30	0.35	1,972	1,203	8,927	4,464	1,972	22	1,972	72	0	48.4
DB	-983058634	Manchester	14	170	62	550.0	250.0	82.0	42.0	0.20	0.20	0.25	2,835	1,788	8,927	4,464	2,835	32	2,835	72	0	54.1
DC	-410289526	5/605 edb	1	71	44	200.0	140.0	34.0	30.0	0.41	0.45	0.77	1,109	1,109	12,878	6,439	1,109	9	1,109	72	0	33.7
DC	-410289526	5/605 edb	2	48	12	140.0	41.0	21.0	11.0	0.21	0.03	1.48	13,796	13,796	12,878	6,439	13,796	107	13,796	72	0	77.1
DC	-410289526	5/605 edb	4	110	32	104.0	79.8	15.1	17.6	0.42	0.31	2.29	23,071	23,071	12,878	6,439	23,071	179	#N/A	72	0	#N/A
DC	-410289526	5/605 edb	5	34	52	110.0	91.3	19.3	18.6	0.25	0.85	0.21	1,221	1,221	12,878	6,439	1,221	9	1,221	72	0	35.2
DC	-410289526	5/605 edb	6	91	50	219.0	82.9	29.8	15.2	0.38	0.32	0.96	12,355	12,355	12,878	6,439	12,355	96	12,355	72	0	71.4
DC	-410289526	5/605 edb	7	150	190	220.0	130.0	30.0	20.0	0.70	0.72	2.57	32,214	32,214	12,878	6,439	32,214	250	#N/A	72	0	#N/A
DC	-410289526	5/605 edb	8	132	13	489.0	78.0	54.0	11.0	0.49	0.29	1.43	12,227	12,227	12,878	6,439	12,227	95	12,227	72	0	71.2
DC	-410289526	5/605 edb	9	208	50	412.0	247.0	52.0	52.0	2.62	0.58	0.44	1,386	1,386	12,878	6,439	1,386	11	1,386	72	0	37.2
DC	-410289526	5/605 edb	10	39	148	68.0	99.0	6.3	6.7	0.16	0.35	4.10	58,830	58,830	12,878	6,439	58,830	457	#N/A	72	0	#N/A
DC	-410289526	5/605 edb	11	164	39	4.6	108.0	18.0	16.0	0.22	0.24	0.54	4,764	4,764	12,878	6,439	4,764	37	4,764	72	0	56.5
DC	-410289526	5/605 edb	12	19	45	56.0	69.0	9.5	9.5	0.24	0.20	3.41	40,358	40,358	12,878	6,439	40,358	313	#N/A	72	0	#N/A
DC	-410289526	5/605 edb	13	69	23	64.0	59.0	11.0	12.0	0.25	0.18	0.67	5,225	5,225	12,878	6,439	5,225	41	5,225	72	0	57.9
DC	-410289526	5/605 edb	14	59	44	119.0	106.0	22.0	21.0	0.51	0.34	0.79	6,119	6,119	12,878	6,439	6,119	48	6,119	72	0	60.4
DB	-1537544463	Greenville Pond	1	98	26	100.0	80.0	10.0	8.0	0.21	0.21	1.21	285,172	275,764	338,026	169,013	285,172	84	285,172	75	0	72.0
DB	-1537544463	Greenville Pond	2	52	19	115.0	78.0	8.0	6.0	0.26	0.22	0.60	190,974	189,802	338,026	169,013	190,974	56	190,974	75	0	65.5
DB	-1537544463	Greenville Pond	3	99	27	92.0	62.0	10.0	6.0	0.30	0.21	1.40	323,471	299,482	338,026	169,013	323,471	96	323,471	75	0	74.0
DB	-1537544463	Greenville Pond	4	67	29	253.0	115.0	27.0	18.0	0.64	0.32	1.98	355,213	310,757	338,026	169,013	355,213	105	355,213	75	0	78.6
DB	-1537544463	Greenville Pond	5	67	18	737.0	612.0	64.0	49.0	0.40	0.38	0.48	115,894	106,781	338,026	169,013	115,894	34	115,894	75	0	57.4
DB	-1537544463	Greenville Pond	6	233	65	1119.0	596.0	93.0	54.0	0.56	0.37	0.54	74,344	70,732	338,026	169,013	74,344	22	74,344	75	0	50.2
DB	-1537544463	Greenville Pond	7	216	41	210.0	165.0	18.0	10.0	0.58	0.48	0.64	96,646	90,041	338,026	169,013	96,646	29	96,646	75	0	54.5
DB	-1537544463	Greenville Pond	8	184	30	96.0	59.0	9.0	4.0	0.30	0.19	9.28	1,519,736	469,736	338,026	169,013	1,519,736	450	#N/A	75	0	#N/A

Table D1. BMP Database Values when Average Storm HRT was Estimated using the Fraction Full Method (3 of 5)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
RP	-875791527	Shop Creek Pond (90-94)	1	72	20	50.0	20.0	10.0	10.0	0.39	0.57			784,000	399,447	199,723	784,000	196	#N/A	30	21	#N/A
RP	-875791527	Shop Creek Pond (90-94)	2		14		20.0		40.0		0.19			39,000	399,447	199,723	39,000	10	39,000	30	21	#N/A
RP	-875791527	Shop Creek Pond (90-94)	3	122	18	10.0	20.0	60.0	20.0	0.54	0.39			156,000	399,447	199,723	156,000	39	156,000	30	21	17.8
RP	-875791527	Shop Creek Pond (90-94)	4	164		110.0		50.0		0.37				95,000	399,447	199,723	95,000	24	95,000	30	21	11.3
RP	-875791527	Shop Creek Pond (90-94)	5	16		60.0		10.0		0.47				240,000	399,447	199,723	240,000	60	240,000	30	21	23.4
RP	-875791527	Shop Creek Pond (90-94)	6	292	18	130.0	20.0	30.0	10.0	0.47	0.19			173,000	399,447	199,723	173,000	43	173,000	30	21	19.1
RP	-875791527	Shop Creek Pond (90-94)	7	656	14	200.0	20.0	50.0	10.0	0.87	0.13			94,000	399,447	199,723	94,000	24	94,000	30	21	11.2
RP	-875791527	Shop Creek Pond (90-94)	8	46	6	50.0	60.0	40.0	20.0	0.36	0.13	0.77		540,000	399,447	199,723	540,000	135	540,000	30	21	40.6
RP	-875791527	Shop Creek Pond (90-94)	9	18	4	50.0	30.0	10.0	10.0	0.32	0.13	0.20		299,000	399,447	199,723	299,000	75	299,000	30	21	26.2
RP	-875791527	Shop Creek Pond (90-94)	10	446	26	190.0	290.0	40.0	10.0	0.71	0.28	1.58		406,000	399,447	199,723	406,000	102	406,000	30	21	30.5
RP	-875791527	Shop Creek Pond (90-94)	11	352	78	60.0	60.0	30.0	20.0	1.08	0.42	1.17		1,189,120	399,447	199,723	1,189,120	298	#N/A	30	21	#N/A
RP	-875791527	Shop Creek Pond (90-94)	12	36	84	100.0	90.0	40.0	30.0	0.39	0.25			220,000	399,447	199,723	220,000	55	220,000	30	21	22.2
RP	-875791527	Shop Creek Pond (90-94)	13	116				30.0		0.44				411,000	399,447	199,723	411,000	103	411,000	30	21	30.9
RP	-875791527	Shop Creek Pond (90-94)	14	46	42	130.0	100.0	20.0	5.0	0.12	0.09			56,670	399,447	199,723	56,670	14	56,670	30	21	4.6
RP	-875791527	Shop Creek Pond (90-94)	15	30	32	60.0	40.0	20.0	5.0	0.34	0.11	0.15		280,660	399,447	199,723	280,660	70	280,660	30	21	25.4
RP	-875791527	Shop Creek Pond (90-94)	21	324	10	140.0	10.0	30.0	5.0	0.54	0.13	0.68		343,840	399,447	199,723	343,840	86	343,840	30	21	28.1
RP	-875791527	Shop Creek Pond (90-94)	22	14	8	30.0	10.0	5.0	10.0	0.25	0.16	0.38		145,900	399,447	199,723	145,900	37	145,900	30	21	16.9
RP	-875791527	Shop Creek Pond (90-94)	26	20	3	60.0	70.0	30.0	5.0	0.37	0.13	0.19		82,060	399,447	199,723	82,060	21	82,060	30	21	9.4
RP	-875791527	Shop Creek Pond (90-94)	28	136	22	50.0	40.0	60.0	30.0	0.47	0.19	0.65		268,060	399,447	199,723	268,060	67	268,060	30	21	24.8
RP	-875791527	Shop Creek Pond (90-94)	30	30	8	30.0	5.0	100.0	5.0	0.34	0.29	0.30		125,410	399,447	199,723	125,410	31	125,410	30	21	14.9
RP	-875791527	Shop Creek Pond (90-94)	31	20	18	40.0	5.0	50.0	1.0	0.25	1.02	0.72		483,150	399,447	199,723	483,150	121	483,150	30	21	36.3
RP	-875791527	Shop Creek Pond (90-94)	32	72	24	150.0	130.0	50.0	5.0	0.16	0.25	2.46		1,419,010	399,447	199,723	1,419,010	355	#N/A	30	21	#N/A
RP	-875791527	Shop Creek Pond (90-94)	46		14							0.20		131,770	399,447	199,723	131,770	33	131,770	30	21	15.6
RP	-875791527	Shop Creek Pond (90-94)	47	74	14	140.0	30.0	60.0	10.0			0.68		395,310	399,447	199,723	395,310	99	395,310	30	21	29.9
RP	-875791527	Shop Creek Pond (90-94)	48	92	16							0.18		80,000	399,447	199,723	80,000	20	80,000	30	21	9.1
RP	-875791526	Shop Creek Pond (90-94)	52	88	18	200.0		30.0				0.17		156,000	399,447	199,723	156,000	39	156,000	30	21	17.8
RP	-875791525	Shop Creek Pond (90-94)	53		40		20.0		10.0			0.69		416,000	399,447	199,723	416,000	104	416,000	30	21	31.2
RP	-875791524	Shop Creek Pond (90-94)	54	44		190.0	20.0	10.0	10.0			0.46		248,000	399,447	199,723	248,000	62	248,000	30	21	23.8
RP	-875791523	Shop Creek Pond (90-94)	55	294	228	240.0	80.0	80.0	40.0			0.64		383,000	399,447	199,723	383,000	96	383,000	30	21	29.5
RP	-875791522	Shop Creek Pond (90-94)	56	182	22	80.0	30.0	30.0	20.0			0.22		132,000	399,447	199,723	132,000	33	132,000	30	21	15.6
RP	-875791521	Shop Creek Pond (90-94)	57	78	14	100.0	20.0	30.0	10.0			0.20		120,000	399,447	199,723	120,000	30	120,000	30	21	14.4
RP	-875791520	Shop Creek Pond (90-94)	58	70		80.0	40.0	10.0	5.0			0.13		78,000	399,447	199,723	78,000	20	78,000	30	21	8.8
RP	-875791519	Shop Creek Pond (90-94)	64	18	6	80.0	10.0	80.0	10.0			2.29		150,000	399,447	199,723	150,000	38	150,000	30	21	17.3
RP	-875791518	Shop Creek Pond (90-94)	109			5.0	30.0	16.5	6.0			0.27		96,430	399,447	199,723	96,430	24	96,430	30	21	11.5
RP	-875791517	Shop Creek Pond (90-94)	110	140	10	130.0	50.0	8.5	5.0	1.03	0.21	0.19		138,560	399,447	199,723	138,560	35	138,560	30	21	16.2
RP	-875791516	Shop Creek Pond (90-94)	112	999	9	420.0	80.0	64.0	7.5	1.16	0.03	0.27		14,620	399,447	199,723	14,620	4	14,620	30	21	#N/A
RP	-875791515	Shop Creek Pond (90-94)	113			60.0	20.0	24.5	5.0			0.17		78,060	399,447	199,723	78,060	20	78,060	30	21	8.8
RP	-875791514	Shop Creek Pond (90-94)	114			5.0	30.0	16.5	16.0			0.22		73,470	399,447	199,723	73,470	18	73,470	30	21	8.0
RP	-111085006	Shop Creek Pond (95-97)	1	306		5.0		5.0		0.43				104,520	399,447	199,723	104,520	26	104,520	30	21	12.6
RP	-111085006	Shop Creek Pond (95-97)	2	153	12	5.0	5.0	5.0	5.0	0.53	0.05			119,710	399,447	199,723	119,710	30	119,710	30	21	14.3
RP	-111085006	Shop Creek Pond (95-97)	3		19		5.0		5.0		0.07			89,590	399,447	199,723	89,590	22	89,590	30	21	10.6
RP	-111085006	Shop Creek Pond (95-97)	7	76	76	60.0	60.0	8.0	8.0	0.18	0.18	2.11		1,073,700	399,447	199,723	1,073,700	269	#N/A	30	21	#N/A
RP	-111085006	Shop Creek Pond (95-97)	14	324	42	200.0	40.0	23.0	7.0	0.75	0.13			481,850	399,447	199,723	481,850	121	481,850	30	21	36.2
RP	-111085006	Shop Creek Pond (95-97)	16	103	5	5.0	5.0	5.0	5.0	0.20	0.08	0.78		630	399,447	199,723	630	0	630	30	21	#N/A
RP	-111085006	Shop Creek Pond (95-97)	18	175	13	590.0	30.0	124.0	16.5	1.00	0.14	0.18		9,470	399,447	199,723	9,470	2	9,470	30	21	#N/A
RP	-111085006	Shop Creek Pond (95-97)	22	182	73	110.0	30.0	11.0	6.5	0.58	0.24	1.00		256,290	399,447	199,723	256,290	64	256,290	30	21	24.2
RP	-111085006	Shop Creek Pond (95-97)	27	40	21	40.0	30.0	7.0	8.0	0.22	0.15	0.69		234,160	399,447	199,723	234,160	59	234,160	30	21	23.1
RP	-111085006	Shop Creek Pond (95-97)	31	203	35	150.0	30.0	14.0	5.5	0.10	0.04	0.57		154,840	399,447	199,723	154,840	39	154,840	30	21	17.7
RP	-111085006	Shop Creek Pond (95-97)	33	59	31	80.0	30.0	8.5	6.0	0.25	0.13	0.22		91,650	399,447	199,723	91,650	23	91,650	30	21	10.9
RP	-111085006	Shop Creek Pond (95-97)	34	124	26	130.0	5.0	17.5	4.5	1.04	0.16	0.11		93,770	399,447	199,723	93,770	23	93,770	30	21	11.2
RP	-111085006	Shop Creek Pond (95-97)	38	13	22	5.0	5.0	5.0	5.0	0.12	0.22	0.58		357,200	399,447	199,723	357,200	89	357,200	30	21	28.5
RP	-111085006	Shop Creek Pond (95-97)	41	150	20	140.0	50.0	34.5	7.0	0.46	0.16	1.84		481,600	399,447	199,723	481,600	121	481,600	30	21	36.2
RP	-111085006	Shop Creek Pond (95-97)	42	501	42	160.0	40.0	15.5	5.5	0.71	0.17	0.87		470,000	399,447	199,723	470,000	118	470,000	30	21	35.3
RP	-111085006	Shop Creek Pond (95-97)	43	221	33	220.0	60.0	22.0	7.0	0.61	0.17	0.23		16,800	399,447	199,723	16,800	4	16,800	30	21	#N/A
RP	-111085006	Shop Creek Pond (95-97)	45	4	27	40.0	30.0	4.5	6.5	0.19	0.12	0.59		434,100	399,447	199,723	434,100	109	434,100	30	21	32.6
RP	-111085006	Shop Creek Pond (95-97)	47	1	10	280.0	30.0	33.0	3.5	0.83	0.09	0.29		136,200	399,447	199,723	136,200	34	136,200	30	21	16.0
RP	-111085006	Shop Creek Pond (95-97)	49	438	10	250.0	30.0	18.0	5.5	0.81	0.06	0.12		64,200	399,447	199,723	64,200	16	64,200	30	21	6.2
RP	-111085006	Shop Creek Pond (95-97)	51	128	12	110.0	5.0	14.0	5.0	0.45	0.09	0.10		50,600	399,447	199,723	50,600	13	50,600	30	21	3.1

Table D1. BMP Database Values when Average Storm HRT was Estimated using the Fraction Full Method (4 of 5)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
Wet Pond	670725923	BMP 12	2	99	32					0.11	0.08		159,234	195,876	127,627	63,814	159,234	125	159,234	33	28	41.2
Wet Pond	670725923	BMP 12	3	178	48					0.31	0.14		124,883	137,819	127,627	63,814	124,883	98	124,883	33	28	32.8
Wet Pond	670725923	BMP 12	5	6	3					0.04	0.03		47,738	62,355	127,627	63,814	47,738	37	47,738	33	28	25.9
Wet Pond	670725923	BMP 12	7	76	19					0.22	0.11		162,204	308,516	127,627	63,814	162,204	127	162,204	33	28	41.9
Wet Pond	670725923	BMP 12	8	128	25					0.52	0.14		42,498	57,679	127,627	63,814	42,498	33	42,498	33	28	25.1
Wet Pond	670725923	BMP 12	9	125	50					0.41	0.20		183,386	211,390	127,627	63,814	183,386	144	183,386	33	28	47.4
Wet Pond	670725923	BMP 12	10	110	27					0.37	0.12		44,500	56,525	127,627	63,814	44,500	35	44,500	33	28	25.4
Wet Pond	670725923	BMP 12	12	52	24					0.17	0.10		286,349	277,213	127,627	63,814	286,349	224	#N/A	33	28	#N/A
Wet Pond	670725923	BMP 12	13	158	44					0.43	0.16		235,157	221,087	127,627	63,814	235,157	184	#N/A	33	28	#N/A
Wet Pond	670725923	BMP 12	14	34	7					0.19	0.07		71,074	82,898	127,627	63,814	71,074	56	71,074	33	28	28.8
Wet Pond	670725923	BMP 12	15	33	10					0.16	0.08		151,853	159,004	127,627	63,814	151,853	119	151,853	33	28	39.3
Wet Pond	670725923	BMP 12	16	203	63					0.45	0.20		271,301	279,653	127,627	63,814	271,301	213	#N/A	33	28	#N/A
Wet Pond	670725923	BMP 12	17	53	15					0.20	0.08		14,733	24,194	127,627	63,814	14,733	12	14,733	33	28	17.5
Wet Pond	670725923	BMP 12	18	46	15					0.19	0.09		29,032	39,281	127,627	63,814	29,032	23	29,032	33	28	22.3
Wet Pond	670725923	BMP 12	19	38	23					0.18	0.11		63,418	80,235	127,627	63,814	63,418	50	63,418	33	28	28.0
Wet Pond	1411032820	BMP 13	1	90	88					0.33	0.40		38,574	77,187	30,441	15,221	38,574	127	38,574	43	30	53.9
Wet Pond	1411032820	BMP 13	2	7	9					0.18	0.11		3,019	4,584	30,441	15,221	3,019	10	3,019	43	30	0.9
Wet Pond	1411032820	BMP 13	4		4									6,544	30,441	15,221	6,544	21	6,544	43	30	14.8
Wet Pond	1411032820	BMP 13	5	144	50					0.42	0.20		9,041	7,172	30,441	15,221	9,041	30	9,041	43	30	20.6
Wet Pond	1411032820	BMP 13	6	12	26					0.20	0.17		90,706	198,920	30,441	15,221	90,706	298	#N/A	43	30	#N/A
Wet Pond	1411032820	BMP 13	8	7	4					0.19	0.11		38,408	52,442	30,441	15,221	38,408	126	38,408	43	30	53.6
Wet Pond	1411032820	BMP 13	9	5	5					0.53	0.30		3,178	7,787	30,441	15,221	3,178	10	3,178	43	30	1.8
Wet Pond	1411032820	BMP 13	10	86	47					0.40	0.30		16,686	31,465	30,441	15,221	16,686	55	16,686	43	30	31.7
Wet Pond	1411032820	BMP 13	11	40	13					0.21	0.09		2,567	2,225	30,441	15,221	2,567	8	2,567	43	30	#N/A
Wet Pond	1411032820	BMP 13	12	73	23					0.30	0.19		20,147	40,841	30,441	15,221	20,147	66	20,147	43	30	35.1
Wet Pond	1411032820	BMP 13	13	455	114					0.76	0.43		21,108	36,522	30,441	15,221	21,108	69	21,108	43	30	35.9
Wet Pond	1411032820	BMP 13	14	31	13					0.20	0.13		7,829	15,235	30,441	15,221	7,829	26	7,829	43	30	18.1
Wet Pond	1411032820	BMP 13	15	46	6					0.39	0.23		6,593	13,603	30,441	15,221	6,593	22	6,593	43	30	15.0
Wet Pond	-1847201712	BMP37	1		12						0.12	1.70		266,509	338,880	169,440	266,509	79	266,509	21	18	20.3
Wet Pond	-1847201712	BMP37	2	31	18					0.26	0.13	3.24	520,432	683,985	338,880	169,440	520,432	154	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	4	89	32					0.24	0.18	1.70	522,163	642,656	338,880	169,440	522,163	154	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	5	25	10					0.08	0.08	0.50	203,056	218,245	338,880	169,440	203,056	60	203,056	21	18	19.2
Wet Pond	-1847201712	BMP37	6	203	45					0.15	0.11	1.20	370,052	441,539	338,880	169,440	370,052	109	370,052	21	18	23.3
Wet Pond	-1847201712	BMP37	7	58	16					0.20	0.12	0.50	146,047	147,767	338,880	169,440	146,047	43	146,047	21	18	17.8
Wet Pond	-1847201712	BMP37	8		71						0.23	1.80		381,642	338,880	169,440	381,642	113	381,642	21	18	24.0
Wet Pond	-1847201712	BMP37	9		74						0.33	1.10		174,917	338,880	169,440	174,917	52	174,917	21	18	18.6
Wet Pond	-1847201712	BMP37	10		97						0.32	2.10		517,243	338,880	169,440	517,243	153	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	11		42						0.27	2.00		734,725	338,880	169,440	734,725	217	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	12		341						0.72	2.07		435,613	338,880	169,440	435,613	129	435,613	21	18	27.4
Wet Pond	-1847201712	BMP37	13		48						0.19	1.38		208,554	338,880	169,440	208,554	62	208,554	21	18	19.3
Wet Pond	-1847201712	BMP37	14		421						0.56	2.65		666,437	338,880	169,440	666,437	197	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	15		46						0.18	0.59		86,881	338,880	169,440	86,881	26	86,881	21	18	15.7
Wet Pond	-1847201712	BMP37	16		162						0.35	1.19		283,142	338,880	169,440	283,142	84	283,142	21	18	20.6
Wet Pond	-1847201712	BMP37	17		146							5.01		1,993,269	338,880	169,440	1,993,269	588	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	18		217						0.44	2.41		1,052,963	338,880	169,440	1,052,963	311	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	19		38						0.18	3.31		1,255,299	338,880	169,440	1,255,299	370	#N/A	21	18	#N/A
Wet Pond	-1847201712	BMP37	20		30						0.22				338,880	169,440	#N/A	#N/A	#N/A	21	18	#N/A

Table D1. BMP Database Values when Average Storm HRT was Estimated using the Fraction Full Method (5 of 5)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
RP	-1123519813	La Costa WB	1	170	4	360.0	41.0	100.0	18.0	0.64	1.50	0.16	1,024	878	9,150	4,575	1,024	11	1,024	24	0	12.6
RP	-1123519813	La Costa WB	2	240	28	700.0	41.0	210.0	17.0	1.60	1.10	0.16	1,024	765	9,150	4,575	1,024	11	1,024	24	0	12.6
RP	-1123519813	La Costa WB	3	60	12	440.0	36.0	800.0	13.0	2.60	1.10	1.45	9,926	7,520	9,150	4,575	9,926	108	9,926	24	0	26.0
RP	-1123519813	La Costa WB	4	350	12	2000.0	45.0	9500.0	14.0	2.60	1.20	0.63	5,768	4,096	9,150	4,575	5,768	63	5,768	24	0	21.6
RP	-1123519813	La Costa WB	5	230	4	330.0	92.0	71.0	31.0	0.68	1.10	0.61	4,025	3,431	9,150	4,575	4,025	44	4,025	24	0	19.7
RP	-1123519813	La Costa WB	6		2		41.0		5.7		1.90	0.60	3,169	2,515	9,150	4,575	3,169	35	3,169	24	0	18.5
RP	-1123519813	La Costa WB	8	300	10	520.0	19.0	120.0	5.1	0.78	0.36	0.21	689	675	9,150	4,575	689	8	689	24	0	10.6
RP	-1123519813	La Costa WB	9	240	10	280.0	28.0	66.0	7.1	0.32	0.29	1.69	11,060	9,086	9,150	4,575	11,060	121	11,060	24	0	29.0
RP	-1123519813	La Costa WB	10	240	12	460.0	18.0	72.0	4.2	0.51	0.28	0.60	4,082	5,067	9,150	4,575	4,082	45	4,082	24	0	19.8
RP	-1123519813	La Costa WB	11	170	28	200.0	37.0	43.0	13.0	0.20	0.85	1.54	8,539	6,350	9,150	4,575	8,539	93	8,539	24	0	23.6
RP	-1123519813	La Costa WB	12	68	2	270.0	37.0	77.0	7.0	0.40	0.45	1.80	8,108	11,008	9,150	4,575	8,108	89	8,108	24	0	23.4
RP	-1123519813	La Costa WB	13	110	1	190.0	21.0	35.0	3.4	0.40	0.50	0.42	1,171	1,315	9,150	4,575	1,171	13	1,171	24	0	13.3
RP	-1123519813	La Costa WB	14	270	18	850.0	37.0	200.0	6.6	0.40	0.21	0.43	2,754	2,532	9,150	4,575	2,754	30	2,754	24	0	17.8
RP	-1123519813	La Costa WB	15	190	12	340.0	31.0	62.0	3.8	2.00	0.23	0.28	1,034	1,506	9,150	4,575	1,034	11	1,034	24	0	12.7
RP	645374081	Shawnee Ridge Retention Pond	4	71	5	40.0	20.0			0.09	0.00	0.42	204,846	303,599	1,347,644	673,822	303,599	23	303,599	13	13	12.0
RP	645374081	Shawnee Ridge Retention Pond	5	72	8	30.0	10.0			0.00	0.00	0.40	103,079	161,001	1,347,644	673,822	161,001	12	161,001	13	13	11.5
RP	645374081	Shawnee Ridge Retention Pond	6	220	14	180.0	20.0			0.60	0.40	0.00	818,350	1,278,197	1,347,644	673,822	1,278,197	95	1,278,197	13	13	13.0

Table D2. BMP Database Values when Average Storm HRT was Estimated using the Peak Flow Approximation Method (only used for the Beltway 8 Surge Basin)

				WQ Results																150		
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow		Outflow					FILTER		
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Peak Inflow (cfs)	Total Inflow Vol (ft^3)	Peak Outflow (cfs)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Recorded Peak Outflow Discharge (cfs)	Calculated Average HRT (hrs)
RP	623746913	Beltway 8 - Surge Basin	1	313		113.0		13.0		0.05		0.52	10.40	30,980			1,742,426	30,980	2	30,980	#N/A	8.7
RP	623746913	Beltway 8 - Surge Basin	2	191		93.0	184.0	14.0	35.0	0.05	0.13	0.62	4.16	18,034	2.9	46,869	1,742,426	18,034	1	18,034	2.88	1.7
RP	623746913	Beltway 8 - Surge Basin	3	130	103	49.0	163.0	7.0	22.0	0.03	0.03	0.58	12.80	494,780	3.4	105,889	1,742,426	494,780	28	494,780	3.41	40.3
RP	623746913	Beltway 8 - Surge Basin	4	313	30	5.0	265.0	5.0	10.0	0.34	0.03	0.64	10.60	183,593	3.0	93,065	1,742,426	183,593	11	183,593	2.97	17.2
RP	623746913	Beltway 8 - Surge Basin	5	166	67	63.9	57.1	5.2	13.6	0.10	0.35	0.48	3.57	78,753	3.0	42,795	1,742,426	78,753	5	78,753	2.97	7.4
RP	623746913	Beltway 8 - Surge Basin	8	3	119	21.9	310.0	3.5	14.6	0.14	0.16	0.29	1.70	8,318	0.5	6,056	1,742,426	8,318	0	8,318	0.50	4.6
RP	623746913	Beltway 8 - Surge Basin	10	87	57	28.5	57.5	7.5	5.8	0.09	0.11	0.36	15.95	30,312	0.5	4,725	1,742,426	30,312	2	30,312	0.46	18.3
RP	623746913	Beltway 8 - Surge Basin	11	377	306	105.0	136.0	14.5	12.7	0.06	0.06	3.86	101.46	667,258	0.9		1,742,426	667,258	38	667,258	0.86	N/A
RP	623746913	Beltway 8 - Surge Basin	12	240	86	65.2	284.0	8.8	9.3	1.00	0.07	1.35	28.28	53,485	3.1	95,848	1,742,426	53,485	3	53,485	3.07	4.8
RP	623746913	Beltway 8 - Surge Basin	13	147	92	45.6	150.0	10.3	8.8	0.23	0.39	0.71	18.20	31,340	2.9	46,705	1,742,426	31,340	2	31,340	2.90	3.0
RP	623746913	Beltway 8 - Surge Basin	14	200	76	47.0	883.0	2.5	142.0	1.19	1.46	1.51	24.68	21,293	3.1	360,240	1,742,426	21,293	1	21,293	3.10	1.9
RP	623746913	Beltway 8 - Surge Basin	15	409	97	142.0	186.0	24.3	19.0	3.62	3.56	0.84	7.89	104,843	2.9	113,770	1,742,426	104,843	6	104,843	2.87	10.1
RP	623746913	Beltway 8 - Surge Basin	16	470	47	199.0	624.0	27.5	30.6	1.98	1.45	0.78	9.30	35,776	3.0	51,167	1,742,426	35,776	2	35,776	2.96	3.4
RP	623746913	Beltway 8 - Surge Basin	17	169	84	54.5	292.0	5.0	5.6	1.91	1.94	1.17	15.40	133,800	2.9	160,425	1,742,426	133,800	8	133,800	2.91	12.8

Table D3. BMP Database Values for Madison, WI, Wet Pond Monroe St. (Required a V-notch Model for the Fraction Full Method)

				WQ Results															150			
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow	Outflow					FILTER			
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Total Inflow Vol (ft^3)	Outflow Vol (ft^3)	Brim Full Volume (cf)	Half Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Brim-Full Drain Time (hr)	Half-full Drain Time (hr)	Calculated Average HRT (hrs)
RP	-240960970	Madison, WI, Wet Pond Monroe St.	1	360	53					1.08	0.36	0.71	110,606	105,384	84,755	42,378	110,606	131	110,606	102	98	99.5
RP	-240960970	Madison, WI, Wet Pond Monroe St.	2	128	15					0.33	0.26	1.02	70,877	67,451	84,755	42,378	70,877	84	70,877	102	98	98.9
RP	-240960970	Madison, WI, Wet Pond Monroe St.	3	52	24					0.20	0.22	0.75	53,572	46,792	84,755	42,378	53,572	63	53,572	102	98	98.6
RP	-240960970	Madison, WI, Wet Pond Monroe St.	4	167						0.40		1.14	142,601	65,862	84,755	42,378	142,601	168	#N/A	102	98	100.0
RP	-240960970	Madison, WI, Wet Pond Monroe St.	5	216	15					1.16	0.18	0.24	17,269	5,180	84,755	42,378	17,269	20	17,269	102	98	86.2
RP	-240960970	Madison, WI, Wet Pond Monroe St.	6	142	15					0.30	0.18	1.69	124,414	125,249	84,755	42,378	124,414	147	124,414	102	98	99.7
RP	-240960970	Madison, WI, Wet Pond Monroe St.	7		37						0.21	1.46	198,751	201,300	84,755	42,378	198,751	235	#N/A	102	98	101.0
RP	-240960970	Madison, WI, Wet Pond Monroe St.	8		20					0.54	0.24	1.38	219,551	211,005	84,755	42,378	219,551	259	#N/A	102	98	101.3
RP	-240960970	Madison, WI, Wet Pond Monroe St.	9	21	4					0.24	0.31	0.08	3,531	2,649	84,755	42,378	3,531	4	3,531	102	98	FALSE
RP	-240960970	Madison, WI, Wet Pond Monroe St.	10	590	16					6.69	0.27	0.95	137,409	139,787	84,755	42,378	137,409	162	#N/A	102	98	100.0
RP	-240960970	Madison, WI, Wet Pond Monroe St.	11	129						0.46		0.28	23,343	23,837	84,755	42,378	23,343	28	23,343	102	98	89.1
RP	-240960970	Madison, WI, Wet Pond Monroe St.	12	52						0.65		0.35	17,234		84,755	42,378	17,234	20	17,234	102	98	86.1
RP	-240960970	Madison, WI, Wet Pond Monroe St.	13	870						1.30	0.23	0.39	20,800	8,829	84,755	42,378	20,800	25	20,800	102	98	87.9
RP	-240960970	Madison, WI, Wet Pond Monroe St.	14								0.18	0.28	18,823	18,846	84,755	42,378	18,823	22	18,823	102	98	86.9
RP	-240960970	Madison, WI, Wet Pond Monroe St.	15	292	18					0.54	0.20	0.87	102,836	101,086	84,755	42,378	102,836	121	102,836	102	98	99.4
RP	-240960970	Madison, WI, Wet Pond Monroe St.	16	556	32			**Values for Total Recoverable Copper were removed from the dataset because of a high detection limit.**		1.15	0.24	0.47	60,494	57,046	84,755	42,378	60,494	71	60,494	102	98	98.7
RP	-240960970	Madison, WI, Wet Pond Monroe St.	17									0.75	34,538	19,882	84,755	42,378	34,538	41	34,538	102	98	94.6
RP	-240960970	Madison, WI, Wet Pond Monroe St.	18									0.24	8,652	6,851	84,755	42,378	8,652	10	8,652	102	98	58.6
RP	-240960970	Madison, WI, Wet Pond Monroe St.	19	388	26					0.36	0.20	2.01	246,249	247,186	84,755	42,378	246,249	291	#N/A	102	98	101.7
RP	-240960970	Madison, WI, Wet Pond Monroe St.	20	232						0.37		3.19	445,035	287,638	84,755	42,378	445,035	525	#N/A	102	98	FALSE
RP	-240960970	Madison, WI, Wet Pond Monroe St.	21	166	17					0.30	0.16	1.77	171,912	178,859	84,755	42,378	171,912	203	#N/A	102	98	100.5
RP	-240960970	Madison, WI, Wet Pond Monroe St.	22	110						0.28		3.23	244,554	78,151	84,755	42,378	244,554	289	#N/A	102	98	101.7
RP	-240960970	Madison, WI, Wet Pond Monroe St.	23	356	13					0.89	0.20	0.55	72,572	53,285	84,755	42,378	72,572	86	72,572	102	98	98.9
RP	-240960970	Madison, WI, Wet Pond Monroe St.	24	148	9					1.62	0.27	0.31	12,113	14,510	84,755	42,378	12,113	14	12,113	102	98	70.0
RP	-240960970	Madison, WI, Wet Pond Monroe St.	25									0.55	61,342	47,675	84,755	42,378	61,342	72	61,342	102	98	98.7
RP	-240960970	Madison, WI, Wet Pond Monroe St.	26	188	27					0.54	0.35	1.14	146,026	146,097	84,755	42,378	146,026	172	#N/A	102	98	100.1
RP	-240960970	Madison, WI, Wet Pond Monroe St.	27	158	27					0.32	0.25	1.61	207,368	209,117	84,755	42,378	207,368	245	#N/A	102	98	101.1
RP	-240960970	Madison, WI, Wet Pond Monroe St.	28	26	66					0.38	0.23	1.06	106,368	105,409	84,755	42,378	106,368	126	106,368	102	98	99.4
RP	-240960970	Madison, WI, Wet Pond Monroe St.	29	45	10					0.17	0.19	0.75	42,378	44,850	84,755	42,378	42,378	50	42,378	102	98	98.4
RP	-240960970	Madison, WI, Wet Pond Monroe St.	30	108	38					0.22	0.18	0.55	25,038	32,800	84,755	42,378	25,038	30	25,038	102	98	89.9
RP	-240960970	Madison, WI, Wet Pond Monroe St.	32	72						0.45		0.08	16,421		84,755	42,378	16,421	19	16,421	102	98	84.3
RP	-240960970	Madison, WI, Wet Pond Monroe St.	33	1330	78					1.70	0.13	0.24	26,769	16,449	84,755	42,378	26,769	32	26,769	102	98	90.8
RP	-240960970	Madison, WI, Wet Pond Monroe St.	34	664	80					0.74	0.23	0.79	84,685	104,576	84,755	42,378	84,685	100	84,685	102	98	99.1
RP	-240960970	Madison, WI, Wet Pond Monroe St.	35	1110	140					1.02	0.25	1.38	223,789	237,602	84,755	42,378	223,789	264	#N/A	102	98	101.4
RP	-240960970	Madison, WI, Wet Pond Monroe St.	36	34	29					0.28	0.21	0.31	28,570	32,745	84,755	42,378	28,570	34	28,570	102	98	91.7

Table D4. BMP Database Values when Average Storm HRT was Estimated using the Outlet Flow Duration

				WQ Results																		150	
				TSS		TR Zinc		TR Copper		Total Phosphorous		Rainfall	Inflow			Outflow						FILTER	
BMP Type 2009	BMPID	BMPName	Storm #	Inflow (mg/L)	Outflow (mg/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (ug/L)	Outflow (ug/L)	Inflow (mg/L)	Outflow (mg/L)	Depth (in)	Start Date and Time	End Date and Time	Total Inflow Vol (ft^3)	Start Date and Time	End Date and Time	Outflow Vol (ft^3)	Brim Full Volume (cf)	Storm Volume (Selection between inflow and outflow, cf)	BMP % Full	Filtered Results (Storm Vol. < 150% BMP surcharge Vol. Included)	Calculated Average HRT (hrs)
RP	453873277	Central Park Wet Pond	2		11	335.0	45.7	24.6	4.9	4.38	1.84	0.90	4/2/1997 16:40	4/3/1997 15:22	53,250	4/2/1997 16:54	4/3/1997 14:57	178,138	812,394	53,250	7	53,250	22.7
RP	453873277	Central Park Wet Pond	4	42	60	80.0	64.0	11.0	6.5	3.34	4.95	1.88	5/9/1997 7:55	5/9/1997 21:03	184,702	5/9/1997 8:04	5/9/1997 14:08	560,488	812,394	184,702	23	184,702	13.1
RP	453873277	Central Park Wet Pond	5	27	37	49.0	42.5	9.0	6.5	2.88	2.71	0.57	5/15/1997 21:13	5/16/1997 2:06	37,409	5/15/1997 21:24	5/16/1997 2:38	125,441	812,394	37,409	5	37,409	5.4
RP	453873277	Central Park Wet Pond	6	28	11	54.5	25.5	5.0	4.0	2.43	2.76	0.76	5/19/1997 21:44	5/20/1997 9:06	43,070	5/19/1997 23:08	5/20/1997 8:56	123,561	812,394	43,070	5	43,070	11.4
RP	453873277	Central Park Wet Pond	8	35	32	38.8	10.0	17.0	7.0	0.18	4.71	0.59	6/6/1997 16:42	6/7/1997 0:14	40,658	6/6/1997 20:09	6/7/1997 0:26	93,599	812,394	40,658	5	40,658	7.7
RP	453873277	Central Park Wet Pond	9	108	61	111.0	44.6	13.0	6.0	3.82	7.41	0.94	6/17/1997 4:53	6/17/1997 7:17	119,843	6/17/1997 5:06	6/17/1997 8:44	342,505	812,394	119,843	15	119,843	3.8
RP	453873277	Central Park Wet Pond	10	72	40	159.0	43.8	18.2	9.5	3.22	2.48	1.11	7/30/1997 17:27	7/30/1997 21:23	72,168	7/30/1997 17:50	7/30/1997 22:08	297,413	812,394	72,168	9	72,168	4.7
RP	453873277	Central Park Wet Pond	11	5	29	134.0	43.9	14.4	5.5	10.30	10.40	2.97	8/7/1997 18:04	8/8/1997 16:04	168,960	8/7/1997 18:06	8/8/1997 8:05	712,821	812,394	168,960	21	168,960	22.0
RP	453873277	Central Park Wet Pond	12	288		413.0		45.8		15.60		0.47	9/9/1997 15:50	9/9/1997 17:34	35,423	9/9/1997 16:07	9/9/1997 19:54	95,857	812,394	35,423	4	35,423	4.1
		Udall Inlet to Pond 1		90	39	170.2	98.57	39.55	19.38	0.663	0.337		10/27/2009 17:32	10/28/2009 11:00		10/27/2009 18:00	10/29/2009 11:00						41.5
		Udall Inlet to Pond 1		146	57	149.3	70.82	25.85	14.32	0.233	0.132		4/21/2010 19:29	4/23/2010 0:00		4/21/2010 20:00	4/26/2010 11:00						111.5
		Udall Inlet to Pond 1		49	30	47.5	39.7	7.72	6.08	0.023	0.064		4/28/2010 23:00	4/29/2010 13:36		4/29/2010 0:00	5/2/2010 12:00						85.0
		Udall Inlet to Pond 1		240	40					0.216	0.116		7/4/2010 17:19	7/5/2010 0:00		7/4/2010 17:00	7/6/2010 22:00						53.0
		Udall Inlet to Pond 1		434	23					0.924	0.330		8/8/2010 19:23	8/8/2010 23:00		8/8/2010 3:00	8/10/2010 8:00						53.0
		Udall Inlet to Pond 1			40						0.116					10/22/2010 15:00	10/25/2010 2:00						59.0
		Udall Inlet to Pond 1		132	53	103.78	67.21	17.58		0.116	0.627		4/13/2011 20:00	4/14/2011 16:00		4/13/2011 22:00	4/16/2011 9:00						61.0
		Udall Inlet to Pond 1		28	42	53	38.21	10.38	6.47	0.092	0.075		4/24/2011 19:00	4/25/2011 7:00		4/24/2011 19:30	4/26/2011 15:00						44.0
		Udall Inlet to Pond 2		146	34	149.3	53.3	25.85	10.9	0.233	0.111		4/21/2010 19:29	4/23/2010 0:00		4/22/2010 0:25	4/27/2010 9:50						134.3
		Udall Inlet to Pond 2		49	12	47.5	29.6	7.72	5	0.023	0.048		4/28/2010 23:00	4/29/2010 13:36		4/29/2010 4:00	5/3/2010 2:00						99.0
		Udall Inlet to Pond 2		240	28					0.216	0.077		7/4/2010 17:19	7/5/2010 0:00		7/4/2010 17:00	7/7/2010 8:00						63.0
		Udall Inlet to Pond 2		434	29					0.924	0.337		8/8/2010 19:23	8/8/2010 23:00		8/8/2010 19:00	8/10/2010 8:00						37.0
		Udall Inlet to Pond 2			16						0.080					10/22/2010 23:00	10/25/2010 20:00						69.0
		Udall Inlet to Pond 2		100	22					0.368	0.113		11/9/2010 12:26	11/9/2010 21:00		11/9/2010 12:00	11/11/2010 5:47						41.8
		Udall Inlet to Pond 2		28	20	53	36.66	10.38	6.44	0.092	0.073		4/24/2011 19:00	4/25/2011 7:00		4/25/2011 0:00	4/27/2011 2:00						55.0
		Howes St. BMP			40		135.8		16.98		0.580					10/27/2009 18:10	10/28/2009 12:05						17.9
		Howes St. BMP			132		115.1		18.28		0.066					3/19/2010 3:10	3/20/2010 2:50						23.7
		Howes St. BMP		49		32.8	33.2	6.59	5.87	0.110	0.131		4/29/2010 0:16	4/29/2010 8:03		4/28/2010 23:45	4/29/2010 23:15						23.5
		Howes St. BMP		525	116					0.363	0.333		7/4/2010 17:25	7/4/2010 22:00		7/4/2010 17:45	7/5/2010 5:00						11.6
		Howes St. BMP		677	25					1.439	0.327		8/8/2010 0:00	8/8/2010 19:23		8/8/2010 19:25	8/9/2010 9:25						33.4
		Howes St. BMP		98	14					0.549	0.257		11/9/2010 12:30	11/9/2010 14:53		11/9/2010 13:00	11/9/2010 23:00						10.5
		Howes St. BMP		140	55	110.65				0.245	0.064		4/13/11/ 21:30	4/14/2011 2:30		4/13/2011 22:00	4/15/2011 0:00						26.0
		Howes St. BMP		56	38	34	35.27	5.88	5.62	0.114	0.083		4/24/2011 19:15	4/25/2011 2:00		4/24/2011 19:00	4/25/2011 7:00						12.0