Water Resources Research Institute
of The University of North Carolina

Report No. 384

IDENTIFYING THE ORIGINS AND ATTACHMENT BEHAVIOR OF NON-POINT SOURCE MICROBIAL CONTAMINANTS

By
Gregory W. Characklis, Otto D. Simmons III, Mark D. Sobsey, Patricia N. Drummey, and Leigh-Anne Krometis

Department of Environmental Sciences and Engineering
University of North Carolina at Chapel Hill
Chapel Hill, NC 27599

June 2008

UNC-WRRI-384

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Principal Investigator:
Gregory W. Characklis

Co-Principal Investigators:
Dr. Otto D. Simmons III
Dr. Mark D. Sobsey

Graduate Research Assistants:
Patricia N. Drummey (M.S.E.E.)
Leigh-Anne Krometis (Ph. D.)

Department of Environmental Sciences and Engineering
University of North Carolina at Chapel Hill

The research on which this report is based was supported by funds provided by the Urban Water Consortium Stormwater Group through the Water Resources Research Institute of The University of North Carolina (WRRI). Contents of the publication do not necessarily reflect the views and policies of the WRRI, nor does mention of trade names of commercial products constitute their endorsement by the WRRI or the State of North Carolina.

This report fulfills the requirements for a project completion report of the Water Resources Research Institute of The University of North Carolina. The authors are solely responsible for the content and completeness of the report.

WRRI Project 50368

June 2008

Executive Summary

This project began with seed funds from the North Carolina Urban Water Consortium (UWC) with additional funds coming later through the North Carolina Department of Environment and Natural Resources (DENR) Non-point Source 319 Program. The objectives of this work were several, with each investigated in the context of Northeast Creek, a 303(d) listed water body in Durham, North Carolina currently identified as biologically impaired. One was to gain an improved understanding of where microbial contaminants originate within a watershed, that is to say, do the microbes come primarily from upland sources (lawns, roofs, parking lots, etc.), or are significant fractions of the overall microbial load mobilized from within the storm sewer system or even from the BMPs themselves (in this case, wet detention ponds). Another was to determine where within this "transport chain" microbes begin to associate with particles, a factor which could have implications for the placement and effectiveness of sedimentation-based BMPs. The effectiveness of wet detention basins was also explored. Lastly, the partitioning behavior of both indicator organisms and *Salmonella* were investigated to compare relative rates of incidence and partitioning behavior. Both factors have the potential to play a strong role in determining whether an indicator is a suitable surrogate for a particular pathogen. While the UWC portion of the project is at an end, the DENR-funded work continues and may be of significant interest to the UWC in the future.

Part I

Wet detention basins are among the most common structural best management practices (BMPs) being implemented as a means of complying with federal Phase II stormwater rules and impending Total Maximum Daily Load (TMDL) limits. The effectiveness of these basins for

removal of microbial contaminants, one of the most frequent causes of water quality impairment, may be significantly affected by the degree of microbial association with particles in stormwater. Little is known with regard to where microbial-particle associations are initiated within the stormwater transport chain as flow travels from upland sources (e.g., lawns, parking lots) through storm sewer systems and BMPs and finally on to receiving waters. A similar lack of information exists on the relative concentrations of microbes at each point in the transport chain. Both of these factors have important implications for the location of wet detention basins within a watershed. This study tracked the concentrations and partitioning behavior of three indicator organisms (fecal coliform, *E. coli*, enterococci) throughout the transport chain and also explored the impacts of partitioning on wet pond removal efficiency. Results suggest that the degree of microbial partitioning does not vary greatly throughout the transport chain (i.e. microbial-particle association is initiated at the source). Microbial concentrations were higher at the residential upland sites (runoff, wet pond inflow and outflow) than in the stream. The overall reduction in microbial concentration brought about by the ponds was less than that assumed by most regulatory agencies, but the ponds did show some evidence of preferentially removing particle-associated fecal coliform and *E. coli*. These findings should provide insights useful in the design and implementation of stormwater management strategies.

Part II

Transport of pathogens to receiving waters via storm runoff presents a potential risk to downstream water users; however, there is little data available comparing pathogen and indicator organism transport characteristics. In particular, pathogen association with settlable particles in stormwaters has not been addressed in environmental samples. In this study, water samples from an urban stream and nearby stormwater detention ponds

were analyzed for both the total and particle-associated concentrations of six indicator organisms (fecal coliforms, *E. coli*, enterococci, *C. perfringens* spores, F+ coliphage, somatic coliphage) and *Salmonella*. *Salmonella* incidence was significantly associated with the presence of fecal coliforms, *E. coli*, enterococci, and somatic coliphage, although *Salmonella* was recovered from 57% of samples meeting the USEPA criteria for recreational contact. Similar fractions of the *Salmonella* and bacterial indicator concentrations were identified as particle-associated (25-35%), but fluctuating in this fraction were not statistically correlated between the indicators and the pathogen. Despite the consistent identification of a particle-associated fraction of microbes in wet pond influents, pond removal efficiencies were modest and effluent microbial concentrations at times exceeded influent concentrations, suggesting either that sedimentation alone was not sufficient for microbial removal, or that pond sediments may serve as a source of microbial loadings.

Acknowledgements

This work was supported by the North Carolina Urban Water Consortium-Stormwater Group through the NC Water Resources Research Institute (project no. 50368) and the North Carolina Department of Environment and Natural Resources Non-point Source 319 program (Contract No. EW07010). Special thanks go to Mayrelis Narvaez and Steve Russo, who assisted with lab work.

Table of Contents

Appendices

List of Figures

List of Tables

PART I

PART II

PART I

Evaluating Microbial Partitioning Along the Stormwater Transport Chain and its Impact on the Effectiveness of Wet Detention Ponds

Introduction

The EPA estimates that 40% of assessed waters in the United States do not meet water quality standards, with microbial contamination identified as a leading cause of impairment (USEPA 2007b). Fecal contamination of natural waters is an environmental and human health concern worldwide, as recreational uses, drinking water quality, aquaculture activities and aesthetics can all be negatively impacted (NRC 2004). Recreational exposure to water contaminated with microorganisms may lead to gastrointestinal and respiratory illness (Haile et al. 1999; Pond 2005; Wade et al. 2003), and statistical links have been observed between rainfall and disease outbreaks in some US watersheds (Curriero et al. 2001).

The 1972 Clean Water Act (CWA) established the National Pollutant Discharge Elimination System (NPDES), which significantly reduced contamination from point sources such as wastewater treatment plants and industrial facilities. However, the CWA's goal of making all waters "fishable and swimmable" has not been achieved in many areas due to the contributions of nonpoint sources, primarily stormwater runoff (NRC 2001). Storm runoff leads to elevated concentrations of microbes in receiving waters, with humans, livestock, wild and domestic animals all serving as potential sources of fecal indicators and pathogens (Atherholt et al. 1998; Kistemann et al. 2002; Medema et al. 2003; Noble et al. 2003). Initiated in 1990 and expanded in 1999, NPDES stormwater regulations stipulate that new municipal developments must implement stormwater management strategies including a combination of structural and/or non-structural Best Management Practices (BMPs) (USEPA 1999). Stormwater inputs are also a primary consideration when setting pollutant-specific standards called Total

Maximum Daily Loads (TMDLs) that are developed for impaired water bodies identified by states. These water bodies are regulated under section 303(d) of the CWA, and the TMDL process involves identifying and quantifying contributions from point and nonpoint sources, then determining the reduction required from each source in order to meet water quality standards (NRC 2001). Sedimentation-based BMPs, such as stormwater wet ponds, are commonly implemented in order to achieve compliance, and the efficiency with which these ponds remove microbial contaminants is an issue of significant concern (USEPA 2001).

The mechanisms of microbial removal in stormwater wet ponds, as well as their efficiency, are not well quantified or understood (Muthukrishnan et al. 2004; USEPA 2007a; USEPA and ASCE 1999). An important consideration when investigating sedimentation as a removal mechanism will be microbial partitioning behavior. Viruses, bacteria, and protozoan parasites can be associated with particles in the water column, and those that are will generally have a faster sedimentation rate than their free phase (i.e. unattached) counterparts. Several studies have been undertaken to investigate the fraction of various organisms associated with particles. Most of these have employed filtration-based separation techniques (Auer and Niehaus 1993; Jeng et al. 2005; Mahler et al. 2000; Schillinger and Gannon 1985), and these studies have suggested that some fraction of fecal indicator bacteria is associated with particles. However, the filtration approach to separation is based only on particle size, not density, both of which affect settling velocity. Given that these particles can be composed of dense inorganic material (e.g. silicates, clays), less dense organic matter, or both, an approach that discriminates between particles and particle-associated microbes on the basis of both size and density

may be valuable in assessing the settling and transport characteristics of attached microbes. Several recent studies have employed a calibrated centrifugation method, which separates suspended matter based on settling velocity, to evaluate microbial partitioning (Characklis et al. 2005; Fries et al. 2006; Krometis et al. 2007). In these studies, bacterial, protozoan and viral indicators were evaluated, with roughly 70% of *C. perfringens* spores, 40% of bacterial indicators (fecal coliforms, *E. coli*, and enterococci) and 10% of total coliphage found to associate with particles. Although a significant level of microbial-particle association was observed in these studies, results suggested that many of these particles were relatively small, and the actual effectiveness of sedimentation-based BMPs for microbial removal remains undetermined.

Studies have shown removal of indicator organisms is highly variable over both different BMP types and storm events (Borden et al. 1998; Davies and Bavor 2000; Davies et al. 2003; Mallin et al. 2002). Although "typical" removal of bacteria in stormwater wet ponds has been estimated at 65% (USEPA 2007a), studies using various sampling and calculation methods have estimated bacterial removal from between -15% and 99% (CALTRANS 2004; Mallin et al. 2002; USEPA 2007b). Although sedimentation is commonly assumed to be a primary mechanism of microbial removal in wet ponds, the relative removal attributable to sedimentation versus other mechanisms (e.g., solar inactivation, predation) has not been quantified (Struck et al. 2006).

When and where microbial-particle association occurs along the transport chain from source (e.g. lawns, parking lots) through the storm sewer system, and eventually to the receiving water (Figure 1) is another area that has not been fully explored and may be an important factor in identifying where best to locate sedimentation-based BMPs. If

significant proportions of microbes in street level runoff are attached to particles, sedimentation-based BMPs located near upland sources may be effective in reducing loading to receiving waters. Conversely, if very few microbes are attached in the runoff but rather become attached after entering the receiving water (either through interaction with particles in the water column or in resuspended sediments), upland sedimentation-based BMPs may be less effective. To date little work has been done to identify variations in particle-microbial association at different points in the transport chain.

This research explores the potential role of microbial partitioning in the effectiveness of stormwater wet ponds while also evaluating microbial concentrations and partitioning behavior at various points along the transport chain. This type of information should provide insights useful to identifying the types and locations of BMPs that will be capable of improving receiving water quality.

Methods

Sampling Northeast Creek is a 303(d) listed stream whose impaired designation is a result of elevated fecal coliform concentrations. The impaired section of the creek is 8.4 miles long (NCDENR 2003) and located within Durham, Chatham, and Wake counties in North Carolina (Figure 2). Water quality concerns are related to both ecological and public health impact, with the latter stemming from the fact that Northeast Creek drains into Jordan Lake, a local drinking water source and recreational area. The northern portion of the watershed is located in the city of Durham and includes residential and commercial land uses, while the southern portion is largely rural. Land use data from 2001 shows that the watershed consists of roughly 50% forested area, 30% urban, 9%

wetland with the remaining 11% designated as pasture, rangeland, cropland, or barren. Stream site 1 is located in the city of Durham, and stream site 2 is located in a rural area adjacent to a waterfowl impoundment. A wastewater treatment plant discharges to the creek between the two steam sampling sites. Ponds 1 and 2 are registered stormwater BMPs (wet detention ponds) located in a recently developed residential area of Durham.

The city of Durham was issued an NPDES stormwater permit in 1995 which requires that stormwater BMPs in newly developed areas be built in accordance with North Carolina Department of Environment and Natural Resources (NCDENR) or Durham design guidelines. The surface area, depth, length to width ratios, dam construction, seepage control, and emergency spillway requirements for BMPs are specified in these guidelines (City of Durham Public Works 2006; NCDENR 1999). Wet detention ponds are designed to hold a permanent pool of water while also being capable of retaining the runoff resulting from 1 inch of rain in the drainage. The drawdown of the temporary pool should occur 48 to 120 hours following a storm with 1 inch of rain; however, the drawdown period was observed to be significantly less in both ponds (under 16 hours). The design guidelines also assume that 85% of Total Suspended Solids (TSS), as well as significant amounts of pollutants attached to suspended solids, will be removed (NCDENR 1999). Pond 2 has a permitted normal (dry-weather) surface area of 12,860 square feet (1190 square meters) which may double during storm events and a normal volume of 46,000 cubic feet (1,303,000 L) that can increase threefold during storms (City of Durham Stormwater Services 2005). The drainage area for pond 2 is 14.6 acres, with approximately half of that area impervious surface. Pond 1 does not have listed surface areas or volumes, but the surface area was estimated at 1,500 square feet (139 square

meters), and assuming the same average depth as pond 2, a volume of 5,400 cubic feet (153,000 L). Pond 1 is nearly round, while pond 2 has a length to width ratio of approximately 2:1.

Phase I (single grab sample sampling) of this study involved grab samples collected under storm and dry weather (background) conditions during the period of June to November 2006. All samples were collected in sterile 4-L plastic bottles or cubitainers and transported on ice to the laboratory. Background conditions were defined as at least three days without appreciable precipitation (i.e., precipitation that caused a change in the streamflow hydrograph). A storm event was defined as rainfall that increased stream flow at least fourfold over pre-storm levels. A total of 8 sites were sampled for each storm event, including street runoff, pond inflow, and pond outflow at ponds 1 and 2, as well as stream sites 1 and 2. Street runoff was obtained as runoff entered the storm sewer drains that were closest to each pond. The runoff and pond sites were sampled several hours after rain commenced, and the stream sites were sampled as close to the peak of the storm hydrograph as possible. Background samples included pond inflow and outflow (there was no runoff), and the two in-stream sites. Samples from seven storm events and five background periods were collected and analyzed during phase I, although three of the storm events did not include runoff as samples were taken too long after rainfall ceased.

Phase II (intrastorm sampling) was conducted June 3-4, 2007 and involved monitoring the inflow and outflow of pond 2 over the course of an individual storm in an effort to find flow-weighted mean concentrations of microbial indicators and particles and estimate the pond's removal efficiency. Flow in and out of the pond was evaluated

using a portable flowmeter (Marash-McBirney Flo-Mate model 2000). The hydraulic residence time for this storm was estimated to be around three and a half hours (see Appendix C for details).

After the completion of phase I, it was discovered that there are actually three inlets in pond 1. In low flow conditions (i.e. background sampling) there is only flow in the sampled inlet, but under storm conditions about 20% of the flow comes through two smaller inlets. Inflow water at the sampling point was compared to samples grabbed at a location where the water from all three inlets was mixed, and it was found that the composition of the water did not differ with respect to fecal coliform, E. coli, and Total Organic Carbon (TOC). There were some differences for enterococci, particle concentration, and TSS, but they were not consistent in direction or magnitude. The data reported here represents the inflow from the single pipe, which appears to be a reasonable estimate of the overall inflow.

Laboratory Analysis The partitioning procedure used in this work has been described in detail in the literature (Characklis et al. 2005; Fries et al. 2006; Krometis et al. 2007), but some brief discussion is offered here. After returning to the laboratory, sampling containers were gently inverted several times in order to resuspend any material that might have settled during transport. The sample was then divided into two parts; one liter was centrifuged and the other liter was not (Figure 3). A Sorvall RC-3B centrifuge with a H-6000A rotor was used to spin the samples at 1164g (2000 rpm) for 10 minutes with a break of 4 while holding the temperature constant at 4°C. This centrifugation procedure was calibrated using standardized glass and latex particle suspensions which serve as surrogates for inorganic particles (e.g. clays, silicates) and organic particles

and/or free phase microbes, respectively. As described in previous work (Characklis et al. 2005; Fries et al. 2006; Krometis et al. 2007), this procedure has been successful in separating the vast majority (>95%) of glass particles >5 μm in diameter, while leaving more than 80% of the latex particles in suspension. These results suggest that this procedure is an effective means of separating organisms attached to larger and/or denser (primarily inorganic) particles from free phase organisms or those associated with smaller or lighter (primarily organic) particles. Subsequent analysis of field samples revealed that the same procedure removed a substantial number of suspended particles, but less than 5% of TOC, lending further support to the notion that the vast majority of particles removed are inorganic, and that those organisms removed are primarily associated with inorganic particles.

Following centrifugation, approximately 700 mL of the supernatant from each 1L bottle was removed and set aside for analysis along with the non-centrifuged (raw) sample. For convenience sake, particles and particle-associated microbes that are removed via centrifugation are referred to as "settleable", while those remaining in suspension are considered to exist in the "free" phase or as being attached to smaller or less dense particles. The concentration of settleable particles and microbes is calculated as the difference between the concentration in the raw sample and that in the supernatant of the centrifuged sample. Previous work has used a mass balance approach to confirm that microbial culturability is essentially unaltered by this procedure (Fries et al. 2006). The same work showed that the percent of particle-associated microbes reported might be taken as a lower limit if multiple microbes attach to individual particles, but remains a reasonable estimate.

The raw sample and centrifugation supernatant from each sample were analyzed to determine particle size distribution, TOC, and the concentration of 3 indicator microbes. Particle analysis involved an electric sensing zone instrument (Coulter Multisizer, Beckman Coulter, Inc.) with a measurement range between 2 μm and 60 μm diameters. Total Organic Carbon (TOC) was measured using a Shimadzu TOC-5000 Combustion-Infrared instrument according to Standard Method 5310B (APHA 1998). Total Suspended Solids (TSS) were evaluated only in phase II raw samples using Standard Method 2540D (APHA 1998).

The microbes assessed were bacterial indicator organisms, which included fecal coliforms, *Escherichia coli,* and enterococci. Fecal coliform and *E. coli* were enumerated using Colilert® and enterococci with Enterolert™ (defined substrate technologies; IDEXX, Westbrook, Maine)(Buckalew et al. 2006). The Colilert ® method was modified to detect thermotolerant (fecal) coliform bacteria and *E. coli* by incubating at 37 °C for 4 hours followed by 20 hours at 44.5 °C (Chihara et al. 2005; Kloot et al. 2006; Yakub et al. 2002). Each assay was run in duplicate using two Quanti-Tray/2000s, an approach that doubles the number of wells and thereby reduces the confidence intervals associated with the Most Probable Number (MPN) of microbes (Hurley and Roscoe 1983). Negative controls (dilution blanks) were processed for each of the assays, and positive controls were also run for the bacterial indicators. Assays were conducted within 24 hours. In order to obtain concentrations within the measurable range of each assay, dilutions were performed using sterile deionized water.

Statistical Analysis Given the nature of the data, non-parametric tests based on ranking the data were used to analyze differences in concentrations and partitioning

behavior (Sheskin 2000). Results were considered statistically significant at $\alpha = 0.05$ (see Appendix A and Table 1 for details on p values). Spearman rank-order correlation coefficients were calculated to determine if data is correlated, with the coefficient ρ (rho) varying from -1 (perfectly inversely proportional) to 1 (perfectly proportional). The Wilcoxon matched-pairs signed-rank test was used with two matched groups, such as inflow and outflow data, to determine difference as well as directionality. The Friedman two-way analysis of variance by ranks test was used to compare multiple groups while controlling for a variable; difference but not directionality can be detected. The Mann-Whitney test compares two independent groups and determines differences and directionality, but is not matched and does not control for any variables.

Results and Discussion

Phase I Average storm concentrations were nearly two orders of magnitude larger than average background concentrations for all bacterial indicators, and storm particle concentrations were about four times higher than background on average (Figure 4). Microbial concentrations were much higher during storms throughout the stormwater transport chain, including wet pond inlets and outlets as well as the stream sites. This is consistent with other studies that have found higher microbial and particle concentrations during storm events (Atherholt et al. 1998; Ferguson et al. 2003; Krometis et al. 2007; Mallin et al. 2000; Young and Thackston 1999). Average storm concentrations for particles and each organism did not vary greatly between the upland sites (runoff, inflow and outflow); the stream sites, however, had lower average concentrations of fecal coliform and *E. coli* and higher particle concentrations than the upland sites. It is

important to note that while average concentrations give an idea of the overall trend, there were large variations across storm events (see Appendix A for summary of statistical analysis including differences across storms). During background periods, average pond outflow concentrations were slightly higher than the average inflow concentrations for all indicators and particles in both ponds with the exception of fecal coliforms in pond 2.

Urban landuse and/or population density have been shown to be positively correlated with stormwater bacterial indicator organism concentration (Mallin et al. 2000; Young and Thackston 1999). Northeast Creek watershed is primarily forested, but the wet ponds are located in developed residential areas which consist of about 50% impervious surfaces. Average storm concentrations of each indicator organism were found to be considerably higher at the more developed pond sites than at the in-stream sites, suggesting that the suburban area where the ponds are located may be contributing a substantial portion of the microbial loading to the creek. Wilcoxon matched-pairs signed-rank tests confirmed higher concentrations of fecal coliform in the pond outflow than in the site immediately downstream (Table 1).

The settleable percentage of both indicator organisms and particles remains reasonably consistent at the sampling points in the stormwater transport chain, with a few exceptions (Figure 5). The settleable percentage did not vary significantly among the different microbes, although the particles did appear to have a higher settleable fraction than the microbes (Table 1). Among upland sites (runoff, inflow, outflow) there was no significant difference in the fractions of microbes or particles that were settleable. The percent settleable in the stream was higher than the upland sites in both storm and

background conditions. As can be seen in Figure 5 the magnitude of the difference in settleable percentage between upland and in-stream sites is not vast, with average microbial settleable percentages ranging from about 20% to 40% at the upland sites and 30% to 45% at the in-stream sites. The range of measured percentage settleable overlaps for all sites and indicator organisms. The settleable percentage for microbes did not vary significantly between storm and background flow, although particles had a higher settleable percentage in storm conditions. Particle-microbial association appears to occur before water enters storm sewers, which implies that sedimentation-based BMPs (such as wet ponds) may be effective in reducing microbial concentration in upland, residential areas. The high microbial concentrations in this suburban area relative to the stream suggest that the area may be a good placement choice for stormwater BMPs. Although a significant portion of microbial indicators appear to be associated with "settleable" particles when they enter the stormwater wet ponds, many factors have the potential to affect whether they will settle out and be removed.

Results from phase I suggest that the two wet ponds examined are relatively ineffective at reducing bacterial or particle concentrations under both storm and background conditions. Figures 6A and 6B show the outflow concentration plotted against the inflow concentration for each of the storms in both ponds. If the ponds were reducing microbial and particle concentrations by a significant amount, the outflow concentrations should be lower than the inflow concentrations (i.e., the points should fall to the right of the 1:1 line shown in each graph). In both ponds, most points fell along the 1:1 line, indicating that inflow and outflow concentrations were relatively equivalent. In pond 1 there were several instances in which outflow concentrations were higher than

inflow concentrations, whereas in pond 2 there was more evidence of microbial removal, with a few instances in which the ponds seemed to achieve a relatively high level of microbial reduction. The Wilcoxon matched-pairs signed-rank test was used to compare inflow and outflow concentrations in each pond. This test revealed a statistically significant increase in particle concentrations within pond 1 as well as a marginally significant increase in enterococci concentrations (i.e., concentration was higher in outflow than inflow more frequently than can be attributed to chance if the concentrations are actually equal). No significant difference was found for fecal coliform and *E. coli* in pond 1 or for any microbes or particles in pond 2.

The reasons that these ponds do not appear effective may be attributable to a number of factors. Marino and Gannon (1991) found that storm drain sediment within a creek can serve as a fecal coliform reservoir, and it is possible that storm drain sediment within these wet detention ponds could serve as a reservoir for microbes. Pond sediment with associated microbes may be resuspended by storm events, raising outflow concentrations and counteracting any reduction in inflow concentration that might occur due to setting or inactivation. The rate of settling for free phase microbes is generally slow given their size and density, and that of particle-associated organisms may not increase dramatically since the particles with which microbes are often associated tend to be relatively small (Schillinger and Gannon 1985). Figures 7A and 7B show the concentrations of settleable microbes and particles in pond inflow and outflow. In both ponds, there are fairly equal concentrations of settleable microbes and particles in the inflow and the outflow, although in pond 1 there are more settleable particles and enterococci at the outlet. Higher concentration of settleable particles and particle-

associated microbes suggests that the rate of resuspension and/or new aggregate formation is greater than the settling rate of existing aggregates, assuming the inflow concentrations and partitioning remains relatively constant. In pond 2 there tends to be slightly more settleable microbes in the inflow, suggesting some removal of the settleable portion is occurring in the pond. However, neither of the ponds appears to be consistently removing significant fractions of settleable particles or microbes.

While total pond removal estimates over the course of a storm are presented in phase II results, in this phase the estimated single grab sample removal was calculated for each constituent (fecal coliform, *E. coli*, enterococci, particles) in each storm and pond as:

$$\text{Single Grab Sample Removal} = 1 - \frac{outlet\_concentration}{inlet\_concentration} \qquad [1]$$

The single sample removal was highly variable between both microbes and storms (Appendix B). In order to determine whether an increase in the settleable percentage leads to an increase in single grab sample removal, Spearman rank correlation coefficients were calculated. The settleable percentage in the inflow was not correlated with the single grab sample percent removal of any constituent in either pond (α=0.05). However, it was found that total inflow concentration was inversely correlated with single grab sample percent removal; that is, higher inflow concentrations tended to lead to less removal. This pattern was observed in pond 2 for *E. coli* and enterococci and in pond 1 for fecal coliform and *E. coli*. Although not necessarily a causal relationship, this is still troublesome since it is most common to refer to removal efficiencies as numbers that are not dependant on the influent concentration.

To estimate mean concentration removal (MC) of pollutants in BMPs over the course of several storm events, the following approach has been used:

$$MC = 1 - \frac{mean\_outlet\_concentration}{mean\_inlet\_concentration} \quad [2]$$

(Karpiscak et al. 2001; USEPA and ASCE 1999). With microbial concentrations, the geometric as opposed to arithmetic mean is often used (Davies and Bavor 2000; Hill and Sobsey 2001; Mallin et al. 2002). Mean concentrations were calculated over 7 storms, and Tables 2 and 3 show the geometric and arithmetic mean concentration removals for the single grab sample samples, both for the total concentrations as well as the settleable fraction. In pond 1, the negative mean concentration removal estimates suggest that the pond is exporting rather than removing microbes and particles. Mean concentration removals for pond 2 vary from 30% to 60% for microbial indicators, but there was little removal of particles. The ponds are located in similar residential areas about half a mile apart and have inflow water quality that is comparable, yet seem to produce different removal results. The outlet design is very different between the two ponds, with 3 foot diameter concrete flat bottom exit pipe in pond 1, and a smaller diameter pipe leading to an outlet box in pond 2, presumably to extend the residence time of the stormwater and reduce the peak outflow. In pond 1, length to width ratio of the pond (not including the forebay) is about 1:1, whereas in pond 2 it is greater than 2:1. Pond 2 appears to be less prone to short circuiting and may have a longer residence time due to the outlet design (see Appendix C for discussion of residence time).

The mean concentration removals of the settleable fraction of microbes were more sensitive to the removal calculation method (geometric or arithmetic mean) than the total concentration removals. Some of the settleable fraction of each microbe was

removed in each pond (with the exception of enterococci in pond 1), although removal estimates varied from less than 10% to nearly 100%. Neither pond 1 nor 2 appeared to reduce the concentration of settleable particles.

With both the geometric and arithmetic mean concentration removals, one or two outliers can affect the overall removal. Some grab samples were acquired earlier in the storm and others later (i.e., those that were sampled when there was no longer runoff), which led to concerts over how variations in microbial concentration and settleable fraction might change over the course of an individual storm. In order to more accurately characterize the total microbial removal by pond 2 as well as to observe changes in concentration and settleable fraction, it was decided to obtain inflow and outflow samples throughout a storm.

Phase II The concentrations of indicator organisms and particles vary with time and flow over the course of an individual storm (Figure 8). Inflow and outflow concentration did not change at the same rate, indicating that single grab samples may not be adequate to fully characterize removal efficiency over the course of a storm. For each of the microbes, higher concentrations were observed with higher flows near the beginning of the storm. As in the phase I samples, settleable percentage did not vary by organism.

In order to characterize the reduction in microbial and particle concentrations throughout a storm, an efficiency ratio (ER) is calculated based on inflow and outflow "event mean concentrations" or EMCs (USEPA and ASCE 1999). The EMC is a flow-weighted average which can be calculated for the inlet and the outlet such that:

$$EMC = \frac{\sum_{i=1}^{n} V_i C_i}{\sum_{i=1}^{n} V_i} \quad [3]$$

where V is the volume of flow during period i, C is the average concentration associated with period i, and n is the total number of measurements taken during the storm event. The efficiency ratio (ER) is calculated for a single storm as:

$$ER = 1 - \frac{outletEMC}{inletEMC} \quad [4]$$

The volume of flow during each period is estimated using the measured inflow and outflow values and linearly interpolating between them (Figure 9 and Appendix D). The following assumptions were made:

- Flow and concentrations vary **linearly** with time
- Inflow is 0 cfs at 10:30 pm June 2 (beginning of rain) and at 8:00 pm June 3 (4 hours after storm ends)
- Flow out begins at 3:30 am June 3 and ends at 8:50 am June 4 (no outflow at those times)
- Inflow and outflow concentrations at the beginning of the storm are average background concentrations

This approach inherently neglects direct rainfall, initial pond storage, infiltration losses and evaporation. The amount of water that is stored in pond 2 is negligible for most storms, since the pond usually has the same volume of water prior to and after each storm. However, due to the unusually long period of dry-weather preceding this storm, the volume of the pond was less than normal at the beginning of the storm and storage

volume accounted for an estimated 8% of the inflow. If there is a large reduction in concentration of microbes and particles (due to dieoff and/or sedimentation) that remain in the pond after the storm event, the calculated efficiency ratio would be an underestimation of the actual load removal. This effect was balanced by the fact that this approach does not account for the rain that falls directly on the pond, which accounted for around 10% to 15% of the total pond outflow in the storm analyzed (Appendix E). Since the rainwater is presumably without fecal contamination, the outflow concentration is diluted by the rainwater. In this case, the efficiency ratios appear to be a slight overestimation of the pond's ability to remove contaminants. In order to present values that are comparable to what has been published in other literature, the efficiency ratio described earlier will be presented.

Overall removal efficiency ratios ranged from about 0.15 to 0.20 for all indicator organisms and for total particle number (diameters from 2 to 60 um) (Table 4). Microbial concentration reductions are in the range of what other studies have found (Borden et al. 1998; Davies and Bavor 2000; Mallin et al. 2002), but remain less than what is considered "typical" according to regulatory guidelines. In addition, the removal efficiency ratio observed for TSS is significantly below the pond design objectives, which call for 85% removal of TSS (NCDENR 1999). Nonetheless, these removal rates are somewhat consistent with other studies that have observed TSS removal levels on the order of 0 to 60% (Borden et al. 1998; Mallin et al. 2002).

Using the EMC approach, it appears that pond 2 is nominally successful at removing microbes, but these observations may also provide some insights into the mechanisms of removal. If sedimentation is a primary removal mechanism, particle-

associated organisms should be removed at higher rates than the overall concentration (assuming that a significant number of microbes do not become particle-associated within the pond). The ratio of settleable microbial removal to overall microbial removal suggests that a significant fraction of the microbial reduction in the pond may be attributable to settling. For fecal coliform and *E. coli*, most of the estimated removal came from the settleable fraction (there was a slight increase in non-settleable fecal coliform). This suggests that sedimentation may be the most significant removal mechanism for fecal coliform and *E. coli*. Research has shown that microbes tend to survive longer when they are associated with particles (Burton et al. 1986; Jamieson et al. 2005; Roper and Marshal 1978; Sherer et al. 1992), thus sedimentation and not faster die-off rates appear to be the most likely mechanism of the settleable fraction of fecal coliform and *E. coli*. It is important to note that many particles and aggregates that are termed "settleable" in this study will not be completely removed via discrete particle settling in this storm given the residence time and depth of the pond.

For enterococci, however, there was actually an increase in settleable organisms between the inflow and outflow, suggesting that they may be becoming particle-associated within the pond or that particle-associated microbes already in the sediments are being resuspended. The phase I geometric and arithmetic mean removal of settleable microbes showed a pattern that was similar to that found in the intrastorm event, especially in pond 1, where there was high removal of settleable fecal coliform and *E. coli* but a net export of settleable enterococci. Some studies have suggested that enterococci may survive longer and be present in higher concentrations than fecal coliform in sediment (Davies 1995; Jeng et al. 2005). If significant resuspension of

sediment is occurring during storm events, prolonged survival of enterococci in the sediment may explain the increase in settleable enterococci from the inlet to the outlet. Neither pond appears to preferentially remove settleable particles over non-settleable particles in both single grab sample samples as well as intrastorm samples. Possible explanations could include that the pond is not reducing particle concentration by sedimentation but rather by some other mechanism, or that both settleable and non-settleable particles are aggregating. Further investigation involving the process of particle-microbial aggregation might help illuminate why there tends to be an increase in settleable enterococci but a decrease in settleable fecal coliform and *E. coli*.

If particles are removed by settling, the larger particles should be removed more efficiently than the smaller particles, as was found in one experimental study on a wet pond (Greb and Bannerman 1997). However, in this study both TSS and larger particles (diameters from 5 to 60 μm) showed an increase in the event mean concentrations between the inlet and the outlet. The increase in larger particles was further examined by finding the event mean concentration of the particle volume (Figure 10). Over the course of the storm, the volume concentration of all measured particles (diameters 2 to 60 microns) did not change (Appendix F for details). However, it appears that while the concentration of smaller particles (about 2 to 4.4 microns) is reduced, while the concentration of particles from 4.4 to 13 microns is increased by the same volume. A possible explanation could be that the smaller particles are aggregating to form larger particles, as has been found in lab-scale studies (Krishnappan and Marsalek 2002).

Conclusions

This study was unique in that it examined microbial partitioning to settleable particles as well as concentration along the stormwater transport chain. The settleable fraction of each organism is roughly constant throughout the transport chain, suggesting that particle-microbe association is initiated at the source. Since the upland residential areas sampled had higher microbial concentrations than the stream sites, the potential for microbial removal via sedimentation in upland BMPs should be high.

Results from both single grab and intrastorm sampling suggest that reduction in microbial concentration in pond 2 is on the order of 10 to 50% with even less removal of particles. There appears to be no reduction of microbes or particles and perhaps an increase in concentrations in pond 1. These results are significantly less than what regulatory agencies consider typical but within the range of those found in other studies.

Sedimentation appears to be a primary mechanism of removal for fecal coliform and *E. coli*. In the intrastorm samples the removal of the settleable portion of these constituents appeared to make up the majority of the total removal; however, this was not the case for enterococci or particles. Although the settleable fraction was not well correlated with single grab sample removal for any constituent in either pond during phase I, the mean concentration removal estimates suggest that the settleable fraction of fecal coliform and E. coli may be removed better than the non-settleable fraction. Enterococci appear to behave differently than the fecal coliform group, showing no preferential reduction of the settleable fraction in either pond.

These results should provide useful insights that will have value in developing stormwater management strategies while also identifying issues deserving of further investigation.

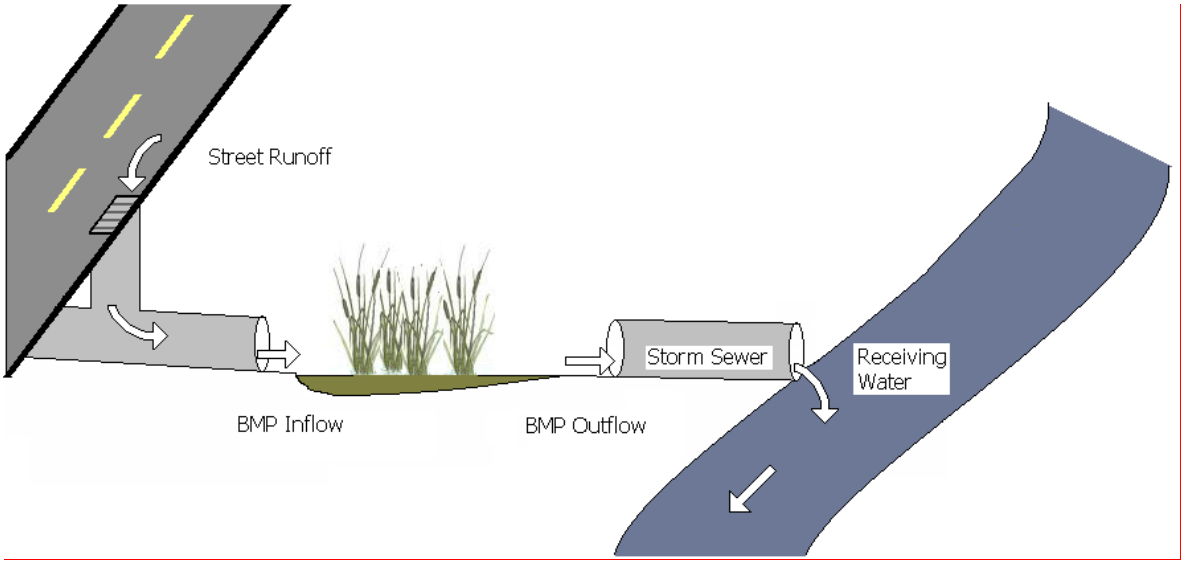

Figure 1: Stormwater transport chain, including street runoff, stormwater pond, storm sewer, and receiving water.

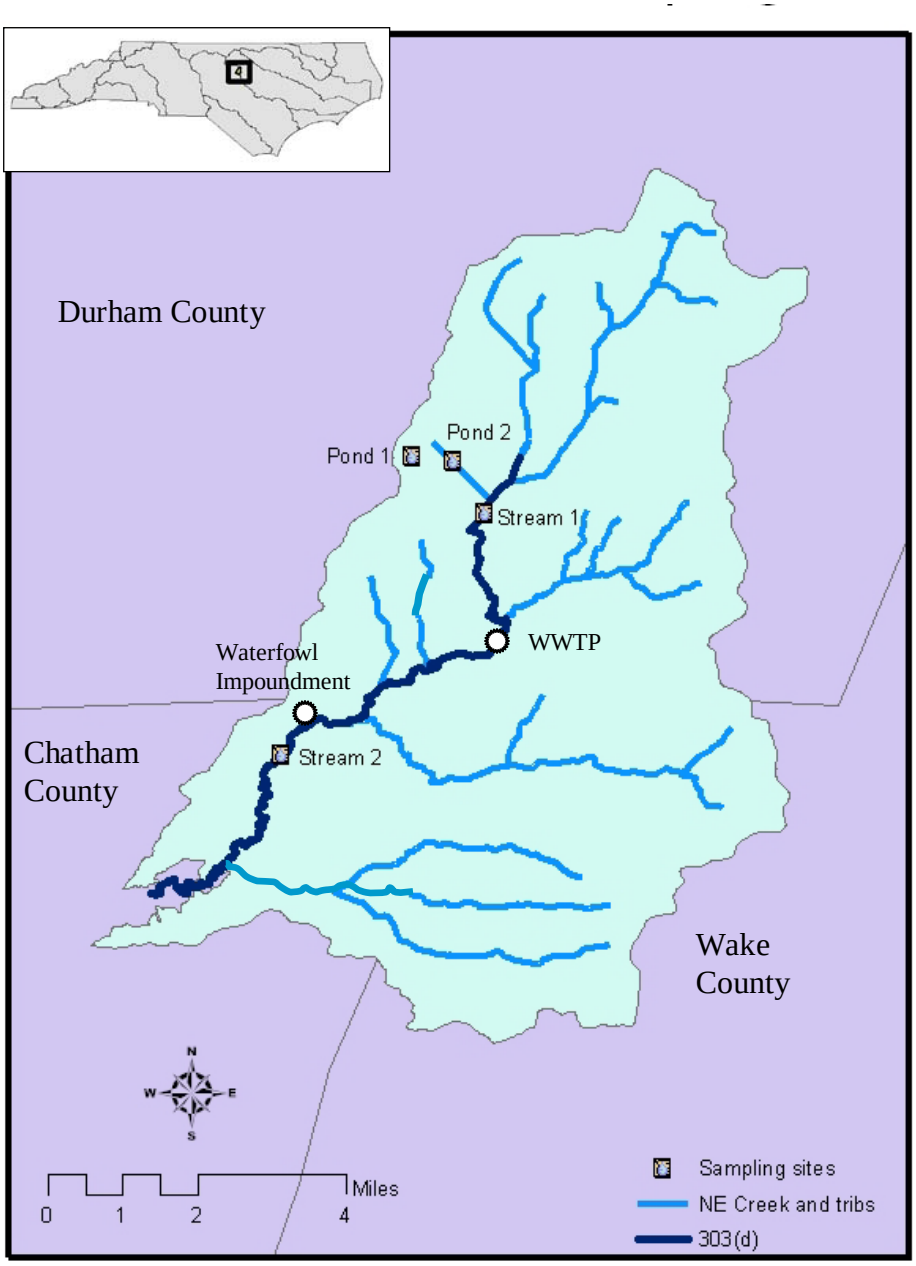

Figure 2: Northeast Creek Watershed, North Carolina. Sampling sites are ponds 1 and 2 as well as stream sites 1 and 2. Dark line for stream indicates 303(d) listed sections for fecal coliform impairment.

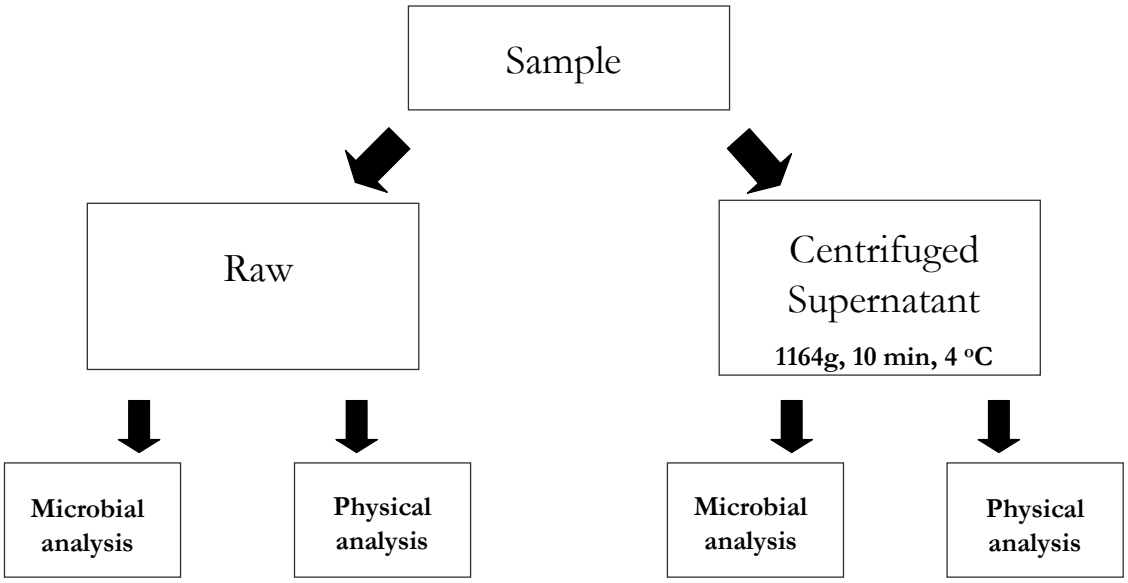

Figure 3: Partitioning technique. Two 1 liter aliquot are taken from the sampling container, one of which remains raw and the other is centrifuged. The supernatant from the centrifuged sample and the raw sample are then analyzed for microbial (fecal coliform, E. coli, enterococci) and physical (particles, TOC) concentrations.

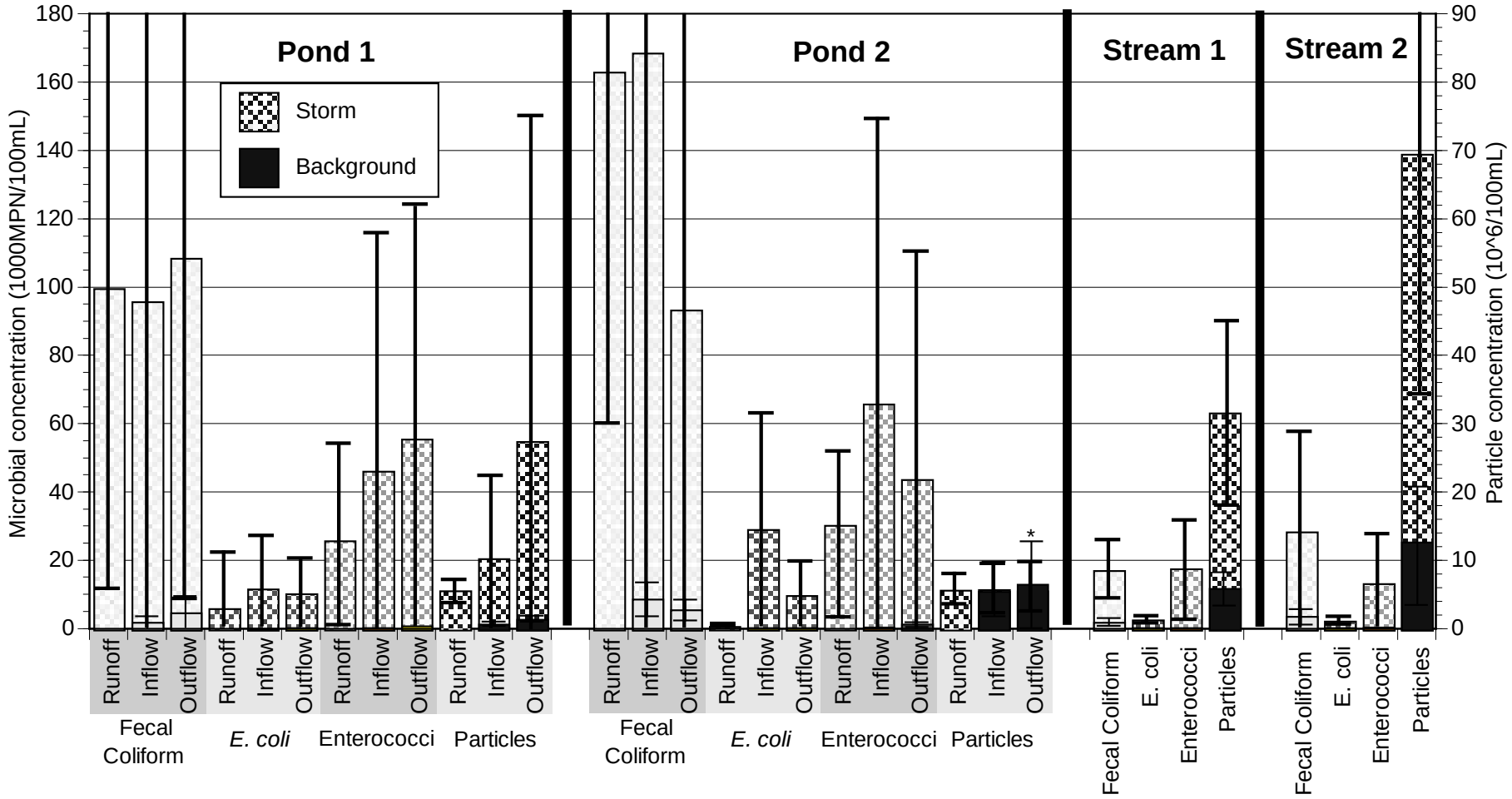

Figure 4: Average bacterial and particle concentrations over 7 storms for ponds 1 and 2 and stream sites 1 and 2. Solid bars represent average background concentrations. Cross hatched bars represent average storm concentrations. Error bars are +/- 1 standard deviation. Note that runoff was only available during 4 storm events. *Pond 2 particle effluent average storm concentration ($5.5x10^6$/100mL) is less than background concentration ($6.4x10^6$/100mL).

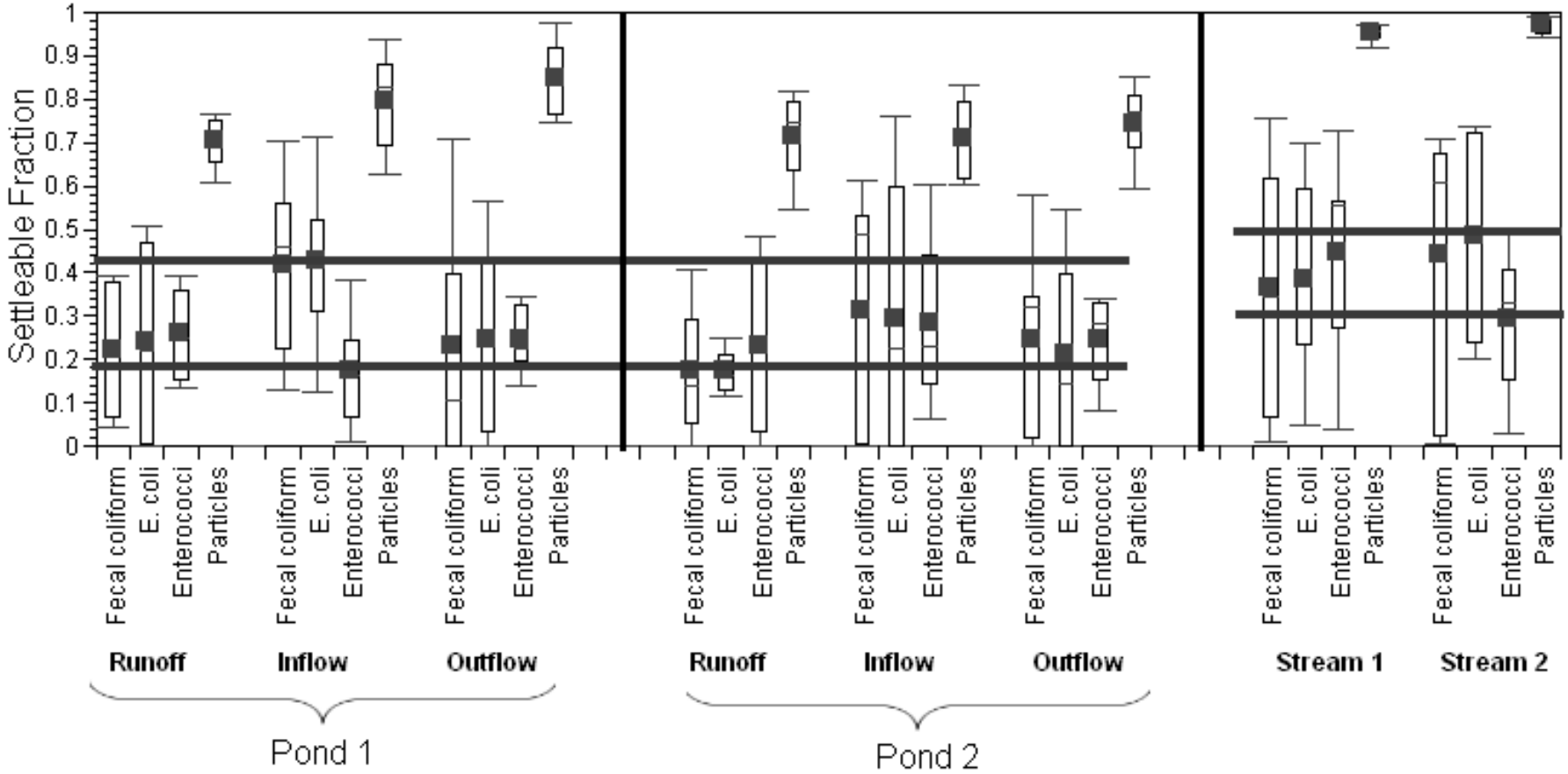

Figure 5: Settleable fractions of microbial and particle concentrations at all sites over storms (n = 7 for inflow, outflow, and stream sites; n=4 for runoff).

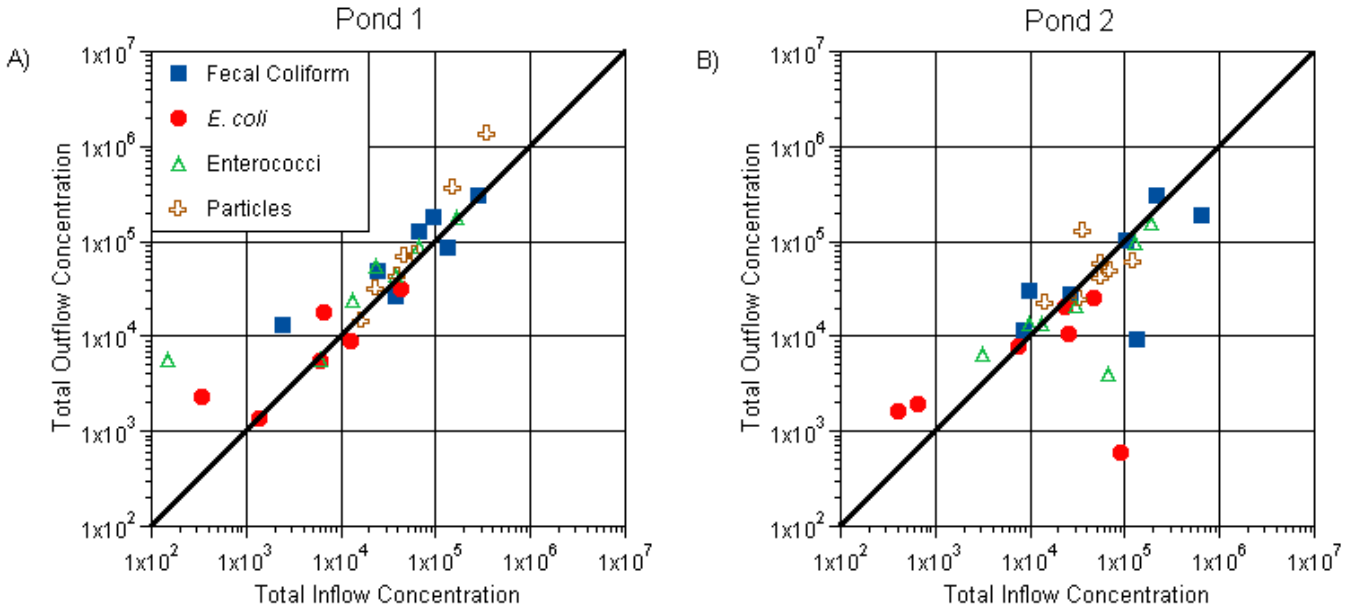

Figure 6: Total inflow and outflow concentrations for 7 storms. A) Total concentrations for pond 1; B) Total concentration for pond 2. Units are MPN/100mL for all microbial indicators and #/mL for particles.

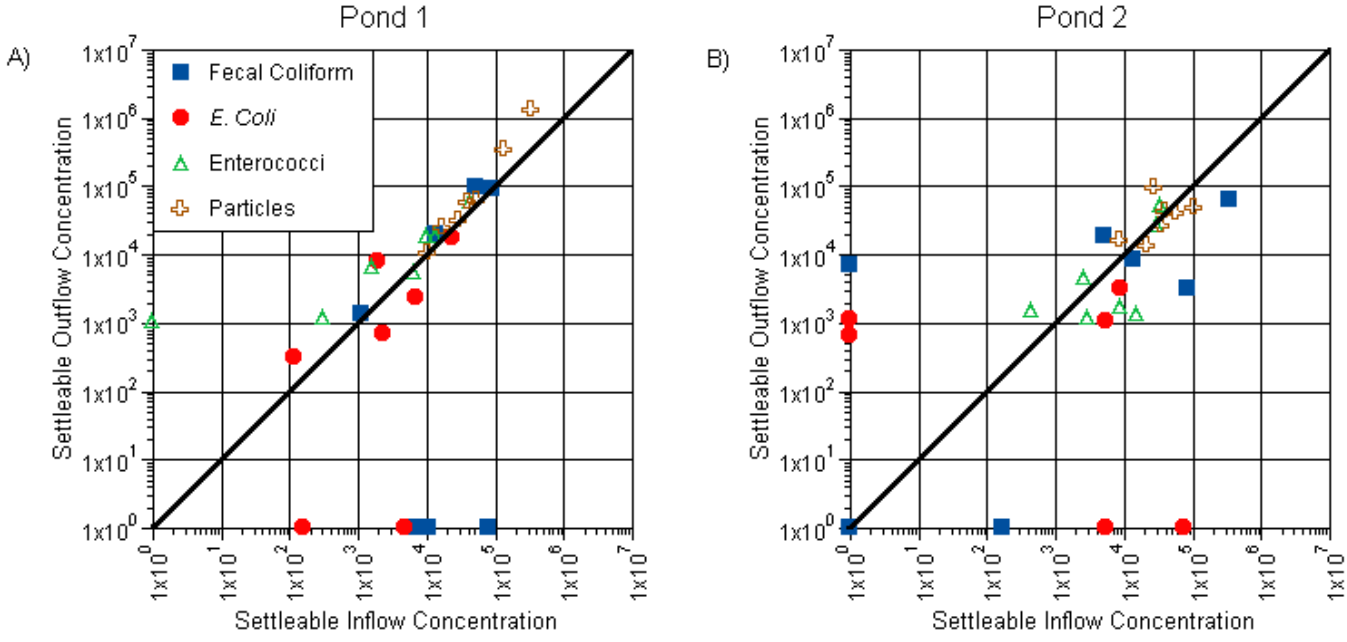

Figure 7: Settleable inflow and outflow concentrations for 7 storms. A) Settleable concentrations for pond 1*; B) Settleable concentrations for pond 2*. Units are MPN/100mL for all microbial indicators and #/mL for particles. ***Microbial assays do have relatively wide confidence intervals, in the case where the measured concentration of "non-settleable" microbes was greater than the total concentration of microbes, it was assumed that there were no "settleable" organisms and that the "non-settleable" concentration is actually equal to the total concentration.***

Table 1: Summary of statistical analysis on microbial and particle concentrations and percent settleable

Question	Statistical Test	Result
Is there a difference between pond outflow and downstream concentrations?	Wilcoxon matched-pairs signed-rank	**Pond 1**: More fecal coliform in outflow (p=0.0312) Marginally more E. coli in outflow (p=0.078) **Pond 2**: Marginally more fecal coliform in outflow (p=0.078) Marginally more E. coli in outflow (p=0.078) More particles in stream (p=0.016)
Does percent settleable vary among sampling sites?	Friedman (control for storm and constituent)	**No** (p=0.7044 storm; p=0.1771 background) among upland sites (runoff, inflow, and outflow) **Yes** (p<0.0001 storm; p=0.0341 background) among upland and stream sites
Is there a difference between inflow and outflow concentrations?	Wilcoxon matched-pairs signed-rank	**Pond 1:** More particles in outflow (p=0.0312) Marginally more enterococci in outflow (p=0.0626) **Pond 2:** No difference
Are inflow concentrations inversely correlated with single grab sample removal?	Spearman correlation coefficient	**Pond 1:** Yes for fecal coliform (ρ=-0.68, p=0.0938) Yes for E. coli (ρ=-0.75, p=0.0522) **Pond 2:** Yes for E. coli (ρ=-0.96, p=0.0005) Yes for enterococci (ρ=-0.68, p=0.0938)

Table 2: Geometric mean concentration removals (MC_{Geo}) for ponds 1 and 2 over 7 storms.

	Geometric Mean Concentration Removal	Fecal Coliform	*E. coli*	Enterococci	Particles
Pond 1	Total	-0.41	-0.24	-1.08	-0.50
	Settleable	0.98	0.86	-3.67	-0.61
Pond 2	Total	0.31	0.48	0.36	0.01
	Settleable	0.08	0.72	0.34	-0.04

Table 3: Arithmetic mean concentration removals (MC_{Arith}) for ponds 1 and 2 over 7 storms.

	Arithmetic Mean Concentration Removal	Fecal Coliform	*E. coli*	Enterococci	Particles
Pond 1	Total	-0.13	0.13	-0.21	-1.70
	Settleable	0.48	0.26	-0.45	-1.90
Pond 2	Total	0.45	0.67	0.34	0.03
	Settleable	0.74	0.94	0.06	0.01

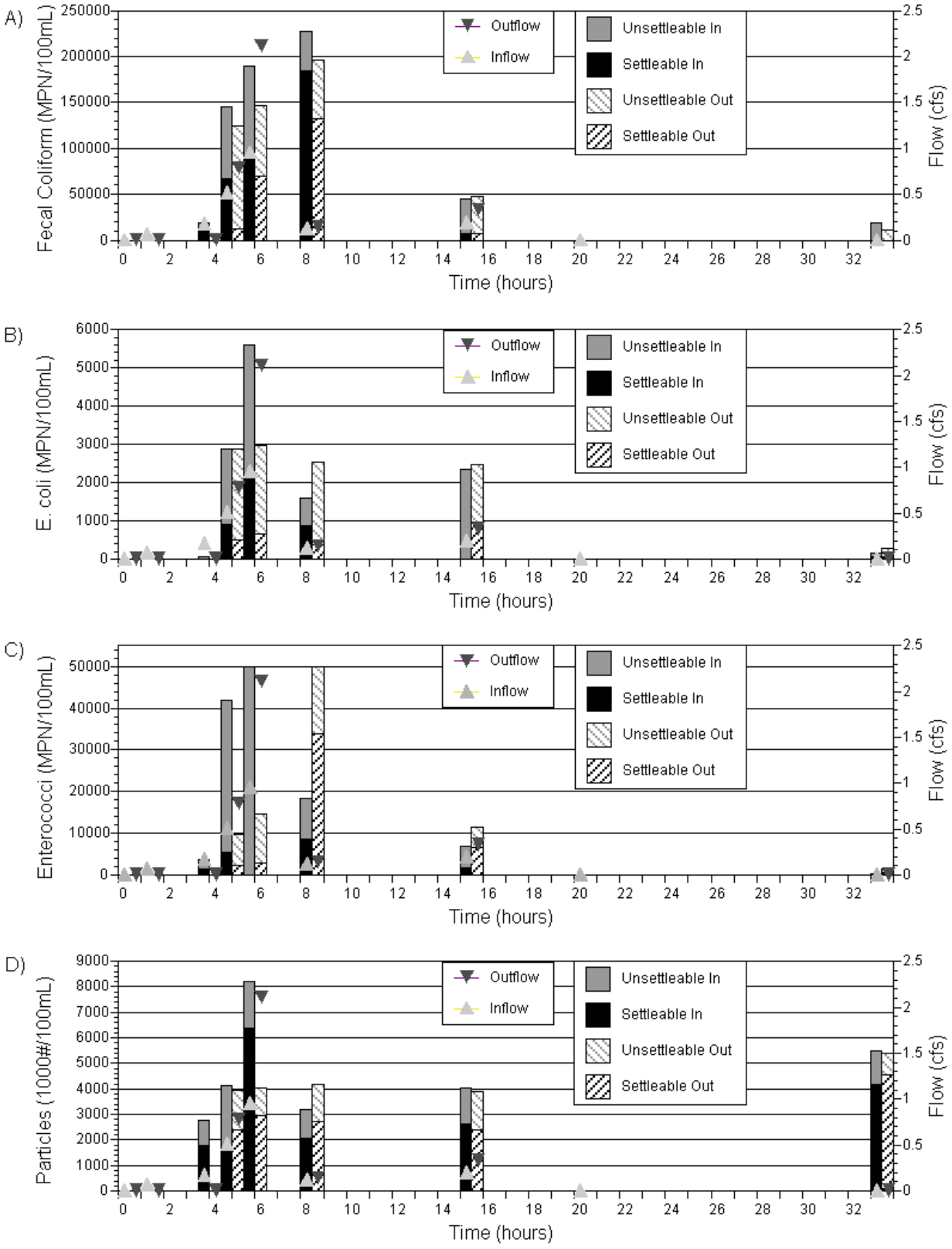

Figure 8. Results from intrastorm sampling at pond 2 on June 3-4, 2007. Bars show A) Fecal coliform concentrations, B) *E. coli* concentrations, C) Enterococci concentration, and D) particle concentrations. Inverted triangles show inflow and triangles show outflow.

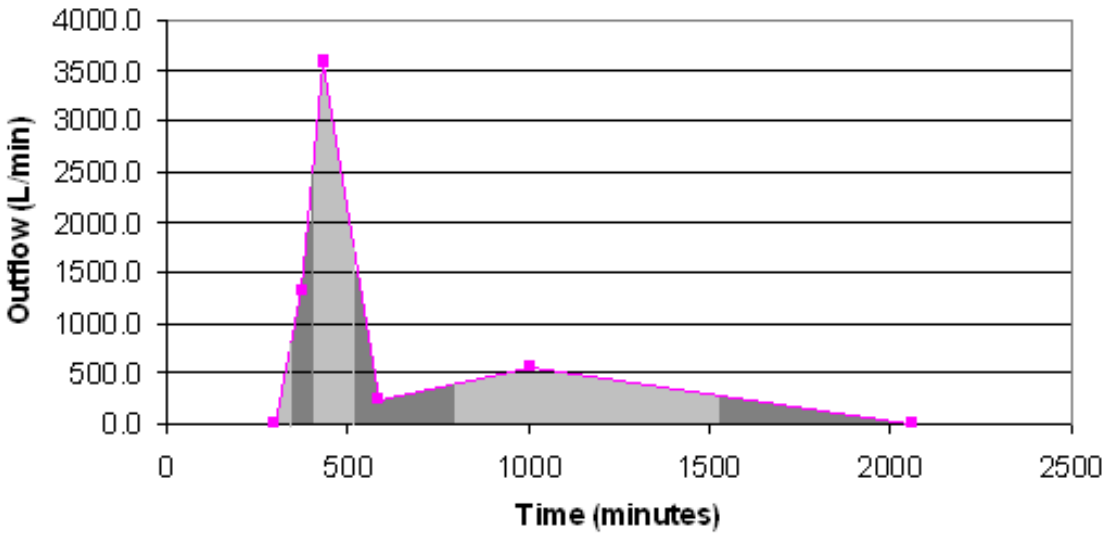

Figure 9. Method used to find water volume associated with each sampling point in order to calculate Event Mean Concentration. Each square is a sampling point except the first one, which is given background values.

Table 4: Results of intrastorm Event Mean Concentration (EMC) and efficiency ratio (ER) calculations.

	Fecal Coliforms (MPN/100mL)	*E. coli* (MPN/100mL)	Enterococci (MPN/100 mL)	Particles (#/100mL)	Particles d >5um (#/100mL)	TSS (mg/L)	TOC (mg/L)
Overall Efficiency Ratio	0.20	0.15	0.20	0.19	-0.18	-0.47	0.33
Settleable Efficiency Ratio	0.38	0.30	-1.90	0.18	-0.22		-1.13
EMC In	134,293	2,938	21,657	5,111,070	297,548	3.0	11.2
EMC Out	106,874	2,487	17,318	4,130,088	351,886	4.5	7.5
Settleable EMC In	75,894	927	2,979	3,444,115	169,168		-0.3
Settleable EMC Out	46,949	650	8,648	2,836,304	206,936		-0.7
Overall Conc. Removed	27,420	451	4,339	980,982	-54,337		3.7
Settleable Conc. Removed	28,945	277	-5,668	607,810	-37,768		0.4
% of Overall Removed That are Settleable	106%	62%		62%			10%

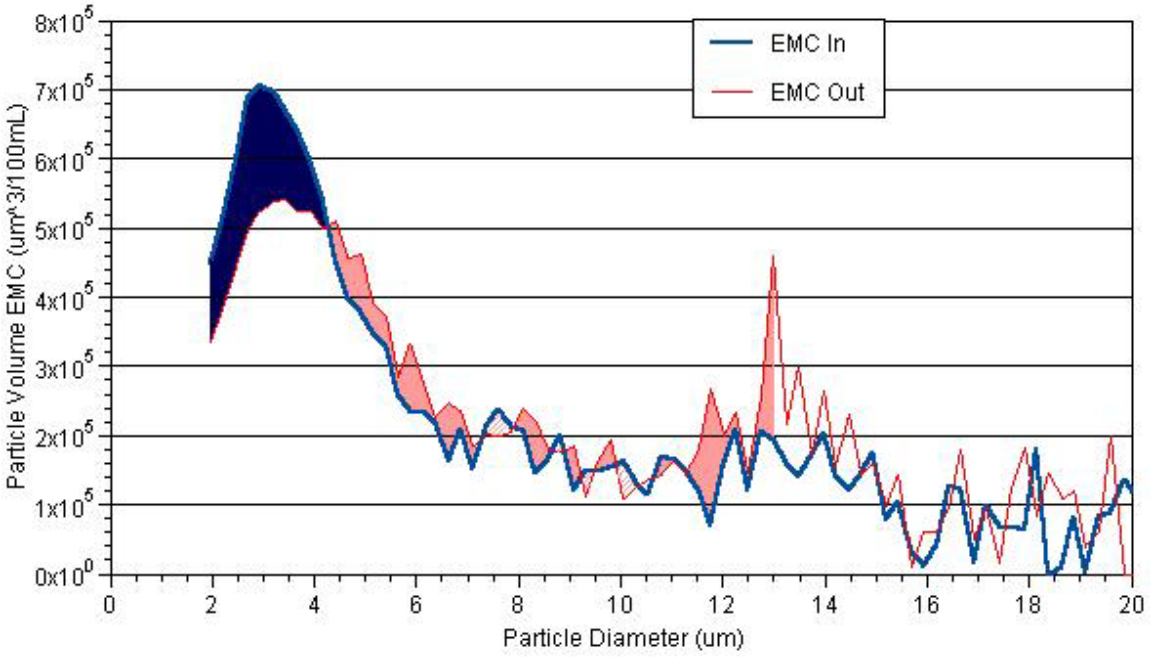

Figure 10. Event Mean Concentration (EMC) of the particle volume distribution from intrastorm sampling. The pond reduced the volume of small particles (diameters of 2-4.4 microns, reduced volume shown in dark shading), but increased the volume of medium sized particles (diameters of 4.4 to 13 microns) by the same amount (increased volume shown in light shading).

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PART II

Comparing the Incidence and Partitioning Behavior of *Salmonella* with that of Traditional Indicator Organisms

Introduction

Storm runoff can mobilize and transport fecal loadings from various nonpoint sources to receiving waters, resulting in elevated downstream microbial concentrations (Hunter et al. 1992; Kim et al. 2005; Noble et al. 2003). Increased precipitation has been linked to outbreaks of waterborne disease (Gaffield et al. 2003; MacKenzie et al. 1994; Rose et al. 2000), and exposure to waters receiving stormwater discharges has been correlated with an elevated risk of illness (Gaffield et al. 2003; Haile et al. 1999). Development of a successful watershed protection or remediation plan requires identification of microbial sources and their transport pathways, with microbial fate and transport models often playing a prominent role. These models require accurate inputs related to microbial transport behavior, as well as improved estimates of the effectiveness of various best management practices (BMPs) for reducing upland microbial loadings.

Despite the relatively large impact of non-point source pollution on downstream microbial contamination, quantitative data describing microbial transport in stormwater is sparse and limits the reliability of modeling efforts (Dorner et al. 2006; Jamieson et al. 2004a; Pachepsky et al. 2006). Specifically, microbes are generally modeled as individual free cells of near neutral buoyancy, even though increasing evidence suggests that microorganisms often partition between a particle-associated and free (unassociated) phase (Ferguson et al. 2003). Quantifying the relative fractions of organisms associated with particles is essential to modeling efforts as observations suggest that the microbes in each fraction behave differently. Previous work links microbial association with sediments to possible prolonged survival (Gerba and McLeod 1976; Gerba and Schaiberger 1975; Howell et al. 1996; Jamieson et al. 2004b) and/or regrowth (Desmarais et al. 2002; Hendricks and Morrison 1967; LaLiberte and Grimes 1982;

Lee et al. 2006). Association with larger, denser particles can also alter transport behavior, as particle-microbe aggregates settle more quickly from the waters column and thus travel shorter distances in receiving waters (Jeng et al. 2005; Schillinger and Gannon 1985).

While indicator organisms are often used as surrogates for waterborne pathogens in monitoring and modeling, differences in partitioning behavior have not been investigated even though they can have a substantial impact on microbial fate and transport. While there have been several lab and field-scale examinations of indicator organism partitioning (Characklis et al. 2005; Jeng et al. 2005; Krometis et al. 2007; Schillinger and Gannon 1985), all investigations of pathogen partitioning have been conducted under laboratory conditions and have focused only on protozoan parasites (Dai and Boll 2003; Medema et al. 1998; Searcy et al. 2005). No concurrent examination of indicator and pathogen association with particles in natural waters has been reported. Additionally, laboratory techniques used to separate and enumerate particle-associated indicator organisms have differed from techniques used to partition pathogens. Because each of these techniques assumes a different operational definition of particle association (e.g. removal by filter of given pore size, particle retention on antibody-coated filter, sedimentation in gravitational fields, etc.) the results are not directly comparable and the implications for using indicators as surrogates for pathogens in fate and transport modeling are unclear.

This study compares the incidence and partitioning behavior of waterborne *Salmonella* spp. With that of six indicator organisms in field samples. This information should prove useful in evaluating the suitability of various indicators as surrogates in microbial fate and transport modeling. Samples for analysis were collected from a freshwater stream in an urban watershed and partitioned into “settleable” (likely particle-associated) and “suspended” fractions using a previously calibrated centrifugation technique (Characklis et al. 2005; Fries et al. 2006). Use of a

single partitioning technique allowed for direct comparison between the behavior of indicators and *Salmonella*. Additional samples of residential wet pond (detention basin) influents and effluents were analyzed to determine whether sedimentation-based best management practices provide similar reductions in indicator and pathogen stormwater loadings, and whether the degree of particle association has an impact on microbial removal.

Methodology

Site selection

Northeast Creek in Durham, North Carolina (NC), USA is currently on the state's 303(d) list of impaired waterways due to the presence of high pathogen indicator organism (fecal coliform) concentrations. As a result, the State requires development of a TMDL plan for reduction of fecal coliform loadings as mandated by the US 1972 Clean Water Act. In North Carolina, a water body is defined as impaired if the fecal coliform concentrations of more than 20% of grab samples exceeds 400 CFU/100 mL or if the geometric mean of the fecal coliform concentration exceeds 200 CFU/100 mL for any 30-day period (NCDWQ 2007). Water quality in Northeast Creek is of particular concern because it is a tributary flowing into Jordan Lake, a drinking water source and popular primary contact recreational area. The stream drains a watershed of approximately 116 km^2. Landuse data from 2001 characterizes the watershed as 30% urban, 50% forest, 9% wetland, and 11% other (agricultural, barren, water, etc). The current (2007) fraction of urban landuse is likely higher, given rapid development in the watershed

Samples were collected at two points along the stream and from two wet ponds (detention ponds) permitted as stormwater treatment structures by Durham County (Figure 11). Two potentially significant sources of microbial loadings exist between the two stream sites: a

wastewater treatment plant (permitted to discharge 23 million liters/day) and a waterfowl impoundment. The wet ponds are located less than a kilometer apart in similar suburban communities. During storm events samples were collected for each pond from three locations: the street gutters directly feeding the storm sewer; the point at which the storm sewer empties into the pond (pond inflow); and the point at which water leaves the pond (pond outflow).

Samples were collected during both dry (background) and wet (storm) conditions. Background conditions were defined as existing after a minimum of three days of no appreciable precipitation (no changes in streamflow). Storm events were defined as precipitation resulting in at least a four-fold flow increase over baseflow. All samples were stored on ice for transport to the laboratory and then refrigerated at 4^{o} C until analysis. Bacterial and particle analyses were initiated within 24 hours of sample collection. Bacterial spore (*C. perfringens*) and phage analyses were completed within 48 hours.

Microbiological analysis

Six indicator organisms were selected for analysis. Fecal coliform, *E. coli*, and enterococci are considered classic indicator bacteria and are frequently used in setting recreational and drinking water quality guidelines and standards (Pruss 1998; USEPA 1986). *Clostridium perfringens* spores have been recommended as potentially more accurate surrogates for protozoan pathogens such as *Cryptosporidium* and *Giardia* and for monitoring impacts of discharges on receiving waters (Bonde 1975; Lisle et al. 2004; Medema et al. 1997; Wiedenmann et al. 2006). Both somatic and male-specific coliphage have been recommended as surrogates for human enteric viruses (Havelaar et al. 1993; Wiedenmann et al. 2006). While the vast majority of past bench-scale investigations of pathogen partitioning focus solely on protozoans (Dai and Boll 2003; Medema et al. 1998), bacteria remain the primary cause of

disease outbreaks in untreated recreational freshwaters in the United States (Craun et al. 2005). Consequently, *Salmonella* was selected as the pathogen target for this study.

Fecal coliform, *E. coli*, and enterococci concentrations were determined using the Colilert and Enterolert defined-substrate methods (IDEXX, Westbrook, Maine). Colilert quantitrays for fecal coliform/*E. coli* analysis were incubated at 37 ^{o} C for 2 hours followed by incubation at 44.5 ^{o} C for 19 +/- 3 hours to select for thermotolerant coliforms (Yakub et al. 2002). The Enterolert procedure was not modified and all quantitrays were incubated at 41 ^{o} C for 21 +/- 3 hours. Concentrations were determined using two quantitrays per sample to narrow the MPN confidence intervals (Hurley and Roscoe 1983).

C. perfringens concentrations were determined using the multiple tube fermentation method with iron milk medium as substrate (AOAC 1995; St John et al. 1982). Prior to addition to the iron-milk medium, sample aliquots for C. *perfringens* spores analysis were heated to 65 ^{o} C for 20 minutes to inactivate any vegetative bacteria. Inoculated tubes were incubated at 41 ^{o} C for 21 +/- 3 hours before examination for stormy fermentation and gas production.

Male-specific (F+) and somatic coliphage concentrations were determined via the single-agar layer method detailed in EPA Method 1602 (USEPA 2000). Samples for male-specific coliphage analysis were combined with tryptic soy agar supplemented with streptomycin-ampicillin and *E. coli* F_{amp} as a host and poured into □etri dishes to solidify. Samples for somatic phage analysis were combined with tryptic soy agar supplemented with nalidixic acid and *E. coli* CN13 as a host. After 18 +/- 2 hours of incubation at 37 ^{o} C, the solidified agar was inspected for clear zones of lysis (coliphage plaques) in the dense host bacteria growth.

Salmonella concentrations were determined for each water sample using a multiple-tube method similar to that described in Lemarchand and Lebaron (2003) and Morinigo et al (1986).

Triplicate sets of buffered peptone water bottles were inoculated with four sample volumes (100 mL, 10 mL, 1 mL, 0.1 mL) and incubated at 37^{o} C for 21 +/- 3 hours as a pre-enrichment to recover and propagate injured cells. After incubation, 100 µL of each bottle of enriched sample was transferred to a tube of Rappaport-Vassilades broth and incubated at 41 ^{o} C for 24 hours. One loopful of liquid from each tube was streaked onto Salmonella-Shigella (SS) agar and incubated for 24 hours at 37 ^{o} C. Suspect colonies (circular, black, surrounded by clear ring of lysis) were confirmed as *Salmonella* spp via the Enterotube biochemical test (Beckton, Dickinson & Co., NJ). The presence of one or more *Salmonella* colonies on the SS agar indicated a positive tube. Four-tube MPN tables were used to determine concentration (lower detection limit = 0.4 MPN/100 mL).

Partitioning technique

Three-liter samples taken at the sampling sites were partitioned using a calibrated centrifugation technique. Briefly, a one-liter subsample was centrifuged at 1164g for 10 min at 4 C (Sorvall RC-3B centrifuge with a H-6000A rotor) with a break of 4 (approx 5 min deceleration time). Settings were intended to remove particle-associated microbes while leaving free-phase cells in suspension. The selection of centrifugation settings is based on experiments using standardized particle suspensions detailed in Characklis et al (2005). Glass particles (density = 2.65 g/cm^3, diameters = 5–60 µm) were used as a surrogate for inorganic particles such as clays or silicates, while latex particles (density = 1.05 g/cm^3, diameters = 5–40µm) were used as a surrogate for organic particles (density = 1.01-1.2 g/cm^3) and/or free phase microorganisms (density = 1.05-1.3 g/cm^3) (Holt 1994; Sharma et al. 1993; Lovins et al. 2002; Chapra 1997; Bratbak and Dundas 1984; Metge et al. 2003). Centrifugation via this regimen removed over 97% of the glass particles from suspension, but left over 80% of the latex particles in suspension

(including essentially all latex particles less than 10 µm in diameter). Following centrifugation, the top 700 mL of supernatant was removed via a vacuum pipette. Both raw and supernatant subsamples were analyzed separately for the six indicator organisms, *Salmonella*, particle concentration, and total organic carbon (TOC). Particles and particle-associated organisms removed via this procedure are termed "settleable", while those remaining in the supernatant are described as "suspended". Settleable concentrations of microorganisms and particles are calculated as the difference between the raw and suspended concentrations. For the purpose of analysis in this study, only those samples with a raw concentration greater than 3 microbes per 100 mL were included in partitioning calculations.

Subsequent application of this procedure to stormwater samples led to the removal of approximately 90% of particles, but less than 10% of the organic carbon, indicating that the vast majority of the particles removed were inorganic (Characklis et al 2005). Comparable results were obtained from analysis of samples in the current study, with an average of 95% of particles removed but only 5% of TOC removed from stormwater samples from the Northeast Creek watershed. Further investigation of microbial survival during this centrifugation technique was conducted by Fries et al (2006) to ensure no loss of organism viability during the procedure. Analysis of raw environmental samples, centrifuge supernatant, and centrifuge pellets using a mass balance approach confirmed that microbial population sizes and particle size distribution were essentially unaltered by the procedure.

Physical analysis

Particle concentration was determined using a Coulter Multisizer I with a 100 µm aperture tube (range: 2 – 60 µm; Beckman Coulter Inc.). TOC was determined using a Shimadzu

TOC-5000 Combustion-Infrared analyzer according to Standard Method 5310B (Standard Methods 1998).

Results

Correlation of pathogens and indicators

Salmonella spp. Were recovered from 22 of 33 (67%) dry weather samples and 45 of 48 (94%) stormwater samples. The frequency of Salmonella-positive samples was significantly higher in wet rather than dry weather samples (Fischer's exact test, p= 0.001). All sampling points, including street runoff, detention basins, and stream sites were positive for *Salmonella* on multiple occasions. Only four samples collected met the North Carolina instantaneous standard of 400 fecal coliform/100 mL. One of these four samples was positive for *Salmonella* (Figure 22), though at a relatively low concentration (0.4 MPN/100 mL). Of the twenty-three samples meeting the EPA recommended criterion of 235 *E. coli*/100 mL for recreational contact (USEPA 1986), thirteen (57%) were positive for *Salmonella* (concentration range: 0.5 – 93 MPN/100 mL) (Figure 13). All samples meeting the North Carolina single sample standard for fecal coliform or the EPA recommended single sample criterion for *E. coli* were collected during dry weather conditions, i.e. all storm samples failed to meet these criteria.

Arithmetic mean concentrations of *Salmonella,* indicator organisms, and physical parameters are given in Table 5. Overall, the highest average and single sample concentrations of *Salmonella* were detected in samples taken from the wet ponds. This is notable, as the wet pond catchment areas are wholly suburban, with no agricultural or wildlife areas in evidence. Birds, including poultry and waterfowl, are considered major carriers of *Salmonella*; consequently, samples from stream site 2, downstream from the waterfowl impoundment, might be expected to

contain the highest *Salmonella* concentrations. Average stormwater *Salmonella* concentrations were significantly higher (Wilcoxon test, $\alpha = 0.05$) in samples from site 2 than in samples taken just upstream from the waterfowl impoundment at site 1. During storms however, concentrations of all indicator organisms, except fecal coliforms, decreased between sites 1 and 2 (no significant differences).

Spearman rankings are among the most common statistic used to test for relationships between pathogens and indicator organisms (Brookes et al. 2005; Horman et al. 2004; Lemarchand and Lebaron 2003; Payment et al. 2000; Rouquet et al. 2000) and so were used assess potential correlations between *Salmonella* and indicator organism incidence in the Northeast Creek watershed (Table 6). Correlations between *Samonella* and fecal coliforms, *E. coli*, enterococci, and somatic coliphage were statistically significant ($\alpha = 0.05$) and of similar strength ($r_s = 0.42$-0.44). *C. perfringens* spore and *Salmonella* incidence was almost significantly correlated ($\alpha = 0.07$). *Salmonella* incidence was not significantly correlated with the presence of F+ (male-specific) coliphages. While F+ coliphage are frequently identified as strong indicators of fecal pollution and human health risks (Colford et al. 2007), they are not always present at adequate concentrations to serve as indicators of pathogen presence in waters primarily contaminated by stormwater (Ferguson et al. 1996). The ideal indicator should always be present at concentrations exceeding pathogen concentration (Savichtcheva and Okabe 2006), but in Northeast Creek, F+ coliphage concentrations only exceeded *Salmonella* concentrations in 51% of samples.

Although the nonparametric statistics used in this study have been identified as the most appropriate for the analysis of microbial data (Tillett et al. 2001), it is important to recognize their limitations. Spearman rankings only identify a similar directionality of data (e.g. fecal

coliform highest/lowest when *Salmonella* highest/lowest) and do not provide a mathematical relationship between pathogens and indicators. Linear regression is still often used to correlate pathogen and indicator presence (Ferguson et al. 1996; LeChevallier et al. 1991; Morinigo et al. 1990) as most risk assessment models assume a constant pathogen-to-indicator ratio when estimating human health risk using dose-response relationships (Gale 2001). Attempts to use linear regression to identify a *Salmonella*:indicator ratio for the Northeast Creek data resulted in equations with r^2 correlation coefficients less than 0.005. Additionally, there was no minimum or threshold indicator organism concentration consistently associated with pathogen presence or absence (i.e. no pathogens when *E. coli* less than a specific concentration); *Salmonella* was detected in samples with *E. coli* concentrations as low as 10 MPN/100 mL. Consequently, though fecal coliform, *E. coli*, enterococci, and somatic coliphage presence may be useful in identifying waters likely contaminated by *Salmonella*, using indicator concentrations is of limited utility in quantitatively predicting actual *Salmonella* concentrations and their resultant risks to human health.

Particle association

Average settleable fractions are illustrated in Figure 14. Considerable variation in observed settleable fractions tended to skew arithmetic means and made comparison of median values more appropriate. In general, the settleable fraction (removed via centrifugation) differed by microbial type. Median values for the settleable fraction of all four non-spore forming bacteria (fecal coliforms, *E. coli*, enterococci, and *Salmonella*) ranged between 25 and 35%, suggesting that partitioning behavior of *Salmonella* and these indicators is similar. *C. perfringens* spores appeared to associate with settleable particles at the highest rate, with over 50% defined as settleable in storm samples. In contrast, the median values for settleable fractions of both

types of phage were less than 10%. Interestingly, a higher fraction of all six microbes appeared to associate with settleable particles in dry weather samples than in stormwater samples, a finding at odds with previous analysis of North Carolina receiving waters (Characklis et al. 2005). However, in the cases of the most dramatic of these weather-related differences, such as *Salmonella* and F+ coliphage, only a very small number of dry weather samples were included in partitioning calculations as the majority of sample concentrations were below method limits (less than 3 organisms/100 mL). Larger sample sizes may narrow this observed variability.

Because the range of settleable fractions observed was large, particularly for *Salmonella*, Spearman rankings were used to determine whether fluctuations in particle association followed similar trends for different microbes. Simultaneous increases or decreases in settleable fraction by indicator organisms and *Salmonella* would suggest similar environmental factors could be responsible for promoting or discouraging particle attachment. Relationships between male-specific coliphages and *Salmonella* were not addressed in this analysis, as more than half of the samples were below method limits (fewer than 2 PFU/100 mL) and were not included in partitioning calculations.

Only two significant correlations between settleable fractions were identified: fecal coliforms and *E. coli* (r_s=0.45, n=40), and *C. perfringens* spores and *Salmonella* (r_s=0.41, n=40). Additionally, the concentration of particle-associated *C. perfringens* spores was significantly correlated with the concentration of particle-associated *Salmonella* (r_s=0.84, n=80). While these results might suggest that similar environmental conditions affect the association of these microbes with settleable aggregates, the identified correlations may partly be due to similarities in enumeration techniques. All five bacteria types, both spore and non-spore forming, were enumerated using MPN techniques; however, the Colilert (IDEXX) system used to enumerate

fecal coliforms and *E. coli* uses far more positive/negative wells (98 at one dilution, and 96 at a lower dilution for two quantitrays) and so confidence intervals are much narrower and MPN concentrations more precise. In contrast, the multiple tube techniques used for *C. perfringens* and *Salmonella* used only 3 tubes at 3 dilutions and 3 tubes at 4 dilutions respectively, resulting in far larger confidence intervals encompassing one to three orders of magnitude. The high variability of settleable fractions observed for these two microbes may be partly due to the less precise methods used for their enumeration in samples.

Increases in the settleable fractions of fecal coliform, *E. coli*, and enterococci were correlated with increases in total particle concentration (Spearman's test, α=0.05); however, this relationship does not exist between particle concentration and attached fractions of *Salmonella*, coliphage, or *C. perfringens* spores. Changes in TOC concentration were not correlated with changes in the settleable fraction of any microorganism. Further investigation is required to determine whether other unidentified environmental factors contribute to fluctuations in microbial partitioning behavior.

Effectiveness of wet ponds

Association of neutrally buoyant microorganisms with larger and/or denser particles to form larger aggregates should increase settling velocity and decrease the time required to remove these microbes from the water column, increasing the effectiveness of sedimentation-based best management practices. However, in this study microbial removal by wet ponds was inconsistent and in many cases concentrations leaving the pond exceeded those entering the pond (Figure 15). Mean concentration removals were not significantly correlated with the fractions of microbes defined as settleable in the pond influent (Spearman's test, $\alpha = 0.05$), i.e. greater fractions of particle-associated microbes did not necessarily result in higher removal efficiencies. On

average, concentrations of fecal coliform and *Salmonella* increased by 13% and 36% respectively for pond 1, and 41% of fecal coliforms and 13% of *Salmonella* were removed by pond 2. Though located less than a kilometer apart in the same subdivision, the ponds differed substantially in design, a factor which could have contributed to the observed differences in average microbial removal. The design of Pond 2 more closely approximated pseudo-plug flow conditions intended to increase detention time; however it still did not achieve the 65% reduction in stormwater microbial loadings cited as "typical" by the USEPA (USEPA 2007). Fecal coliform behavior was generally representative of the behavior of all indicators investigated. A more detailed discussion of indicator bacteria loadings and pond performance is given by Drummey (2007).

In the cases where observed effluent concentrations exceeded influent concentrations, these ponds may actually be serving as sources of downstream microbial loadings. Several studies have indicated that indicator bacteria may persist longer in bottom sediments or even undergo regrowth (Burton et al. 1987; Desmarais et al. 2002; Howell et al. 1996; LaLiberte and Grimes 1982; Lee et al. 2006). Laboratory-scale microcosm studies have confirmed similar behavior for *Salmonella* in freshwaters (Fish and Pettibone 1995). Reservoirs of bacteria in bottom sediments may then be resuspended by future stormflows (Jamieson et al. 2005; McDonald et al. 1982); therefore, even total removal of influent loadings may be overshadowed by resuspension of accumulated loadings. Though sediment storage and resuspension were not explicitly examined in this study, these processes seem likely contributors to observed microbial concentrations in pond effluents, as evidenced by dry weather observations. During dry weather, *Salmonella* were detected in pond effluent when influent concentrations were zero once in pond 2 and three times in pond 1, suggesting some storage of bacteria occurs in ponds between storm

events. Further research is required to determine the relative impacts of new stormwater inputs and resuspended bottom sediment loadings of microbes in pond performance, and to determine whether specific maintenance or design techniques could reduce microbial storage.

Several studies have reported that microbes preferentially associate with small (>30 μm) particles that settle very slowly (Auer and Niehaus 1993; Davies and Bavor 2000; Davies et al. 2003; Jeng et al. 2005). It is unknown whether in this study preferential attachment to small, nonsettlable aggregates or poor pond construction and maintenance was primarily responsible for the low microbial removals. Both ponds were designed to retain water for over twelve hours; however, intrastorm flow observations revealed the actual hydraulic retention times to be only three to four hours (Drummey 2007). Though microbial reductions by the wet ponds were modest at best, it is worth noting that both indicator organism concentrations at both in-stream sites were much lower on average than in the wet ponds, likely due to dilution by non-urban flows entering the stream.

Conclusions

Salmonella were recovered from surface water samples meeting current indicator bacteria water quality standards for recreational contact. However, correlations between fecal indicator bacteria (fecal coliforms, *E. coli*, and enterococci) and *Salmonella* concentrations were relatively strong and statistically significant. These results suggest that concentrations of fecal indicator bacteria and *Salmonella* are interrelated, but that current recreational water quality standards for fecal indicator bacteria concentrations do not preclude *Salmonella* presence at readily detectable levels in 100 mL samples. Additionally, this study suggests that similar average fractions of *Salmonella* and these bacterial indicators are associated with settleable particles, supporting the

continued use of hydrologic models using these microorganisms as surrogates for the behavior of pathogenic bacteria. None of the alternative microbial indicators investigated exhibited both a better correlation with *Salmonella* incidence and similar partitioning behavior. Therefore, the use of fecal indicator bacteria as surrogates for *Salmonella* appears to be preferred in modeling waterborne transport and settling. However, it is important to note that the ratio of *Salmonella* to these indicators is not constant, which would make prediction of downstream *Salmonella* concentrations and quantification of resultant human health risks difficult.

Between 25-35% of the bacteria in this study were identified as likely associated with settleable particles; however, removal by sedimentation-based wet ponds was minimal and not statistically related to the fraction of particle-associated organisms in pond inflows. High concentrations in pond outflows during both dry weather and storm events suggest that microbial loadings may accumulate or even regrow in pond sediments. Further research is required to quantify the relative amounts of effluent microbial concentrations attributable to fresh inputs and to resuspension in order to assess the utility of these best management practices in removing particle-associated microorganisms. Additional research is also needed to determine the extent to which differential die-off or proliferation of *Salmonella* and fecal indicator bacteria also contribute to the variability observed in their associations and quantitative ratios in the different waters studied under dry and wet weather conditions.

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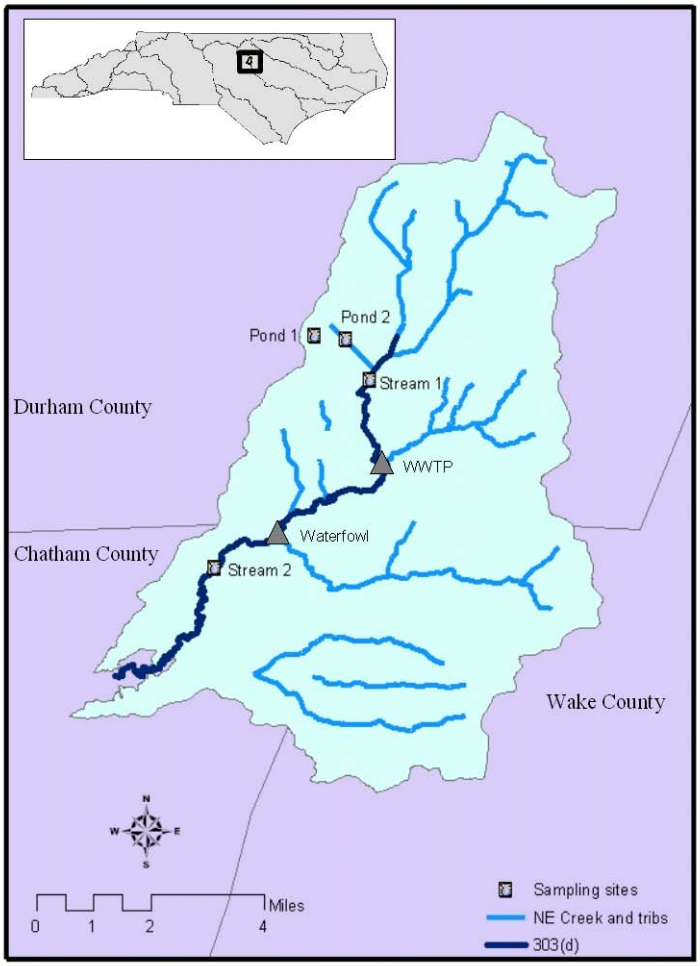


Figure 11 Northeast Creek Watershed

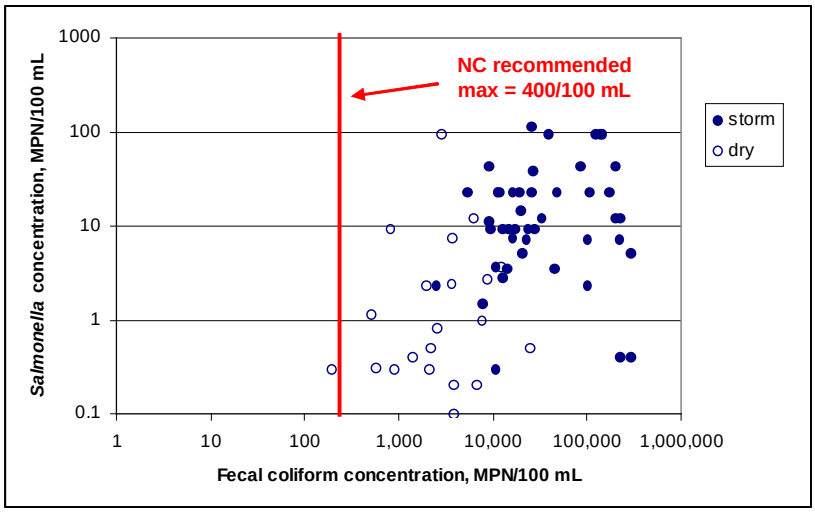


Figure 12. *Salmonella* and fecal coliform occurrence in Northeast Creek

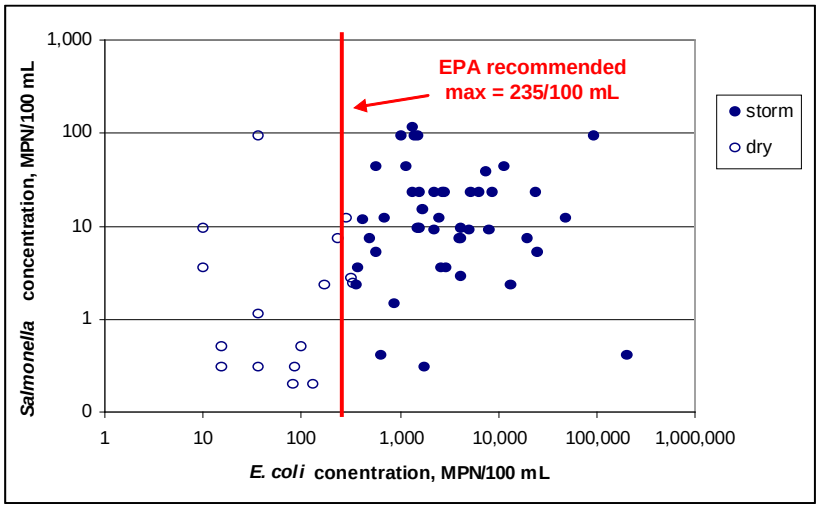


Figure 13. *Salmonella* and *E. coli* occurrence in Northeast Creek

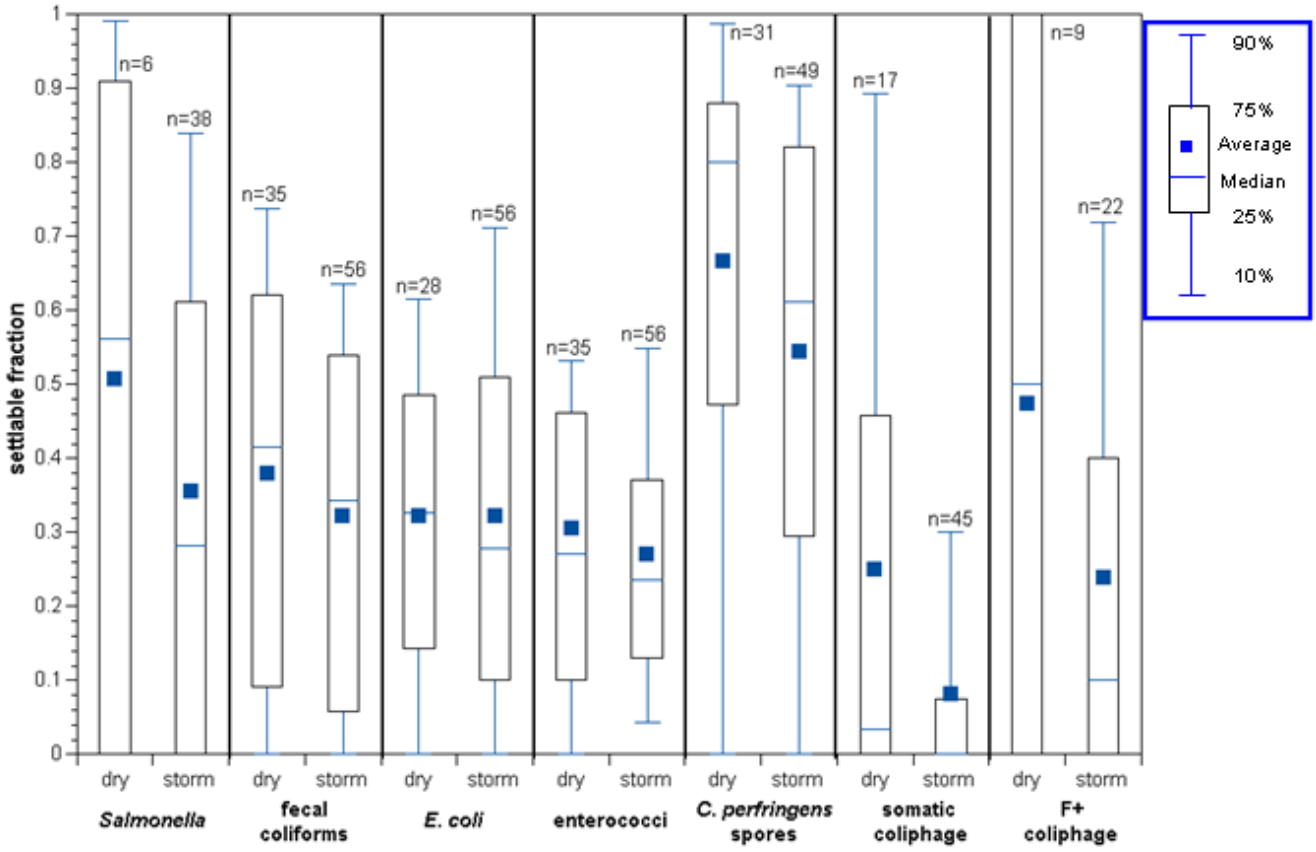


Figure 14. Average settlable fractions of microorganisms in Northeast Creek

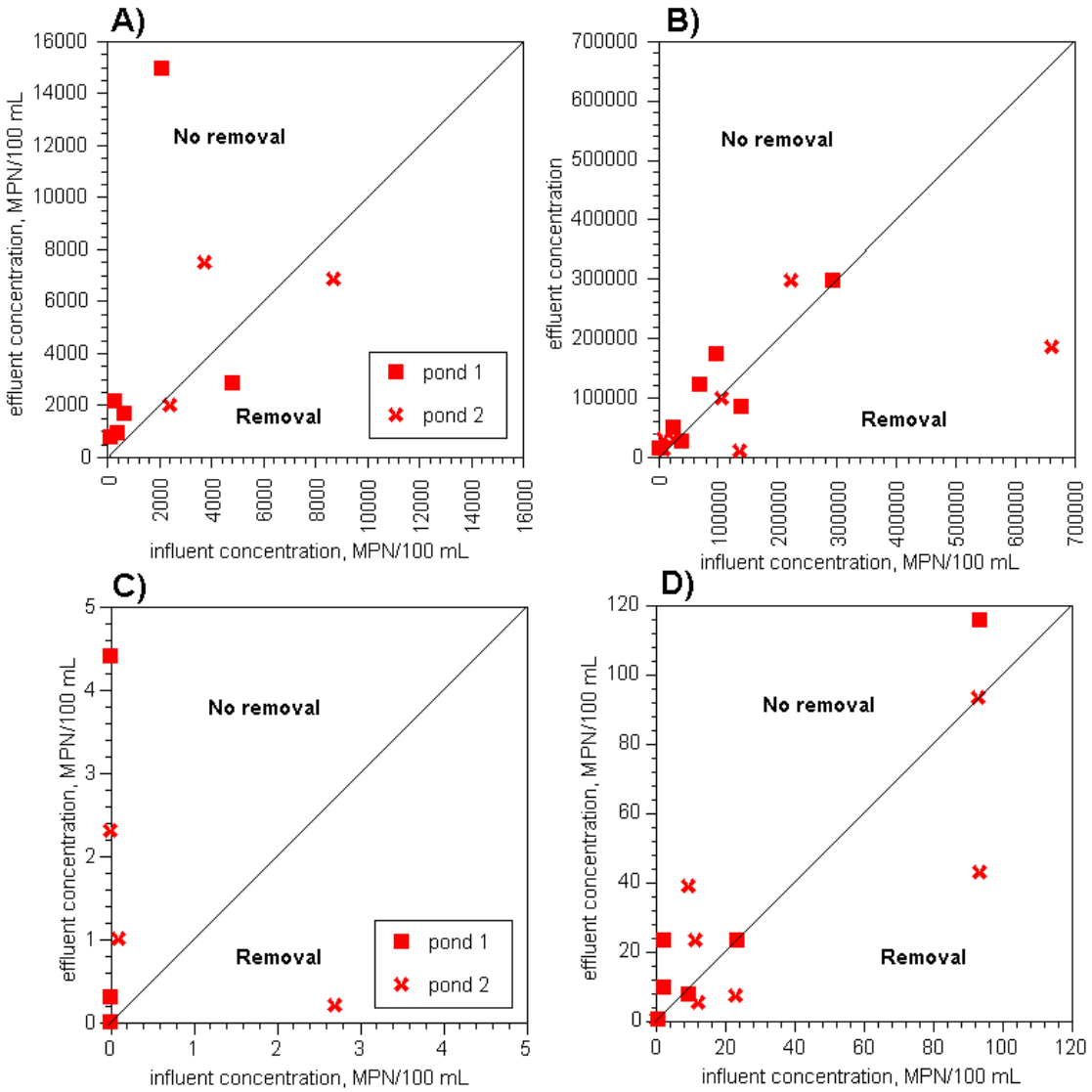


Figure 15. Wet pond reductions in microbial concentrations for A) fecal coliforms, dry weather B) fecal coliforms, storms C) *Salmonella,* dry weather D) *Salmonella,* storms

Table 5. Average water quality parameters

			Fecal coliforms (MPN/100 mL)	*E. coli* (MPN/100 mL)	Enterococci (MPN/100 mL)	*C. perfringens* spores (MPN/100 mL)	*Salmonella* , (MPN/100 mL)	F+ coliphage (PFU/100 mL)	Somatic coliphage (PFU/100 mL)	Particle Concentration (#/100 mL)	TOC (mg/L)
Pond 1	**street runoff**	**n=4**	81,600	4,960	21,000	246	14	2	263	5,257,000	10.9
	influent	**storm (n=7)**	85,800	30,000	44,500	426	218	51	181	10,280,000	10.3
		dry (n =6)	1,420	5	94	2	0	0	8	515,000	3.8
	effluent	**storm (n=7)**	96,700	9,260	51,900	1,380	263	22	890	25,370,000	11.1
		dry (n =6)	3,850	24	503	140	10	2	45	2,003,000	6.3
Pond 2	**street runoff**	**n=4**	163,000	478	30,000	543	66	14	325	5,557,000	8.5
	influent	**storm (n=7)**	168,000	28,900	65,600	2,030	219	50	408	5,625,000	9.2
		dry (n=5)	10,300	87	244	932	7	3	10	5,377,000	6.5
	effluent	**storm (n=7)**	93,000	9,430	43,400	687	24	13	304	5,477,000	6.8
		dry (n=4)	4,100	95	858	813	10	0	0	6,210,000	9.2
Stream Site 1		**storm (n=8)**	15,400	2,330	14,400	277	30	38	820	34,380,000	8.9
		dry (n=6)	1,490	112	160	89	7	4	103	5,256,000	7.6
Stream Site 2		**storm (n=6)**	28,200	2,040	12,900	116	119	22	724	69,430,000	10.5
		dry (n =6)	3,180	150	2,340	75	27	12	72	11,510,000	8.1

Table 6. Spearman coefficients comparing indicator organism and *Salmonella* incidence, N=71

	Fecal coliforms	*E. coli*	Enterococci	*C. perfringens* spores	Somatic coliphage	F+ coliphage	*Salmonella*
Fecal coliforms	1	0.80*	0.87*	0.62*	0.53*	0.35*	0.42*
E. coli	0.80*	1	0.86*	0.55*	0.66*	0.37*	0.44*
Enterococci	0.87*	0.86*	1	0.56*	0.64*	0.38*	0.42*
C. perfringens	0.62*	0.55*	0.56*	1	0.26*	0.23	0.22
Somatic coliphage	0.53*	0.66*	0.64*	0.26*	1	0.49*	0.43*
F+ coliphage	0.35*	0.37*	0.38*	0.23	0.49*	1	0.17
Salmonella	0.42*	0.44*	0.42*	0.22	0.43*	0.17	1

*statistically significant at α=0.05

Appendix A: Statistical analysis summary

For the purposes of analysis, results are considered statistically significant at a significance level (α) of 0.05, with significance up to 0.10 considered possibly significant.

Phase I

Tables A1 and A2 summarize the analysis of the concentrations and percent settleable, respectively, of particles and microbes from phase I. There were significantly higher concentrations of microbes and particles during storm events than in background periods. There was no difference between background and storm percent settleable for all microbes, but there was a higher percent settleable of particles in the storm samples. The percent settleable was not different between microbes (i.e., fecal coliform, *E. coli*, and enterococci are all associated with settleable particles at a similar rate).

Large variations in concentrations as well as percent settleable among different storm events were noticed. Past work has shown variations in microbial concentrations due to seasonality as well as individual storms. There were differences in microbial and particle concentrations as well as percent settleable from one storm to another. The single grab sample percent removal of microbes by the ponds was also examined and may differ by storm. However, neither concentration nor settleable percentage was correlated to the amount of rainfall, the amount of previous rainfall, the days of preceding dry weather, or the average air temperature.

Table A1: Summary of statistical analysis on microbial and particle concentrations in phase I.

Question	Statistical Test	Result
Is there a difference between storm and background concentrations?	Mann-Whitney (for each organism and particles)	Yes for fecal coliform ($p<0.0001$) Yes for E. coli ($p<0.0001$) Yes for enterococci ($p<0.0001$) Yes for particles ($p=0.0004$)
Do concentrations vary among storms?	Friedman (control for location and constituent)	Yes ($p<0.0001$)
Does single grab sample removal differ by storm?	Friedman (control for constituent)	Perhaps ($p=0.079$)
Is microbial or particle concentration correlated with amount of rainfall?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle concentration correlated with previous rainfall?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle concentration correlated with days of preceding dry weather?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle concentration correlated with air temperature?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents

. Table A2: Summary of statistical analysis on microbial and particle percent settleable in phase I.

Question	Statistical Test	Result
Does storm percent settleable vary among particle or organism types?	Friedman (control for location and storm)	No among microbes; Yes among microbes and particles ($p<0.0001$)
Is there a difference between storm and background percent settleable?	Mann-Whitney (for each organism and particles)	Yes (more settleable in storm) for particles ($p=0.0099$); No difference for fecal coliform, E. coli, or enterococci
Is there a difference between storm inflow and outflow settleable concentration?	Wilcoxon matched-pairs signed-rank	**Pond 1**: Yes for particles ($p=0.0156$); Yes for enterococci ($p=0.0469$); (more settleable in outflow) **Pond 2**: No difference
Does percent settleable vary among storms?	Friedman (control for location and constituent)	Yes ($p<0.0001$)
Is microbial or particle percent settleable correlated with amount of rainfall?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle percent settleable correlated with amount of previous rainfall?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle percent settleable correlated with days of preceding dry weather?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents
Is microbial or particle percent settleable correlated with amount average air temperature?	Spearman correlation coefficient	**Pond 1**: No for all constituents **Pond 2**: No for all constituents

Phase II

Table A3 shows the analysis from phase II, the intrastorm samples. As in the phase I samples, settleable percentage did not vary by organism. Higher *E. coli* concentrations were significantly correlated with higher flows, but not significant correlation was found for other organisms.

Table A3: Summary of statistical analysis in phase II.

Question	Statistical Test	Result
Does storm percent settleable vary among organism types?	Friedman (control for location)	No among microbes
Is microbial or particle concentration correlated with flow?	Spearman correlation coefficient	Yes for E. coli ($\rho = 0.852$, $p = 0.0009$); No for fecal coliform, enterococci, and particles

Appendix B: Single Grab Sample and Mean Concentration Removals

The single grab sample removals are shown for each storm under the date of the storm for each constituent. The geometric mean concentration removals and the arithmetic mean concentration removals are shown in the shaded columns.

Pond 1	**3-Jun**	**25-Jun**	**25-Jul**	**5-Sep**	**25-Sep**	**28-Oct**	**7-Nov**	MC_{Geo}*	MC_{Ari}
Total Fecal Coliform	-0.73	0.40	0.00	0.34	-4.05	-0.86	-0.75	-0.41	-0.13
Settleable Fecal Coliform**	-0.82	1.00	0.00	1.00	-0.14	-0.45	1.00	0.98	0.48
Total *E. coli*	-1.50	0.15	0.33	0.05	-5.11	0.18	0.35	-0.24	0.13
Settleable *E. coli***	-3.15	0.70	0.23	-1.60	1.00	1.00	0.67	0.86	0.26
Total Enterococci	-1.25	-0.27	0.00	0.13	-35.49	-0.09	-0.69	-1.08	-0.21
Settleable Enterococci**	-0.87	-0.33	-0.35	-2.92	-1.00	0.15	-3.05	-3.67	-0.45
Total Particles	-0.42	-0.05	-0.17	-0.29	0.11	-2.63	-1.36	-0.50	-1.70
Settleable Particles**	-0.46	-0.08	-0.18	-0.49	-0.08	-2.77	-1.48	-0.61	-1.90
Pond 2									
Total Fecal Coliform	-1.83	-0.31	0.72	-0.23	0.94	0.03	0.09	0.31	0.45
Settleable Fecal Coliform**	-2.48	0.00	0.82	1.00	0.96	0.36	-1.00	0.08	0.74
Total *E. coli*	-1.50	0.15	0.33	0.05	-5.11	0.18	0.35	0.48	0.67
Settleable *E. coli***	-1.00	0.00	0.64	-1.00	1.00	0.80	1.00	0.72	0.94
Total Enterococci	-0.31	0.30	0.21	-0.91	0.95	0.03	0.37	0.36	0.34
Settleable Enterococci**	-0.69	0.15	-0.58	-2.45	0.59	0.81	0.91	0.34	0.06
Total Particles	-2.55	-0.02	0.51	-0.51	0.31	0.28	0.29	0.01	0.03
Settleable Particles**	-2.49	-0.12	0.52	-0.81	0.25	0.33	0.22	-0.04	0.01

*Settleable concentrations that were found to be 0 or negative were taken as 1 to calculate geometric mean removal of the settleable fraction.
**Settleable concentrations that were negative were taken to be 0 to calculate single grab sample removal; when there was no settleable concentration out with positive concentration in, single grab sample removal was taken to be 1

Appendix C: Residence Times and Ideal Reactor Comparisons

According to both 1999 and 2007 NCDENR guidelines, wet ponds should be designed with outlet devices such that the volume of water that enters the pond during a 1-inch storm will be drawn down over a period between 48 and 120 hours. However, complete drawdown of the temporary pool has been observed within 16 hours after rain ends in pond 2 and in less time in pond 1. In this appendix, hydraulic residence times will be estimated for a variety of idealized rain events using the pond volumes listed in the City of Durham's Stormwater BMP database for pond 1 and estimated values for pond 2. Overflow rates will also be calculated to estimate particle removal characteristics. Finally, pond 2 will be modeled as a plug flow reactor (PFR) and completely mixed flow reactor (CMFR).

Table C1: Pond surface areas and volumes (City of Durham Stormwater BMP database)

Facility ID	Drainage Area (Ac)	% Impervious	Surface Area (SF)	Max Surface Area (SF)	Volume (CF)	Max Volume (CF)
Pond 1			1500*		5355*	
Pond 2	14.6	51%	12862	24545	46000	153968

*estimated using satellite imagery

**estimated assuming the same average depth as pond 2 (3.58 feet)

The volume of runoff resulting from given rainfall events will be estimated using the "Simple Method" as described in the 2007 NCDENR Stormwater BMP Manual using the land data from pond 2 since there is no data for pond 1. The resulting inflow volumes will then be used in both ponds to find ranges of hydraulic residence times. The volume of runoff can be calculated as

$$V = 3630 * R_D * R_V * A \qquad [C.1]$$

where V = Volume of runoff that must be controlled for the design storm (ft3), R_D = Design storm rainfall depth (in), A = Watershed area (ac) and R_V is the runoff coefficient [storm runoff (in)/storm rainfall (in)], calculated as

$$R_V = 0.05 + 0.9 * I_A \qquad [C.2]$$

where I_A = Impervious fraction [impervious portion of drainage area (ac)/drainage area (ac)]. The following table shows the volume of inflow as well as the average flow for different amounts of rain falling over a period of 6 hours in the drainage basin of pond 2:

Table C2: Inflow volumes and flows for different 6-hour rain events

Rain (Inches)	0.1	0.25	0.5	1	1.5	2	3	6
Inflow Volume(CF)	2,692	6,731	13,462	26,924	40,386	53,847	80,771	161,542
Inflow Volume (L)	76,248	190,620	381,240	762,479	1,143,719	1,524,959	2,287,438	4,574,877
Average Inflow (cfs)	0.12	0.31	0.62	1.25	1.87	2.49	3.74	7.48
Average Inflow (lps)	3.5	8.8	18	35	53	71	106	212

The average inflows will be used in order to calculate hydraulic residence times for each pond. The inflows may be an overestimate of flows in pond 1, given that it appears smaller than pond 2 and thus was probably designed for a smaller drainage basin area. These calculations should still give an estimation of residence times. Hydraulic residence time is calculated as:

$$HRT = \frac{V}{Q} \qquad [C.3]$$

Where HRT is mean hydraulic residence time, V is the volume of the pond, and Q is the average inflow. If the ponds behave as plug flow reactors, as design guidelines suggest, the HRT will be the actual time water spends in the pond (with the exception of the water that enters at the end of the storm, which will presumably remain in storage until the next storm event). If, on the other hand, the ponds behave more like completely mixed flow reactors (CMFR), the HRT is the average amount of time a particular water parcel remains in the pond, with some parcels exiting sooner than the HRT and others exiting later. It should also be noted that for the smaller design storms, the total inflow volume is less than the pond volume. In an ideal situation, none of the storm water would exit the pond, only the water that was previously stored.

Table C3: Hydraulic residence times for several different inflow scenarios.

Average Inflow (cfs)	0.12	0.31	0.62	1.25	1.87	2.49	3.74	7.48
Pond 1 HRT (hours)	12	4.8	2.4	1.2	0.8	0.6	0.4	0.2
Pond 2 HRT (hours)	103	41	21	10	6.8	5.1	3.4	1.7

NCDENR guidelines assume plug flow in wet detention basins. Surface area of the pond is specified in order to meet required TSS removal of 85%, since for idealized plug flow reactors with discrete particle sedimentation, removal of particles for a given flow is dependant only upon the surface area of the pond. The overflow rate, or v_c, is calculated as

$$v_c = \frac{Q}{A} \qquad [C.4]$$

where Q is the flow and A is the surface area of the pond. The overflow rate is equal to the slowest settling velocity with which all particles will be removed. The following table shows the overflow rate for each pond and each flow.

Table C4: Overflow rates for several different inflow scenarios.

Average Inflow (cfs)	0.12	0.31	0.62	1.25	1.87	2.49	3.74	7.48
Pond 1 v_c (feet/hour)	0.30	0.75	1.50	2.99	4.49	5.98	8.97	17.95
Pond 2 v_c (feet/hour)	0.03	0.09	0.17	0.35	0.52	0.70	1.05	2.09

Discrete particle settling can be estimated using Stoke's Law, that is

$$v_s = \frac{g}{18}\frac{\rho_p - \rho}{\mu} d_p^{\,2} \qquad [C.5]$$

Where v_s is the settling velocity, g is gravitational acceleration, ρ_p is the density of the particle, ρ is the density of water, μ is the viscosity of water, and d_p is the diameter of the particle. Particles are all assumed to be perfect spheres. Assuming a water temperature of 20 degrees Celsius, settling velocity can be calculated for any particle size-density combination.

All particles with settling velocity greater than the pond overflow velocity will settle out. Particles with settling velocities less than the overflow rate will settle out at a rate proportional to their settling velocity relative to the overflow rate. The following graph shows the particle density and diameter that are necessary to achieve a settling velocity equal to several different overflow rates, ranging from the lowest to the highest overflow rates calculated in table C4.

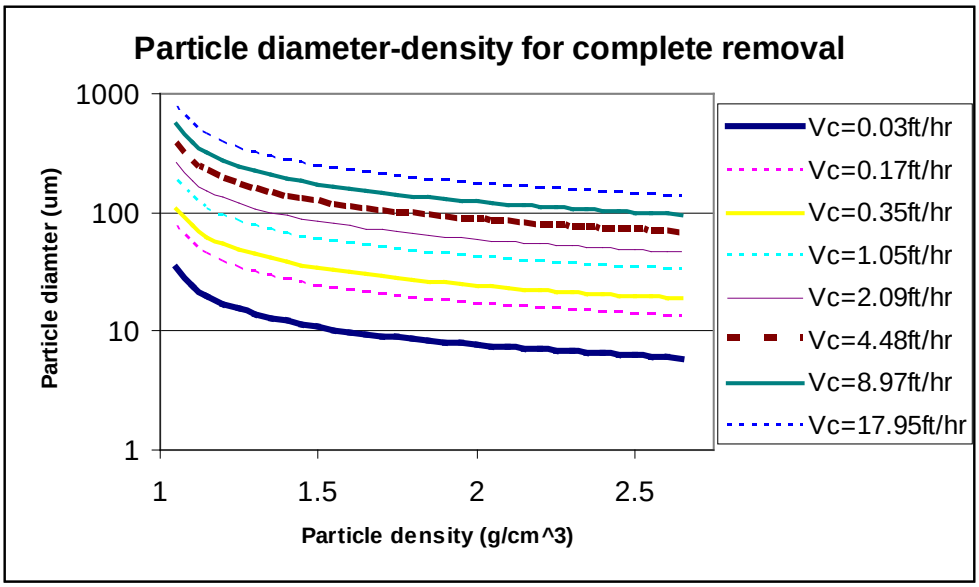


Figure C1: Lines showing minimum diameter and density needed to achieve complete removal for several overflow rates.

The graph shows that for an overflow rate of 17.95 ft/hr (as in pond 1 with an inflow of 17.48 cfs), the pond should remove all particles with a density of 1.05 and a diameter of at least 775 microns, as well as all particles with a density of 2.65 and a

diameter of at least 135 microns. On the opposite end of the spectrum, for an overflow rate of 0.03 ft/hr (which was calculated for a 0.1 inch storm for pond 2), the pond should remove all particles with a density of 1.05 and a diameter of at least 34 microns, as well as all particles with a density of 2.65 and a diameter of at least 6 microns. It is interesting to note that in the intrastorm sample (with about 1.8 inches of rain), the particles from 2 to 5 microns were reduced, but it does not appear that the reduction could be due to discrete particle settling.

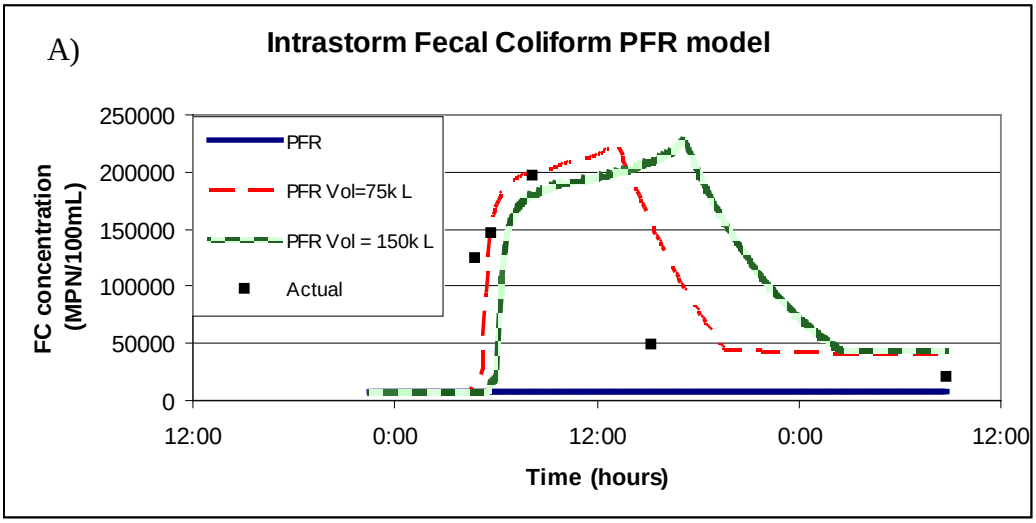
These calculations are based on many assumptions, including the accuracy of the given volume of pond 2 and the assumed volume of pond 1, and should only be considered rough estimates.

In the intrastorm phase of this study, flow measurements were taken in pond 2 for a storm that had an estimated rainfall of 1.8 inches (calculated as the average rainfall at RDU and Chapel Hill airports). To get a very general idea of the behavior of the pond, each of the microbes as well as particles can be modeled as if they were conservative species (reductions were actually on the order of 15 to 20%, so if the pond is accurately modeled with this assumption the measured concentrations of the microbes and particles should be less than the model predicts). The first model considered will be a plug flow reactor (PFR), since that is the assumption that is made to find the surface area of the pond necessary to reduce TSS by 85% (NCDENR 2007). A completely mixed flow reactor (CMFR) model will also be examined. For both of these models, the assumptions about inlet flow and concentration will be the same described in the body, namely that:

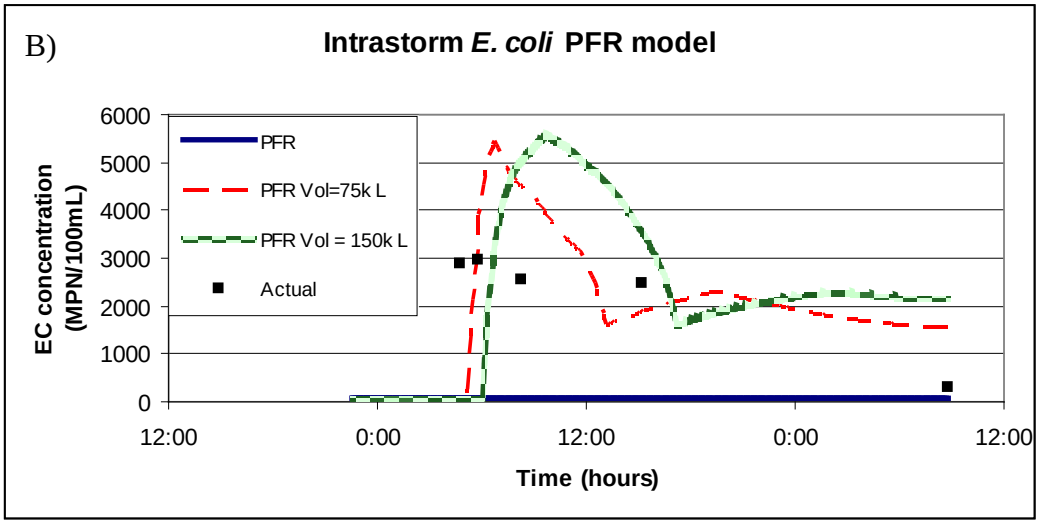
- Flow and concentrations vary **linearly** with time
- Inflow is 0 cfs at 10:30 pm June 2 (beginning of rain) and at 8:00 pm June 3 (4 hours after storm ends)
- Inflow concentrations at the beginning of the storm are average background concentrations

The following graphs show the predicted outflow concentration as a function of time using measured inflow concentrations and assuming conservative constituents and plug flow with no increase in pond volume. The measured inflows are used, which may be an underestimation of the actual inflow (Appendix E), and several volumes are used to see which volume best predicts the outflow concentrations.

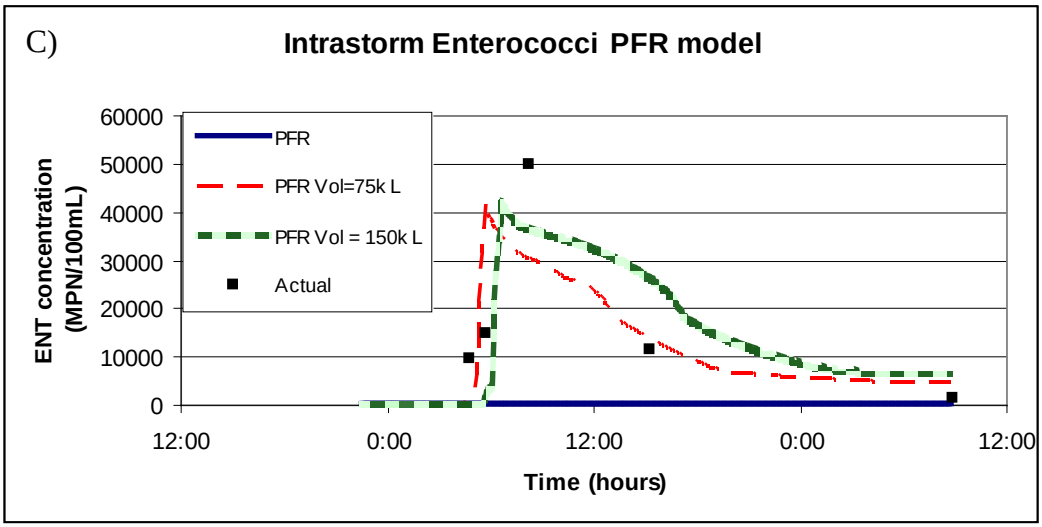
A)

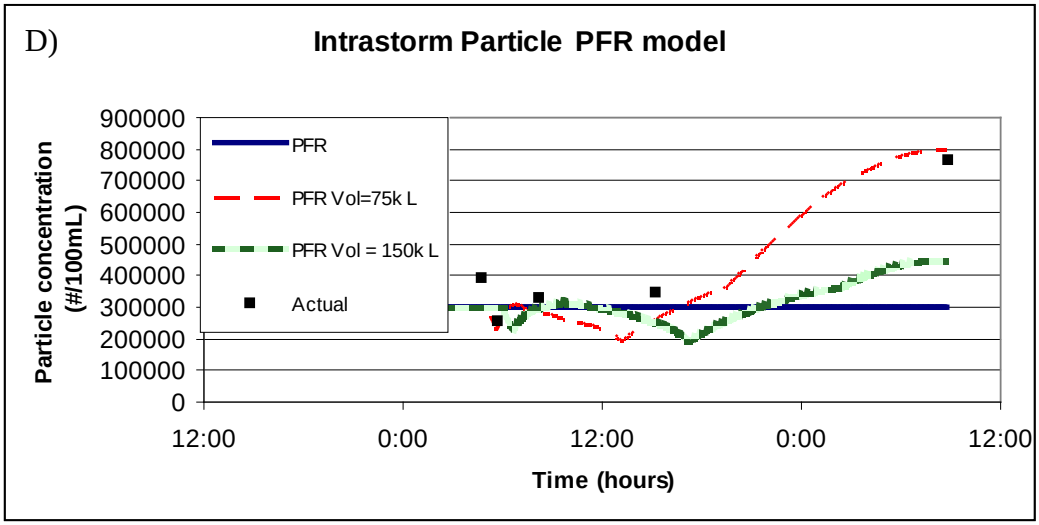

Intrastorm Fecal Coliform PFR model
FC concentration (MPN/100mL)
250000
200000
150000
100000
50000
0
PFR
PFR Vol=75k L
PFR Vol = 150k L
Actual
12:00
0:00
12:00
0:00
12:00
Time (hours)

B)


Intrastorm E. coli PFR model
EC concentration (MPN/100mL)
6000
5000
4000
3000
2000
1000
0
PFR
PFR Vol=75k L
PFR Vol = 150k L
Actual
12:00
0:00
12:00
0:00
12:00
Time (hours)

C)


Intrastorm Enterococci PFR model
ENT concentration (MPN/100mL)
60000
50000
40000
30000
20000
10000
0
PFR
PFR Vol=75k L
PFR Vol = 150k L
Actual
12:00
0:00
12:00
0:00
12:00
Time (hours)



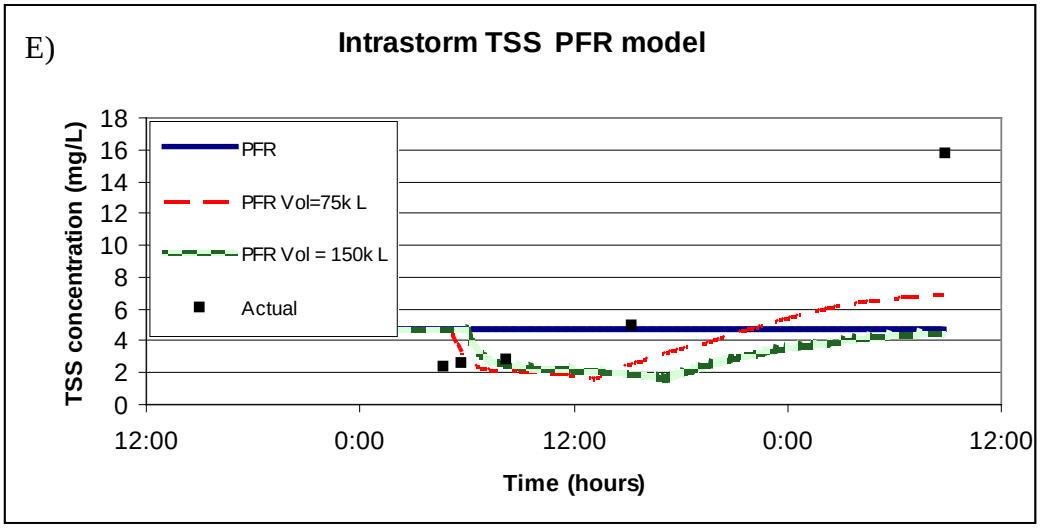
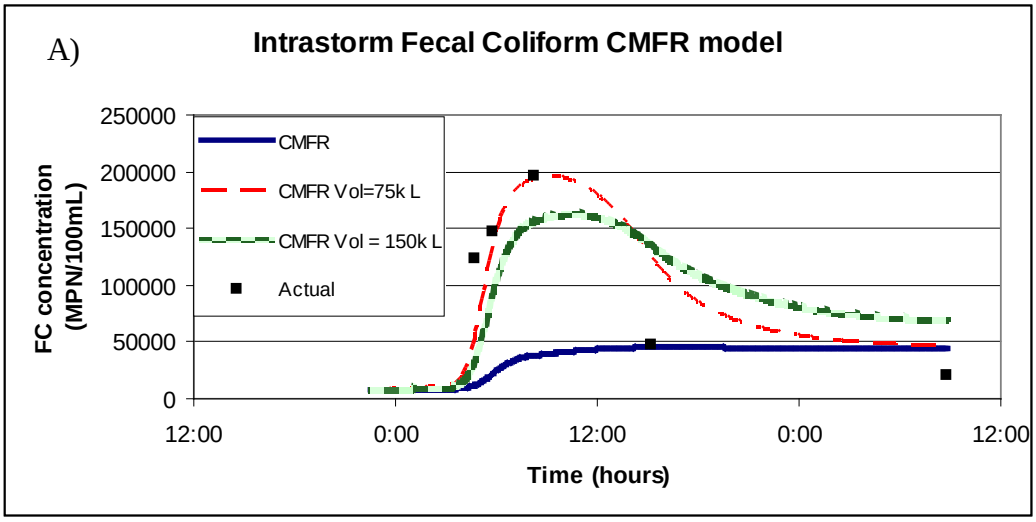


Figure C2: Graphs showing pond as an idealized plug flow reactor (PFR) with the given volume (1,300,000 L), a volume of 75,000 L, and a volume of 150,000 L for A) fecal coliform, B) *E. coli*, C) enterococci, D) particles and E) TSS. Inflow measurements are used to find the expected outflow concentrations (plotted as lines), and actual concentrations are shown as squares.

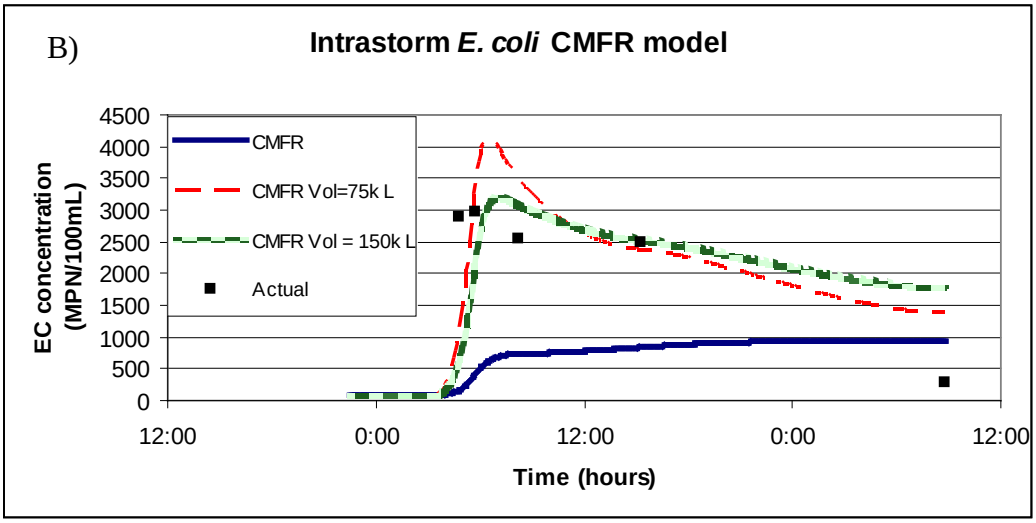
If the pond has an actual volume equal to that on its permit (1,303,000 L or 46,000 cubic feet) and the water actually travels though the pond in plug flow, every sample taken at the outflow would have been of water that had been stored in the pond for several weeks and the microbial and particle concentrations should have been relatively consistent with background values. However, this was not the case, and the two other volumes explored (75,000 and 150,000 L) seem to provide much better estimates of the pond. Actual concentrations should be less than the predicted values if there is any removal in the pond.

The results from the plug flow reactor model can be compared with the following results from a completely mixed flow reactor (CMFR):

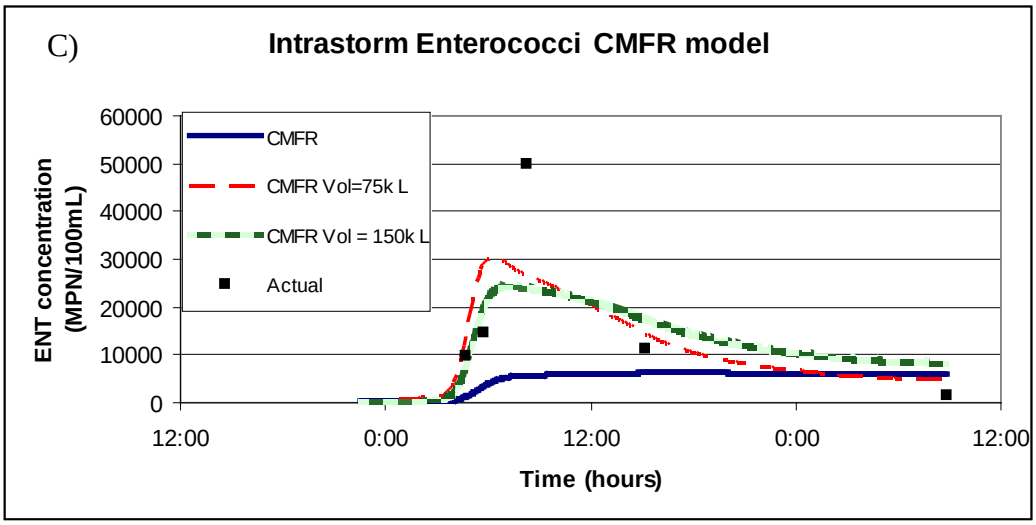
A)

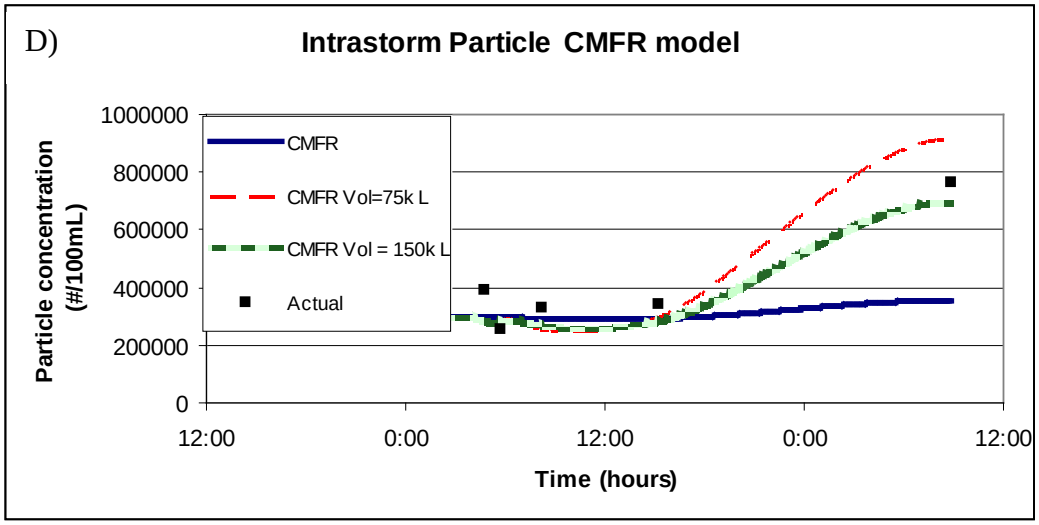


B)



C)





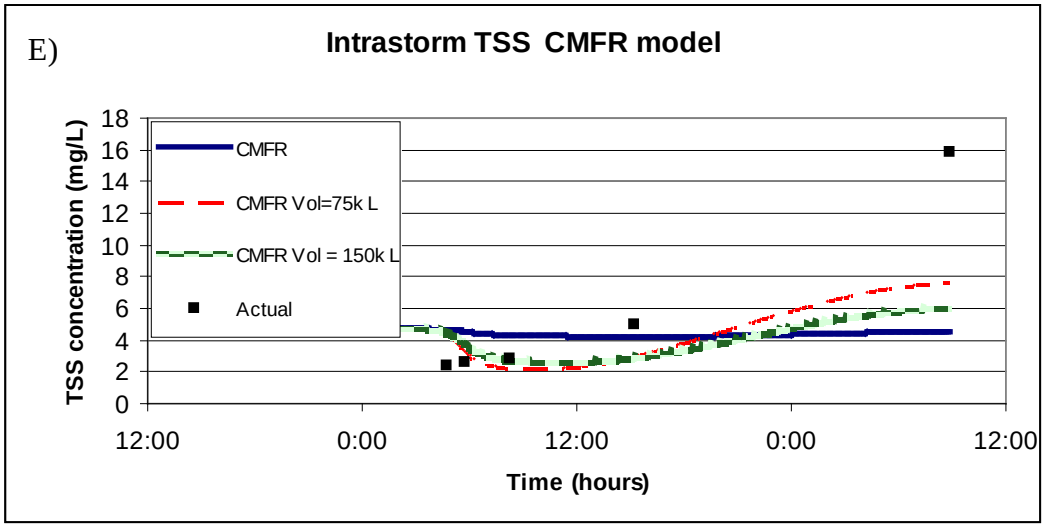


Figure C3: Graphs showing pond as an idealized continuously mixed flow reactor (CMFR) with the given volume (1,300,000 L), a volume of 75,000 L, and a volume of 150,000 L for A) fecal coliform, B) *E. coli*, C) enterococci, D) particles and E) TSS. Inflow measurements are used to find the expected outflow concentrations (plotted as lines), and actual concentrations are shown as squares.

It is not obvious which type of reactor better models this system, in part because the actual volume of the pond is unknown. The CMFR appears to model the particles better, but the PFR seems slightly better for enterococci. In reality, the pond is probably behaves someplace between a PFR and a CMFR, and it is also possible that there are dead areas and channeling occurring within the pond. The ponds behavior also seems somewhat consistent with a reactor between about 75,000 and 150,000 liters, or one tenth of the permitted volume of the pond.

If the volume of water that was measured at the inflow during the intrastorm sample is averaged over the course of the storm (21.5 hours) and the pond is considered to be 75,000 liters, the average hydraulic residence time for this storm can be calculated:

$$HRT = \frac{V}{Q} = \frac{75{,}000\,L}{448{,}000\,L/21.5\,hours} = 3.6\,hours$$

Even if the reactor behaved like a plug flow reactor, some water would have a longer/shorter residence time since the flow changes with time.

The overflow rate can also be calculated for this particular storm, although there are uncertainties surrounding the permitted pond surface area as well as the ability of this pond to behave as a plug flow reactor. However, if these assumptions are made, the overflow rate becomes

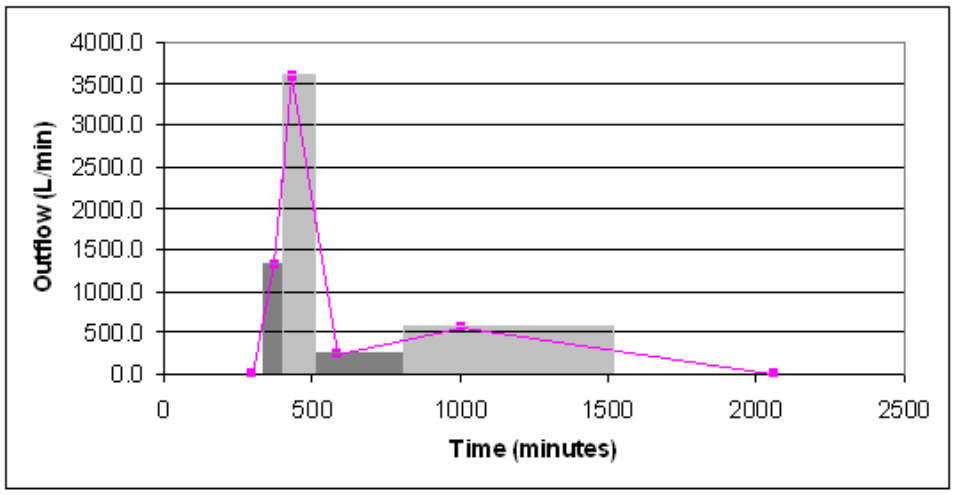
$$v_c = \frac{Q}{A} = \frac{(448{,}000L * \frac{1\,ft^3}{28.3L}) / 21.5 hours}{24545\,ft^2} = 0.030\,feet/hour$$

With this overflow rate, there should be significant removal of particles (see figure C1), which was not seen in the particle analysis. It is probable that the actual inflow was higher than measured due to large fluctuations in flow over short periods of time. It is also probable that the actual surface area is less than the permitted area, and that the pond does not behave exactly as a plug flow reactor.

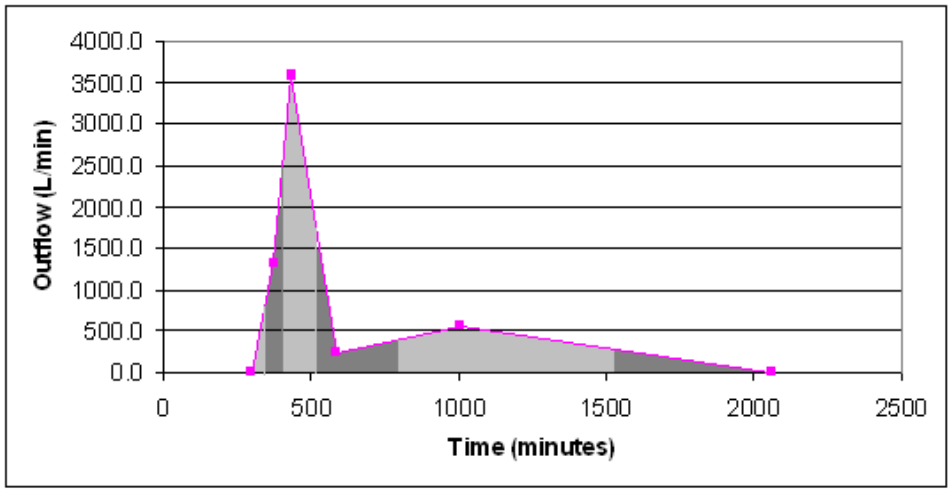
Appendix D: Intrastorm EMC Calculations

Two methods to calculate water volumes were explored which each yield the same total volume of water. Each involves finding the midpoints between sampling times, and the total volume can either be calculated by:

1) Multiplying the flow at the sampling point of interest by the time between midpoints



2) Finding the total volume as discussed in section 1 by linear interpolation



With the first method, the volume for the points at t = 430 and t = 1000 are overestimated while they are underestimated for the endpoints and middle point. The results from both methods are shown below:

Method 1:

	Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100 mL)	Particle Concentration (#/100mL)	Particle >5um Concentration (#/100mL)	TSS (mg/L)	TOC (mg/L)
EMC In	131698	3259	22886	5449054	298172	3.0	11.4
EMC Out	104945	2723	15248	3967251	312336	3.6	7.5
Efficiency Ratio	0.20	0.16	0.33	0.27	-0.05	-0.21	0.34

Method 2:

	Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100 mL)	Particle Concentration (#/100mL)	Particle >5um Concentration (#/100mL)	TSS (mg/L)	TOC (mg/L)
EMC In	134293	2938	21657	5111070	297548.4	3.0	11.2
EMC Out	106874	2487	17318	4130088	351885.7	4.5	7.5
Efficiency Ratio	0.20	0.15	0.20	0.19	-0.18	-0.47	0.33

*Efficiency Ratio: 1 is total removal, 0 is no removal, and negative is export of contaminant

These methods yield similar results, with method 2 resulting in slightly lower efficiency rations for most constituents. Since linear interpolation was assumed in the mass balance calculations, method 2 (which assumes linear change in flow as well) will be used.

The settleable fraction was analyzed separately. The results are below:

Settleable Fraction Method 1:

	Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100 mL)	Particle Concentration (#/100mL)	Particle >5um Concentration (#/100mL)	TOC (mg/L)
EMC In	69228	1011	2429	3811964	183729	-0.3
EMC Out	41570	749	6578	2643414	172655	-0.7
Efficiency Ratio	0.40	0.26	-1.71	0.31	0.06	-1.18

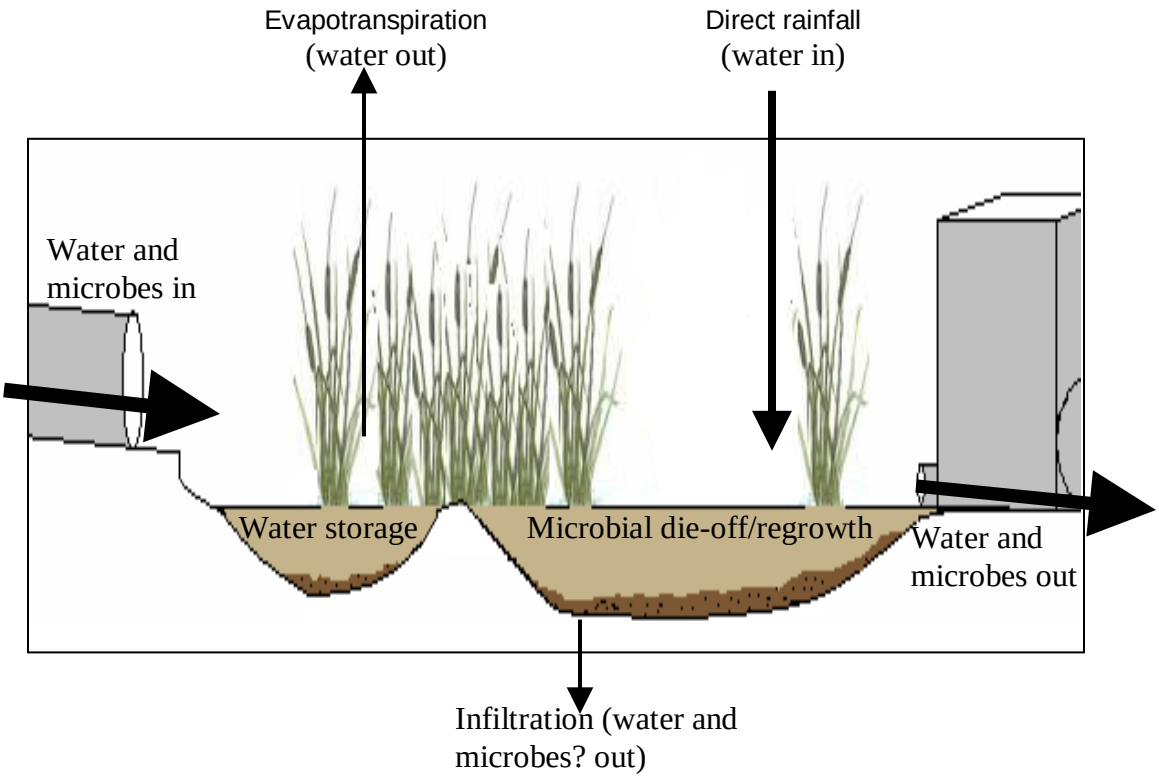
Settleable Fraction Method 2:

	Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100 mL)	Particle Concentration (#/100mL)	Particle >5um Concentration (#/100mL)	TOC (mg/L)
EMC In	75894	927	2979	3444115	169168.4	-0.3
EMC Out	46949	650	8648	2836304	206936.3	-0.7
Efficiency Ratio	0.38	0.30	-1.90	0.18	-0.22	-1.13

Since method 2 incorporates data from all samples collected (including the last one, which is not included in method 1), it will be utilized.

Appendix E: Intrastorm Rainfall and Storage Calculations

Calculations will be made to estimate rainfall and storage within pond 2 for the intrastorm sample in order to better understand the assumptions involved in the Efficiency Ratio as well as to explore a "Mass Based Efficiency Ratio". The following schematic shows possible sources and sinks that need to be considered when performing a mass balance around a wet pond for water and/or microbes.



Evapotranspiration and infiltration will not be considered in the water balance. Infiltration would presumably not change the concentration of microbes in the pond if both water and microbes are able to infiltrate thought the bottom or sides of the pond at the same rate. Potential Evapotranspiration was estimated to be only a small fraction of the total rainfall over the storm period for which the pond was monitored. In addition to presumably being negligibly small, evaporation and infiltration are also difficult to measure and separate and will therefore not be considered.

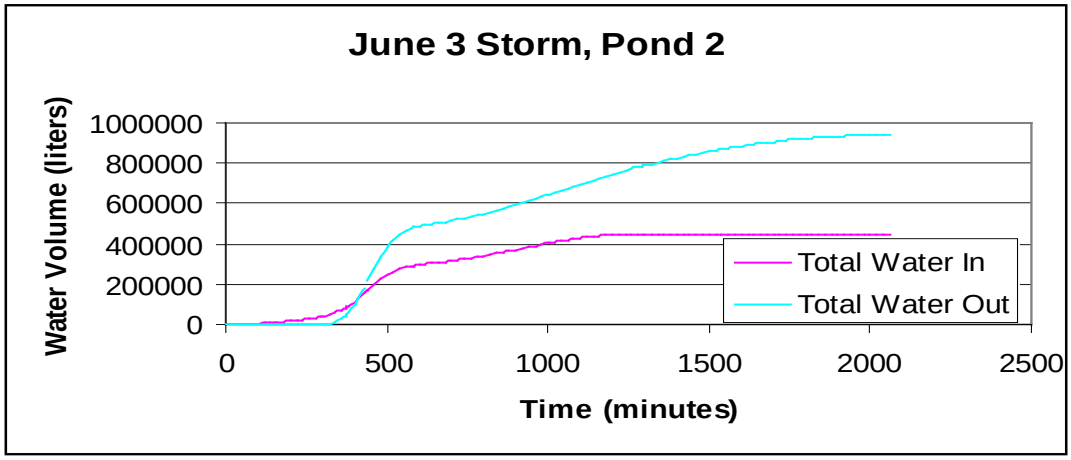
Neglecting evaporation and infiltration, the water balance on the pond takes the form:

$$\text{Water Out} = \text{Water In} + \text{Rain In} - \text{Storage}$$

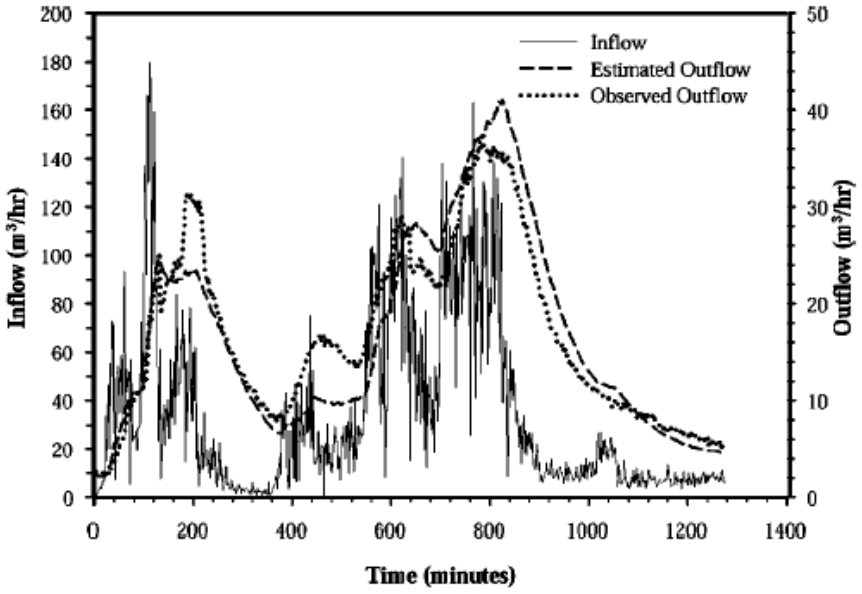
Where Storage is the volume of available storage in the pond that must fill before any water will flow out of the pond.

Storage = Water In before outflow starts + Rain In before outflow starts

There was a discrepancy in inflow and outflow measurements. Inflow was estimated at 448,000 liters, whereas outflow was estimated at 941,000 liters. The following chart shows the cumulative volume of water into and out of the pond. Note that there is much more water (2.1 times as much) leaving than entering the pond, which is problematic for a mass balance approach.



It is not possible that 2.1 times as much water exited the pond than entered the pond, so either there were errors in flow measurement or the inflow (and possibly outflow) flow changed dramatically over short periods of time, and inflow happened to be measured at points of low flow whereas outflow may have been measured at points of higher flow. The following figure is from a study done in Washington, and illustrates the high variability of stormwater wet detention pond hydrographs.



Spokane, Washington. Drainage area was 0.1769 km^2 of mostly highway pavement and right-of-way. Measured using Doppler velocimeter, measurements recorded every 2 minutes.
Wang, G., Chen, S. Barber, M.E., Yonge, D.R. 2004. "Modeling Flow and Pollutant Removal of Wet Detention Pond Treating Stormwater Runoff". Journal of Environmental Engineering, 130 (11) 1315-1321.

It is quite possible that the hydrograph for pond 2 in this study is just as variable as the one in Washington, especially considering that the drainage area is only 0.059 km^2 with about half of that area consisting of impervious surfaces.

Using the "Simple Method" (NCDENR 2007 BMP Manual chap 3), the expected inflow for this rain event can be calculated. The percent impervious is listed in the list of permited Durham Stormwater BMPs as 51%, and the estimated rainfall is 1.8" (average of rainfall at RDU and Chapel Hill airports). The expected inflow volume is calculated to be 1,375,000 liters.

The outflow measurements will be assumed accurate since

- they are closer to the estimated flow for this rain event
- the inflow measurements were taken in a submerged pipe, so it was difficult measure flow since it was in the lowest measurable range of the flow meter

About 8% of the total measured inflow had entered the pond when outflow commenced. Storage can now be expressed:

Storage = 0.08 (Water In) + Rain In before outflow starts

Several different scenarios are used to estimate the rainfall on the pond:

1) Neglect rainfall

2) Minimum rainfall, the amount of rain that falls only on the normal pool surface area (area from City of Durham Stormwater Services)
3) Maximum rainfall, the amount of rain that falls within the embankment (area calculated using satellite map)
4) Best estimate, the amount of rain that falls on the normal pool plus 79% of the rain that falls within the embankment (0.79 is value given to poor condition, open pervious space in Durham county in NCDENR BMP manual)

Rainfall can be calculated with the known data, and storage and inflow are calculated using an iterative procedure. The following chart shows the resulting volumes for each of the scenarios:

	Best Estimate	Maximum Rain	Minimum Rain	No Rain
Calculated Rain (Liters)	107,327	121,334	54,638	0
Calculated Storage (Liters)	124,316	129,864	103,444	81,800
Adjusted Inflow (Liters)	957,686	949,228	989,503	1,022,497
Rain (% of Inflow)	11.2%	12.8%	5.5%	0.0%
Storage (% of Inflow)	13.0%	13.7%	10.5%	8.0%

The efficiency ratio calculated in the text can be modified to yield a mass-balance approach that will take into account differences in inflow and outflow due to storage and direct rainfall. The modified version of the Mass Based Efficiency Ratio (MBER) is defined as:

$$\text{Mass Based Efficiency Ratio } = 1 - \frac{EMC_{out} V_{out}}{EMC_{in} V_{in}}$$

This assumes the Event Mean Concentration, which is flow-weighted, is accurate. This seems to be a reasonable assumption, since the inflow measurements only need to be accurate relative to one another (not relative to the outflow). The Mass Based Efficiency Ratio can be found for each of the constituents and for each of the rainfall scenarios to see how important the rainfall assumptions can be.

	Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100 mL)	Particle Concentration (#/100mL)	Particle >5um Concentration (#/100mL)	TSS (mg/L)	TOC (mg/L)
EMC In	134293	2938	21657	5111070	297548	3.0	11.2
EMC Out	106874	2487	17318	4130088	351885	4.5	7.5
Efficiency Ratio	0.20	0.15	0.20	0.19	-0.18	-0.47	0.33
MBER Best Rain Estimate	0.22	0.17	0.21	0.21	-0.16	-0.44	0.34
MBER Maximum Rain	0.21	0.16	0.21	0.20	-0.17	-0.45	0.33

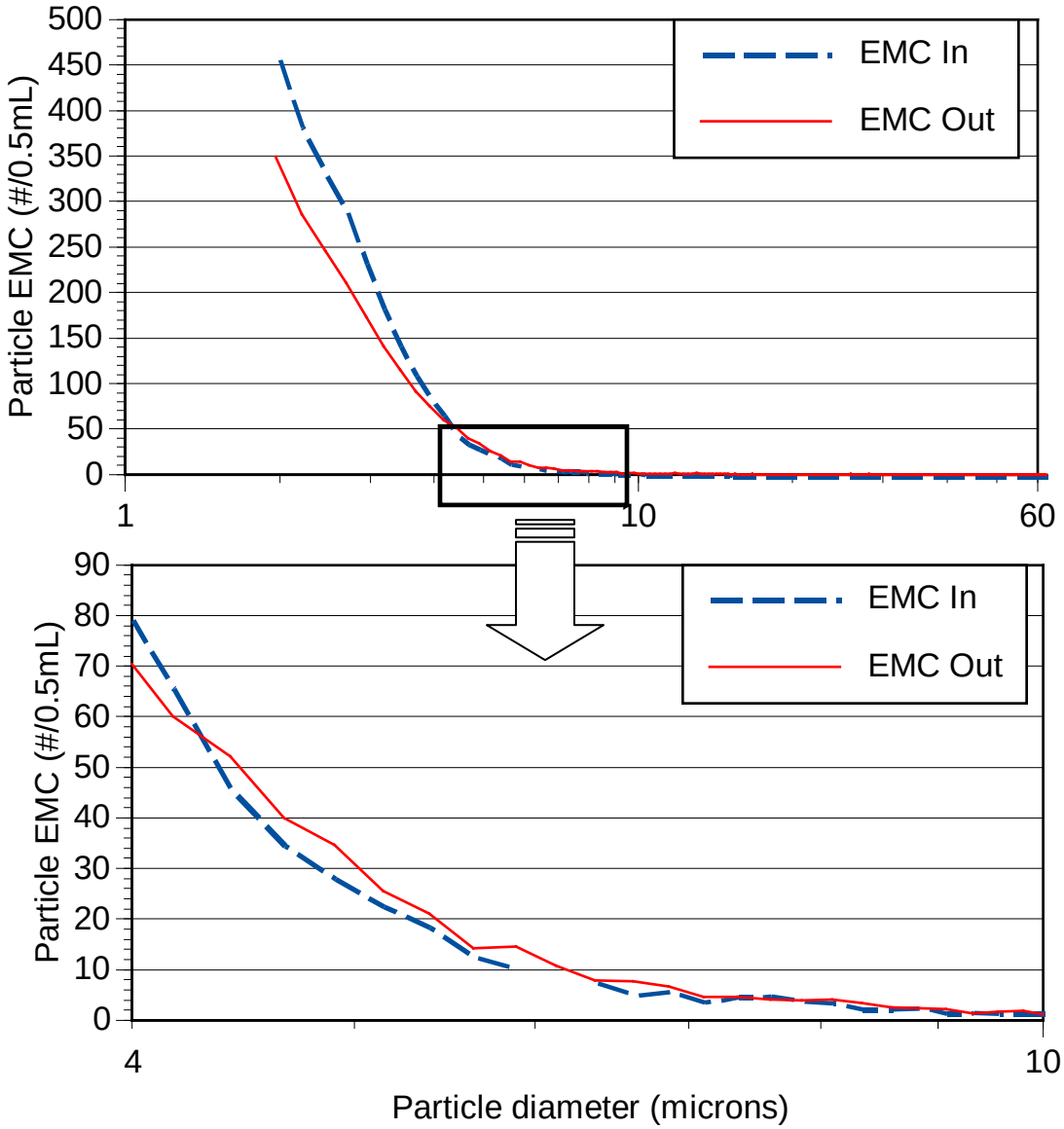
MBER Minimum Rain	0.24	0.20	0.24	0.23	-0.12	-0.39	0.36
MBER No Rain	0.27	0.22	0.26	0.26	-0.09	-0.35	0.38

For this storm event, the efficiency ratio does not change significantly if a mass based efficiency ratio is used with various estimates of rainfall. Since there was a significant volume of storage (which is fairly atypical for this particular pond) available at the beginning of the storm, the rainfall (which would generally bring the MBER down if there were no storage) was more than balanced out by the storage.

Appendix F: Intrastorm Particle Event Mean Concentrations

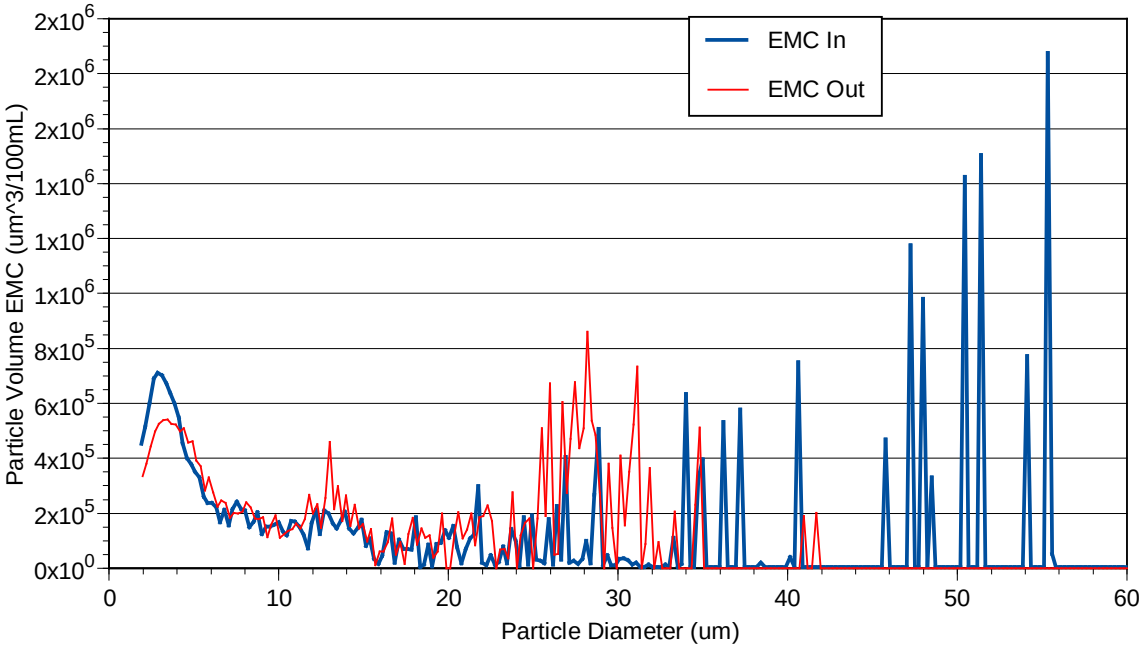
The Event Mean Concentration (EMC) was calculated for each size bin within the entire particle distribution. The EMC was calculated in two manners: *number* of particles per volume of water and *volume* of particles per volume of water. The number concentration was used for most analysis as it is very consistent when multiple measurements are made on the same sample. The volume concentration can change dramatically from one measurement to the next within the same sample since a single large particle will greatly affect the total volume.

Two graphs showing the number event mean concentration are shown below. The top graph shows the entire particle distribution and the bottom graph is focused only on particles with diameters between 4 and 10 microns.



The number concentration of particles smaller than 4 microns appears to greater in the inflow than the outflow, while the number concentration of particles between 4 and 10 micron diameter is slightly higher in the outflow than the inflow. There are very few particles larger than 10 microns in either the outflow or inflow. This graph helps explain why when all particles (diameter 2 to 60 microns) were considered, there was a net removal by the pond, but when only microns with diameters of 5 to 60 were included, the concentration increased from inflow to outflow.

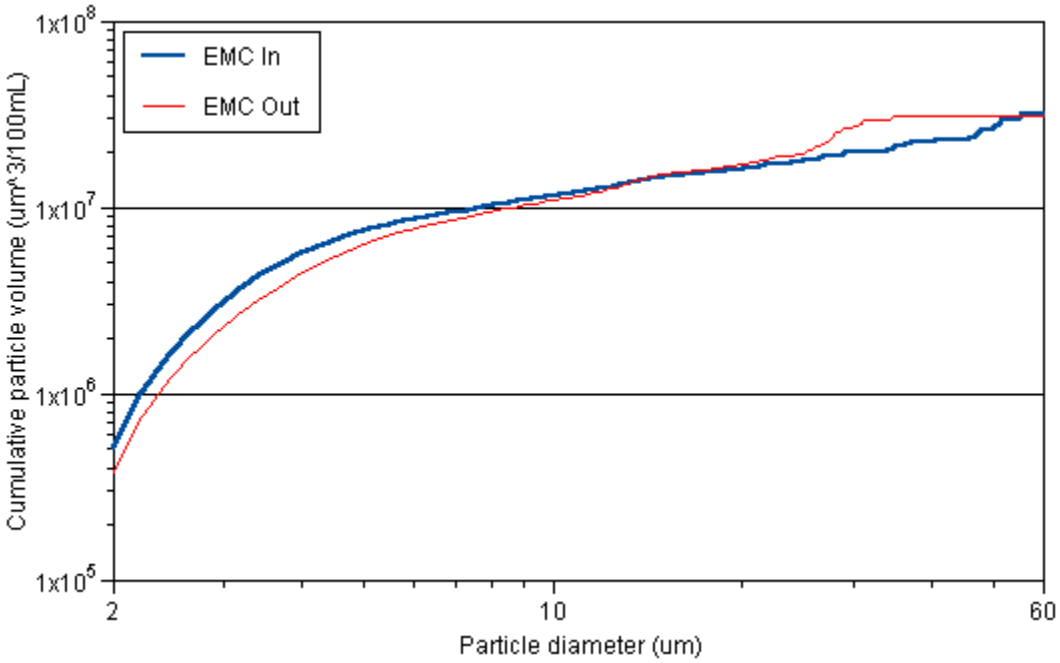
In order to further explore the fate of the particles, the volume EMC was found and graphed across the entire range of particle diameters.



The spikes shown for the larger diameter particles show that one or two larger particles can have a very large effect on total particle volume, although not on the total particle number. This may help explain the net export of TSS within the pond. TSS includes all particles larger than about 1 micron diameter, so if there were just a few large particles in the outflow, their volume and weight could dominate over any effect the pond may have on smaller particles.

Figure 10 in the text is the same as the figure above, but only shows the particles with diameters less than 20 microns. The smallest particles (diameters 2 to 4.4 microns) are reduced by the pond, but those with diameters from 4.4 to about 35 microns generally have higher volume EMCs in the outflow than the inflow. The volume that is lost within the pond by particles with diameters from 2 to 4.4 microns is the same volume that is gained by particles from 4.4 to 13 microns.

The cumulative particle volume EMC is shown in the graph below. The total volume concentration of particles that enter (or exit) the pond with a given diameter or smaller is shown with lines. Note that both axes are on log scales.



The same total volume of particles (diameters from 2 to 60 microns) enters and exits the pond. The inflow and outflow cumulative EMCs also overlaps at particle diameter of 13 microns. This shows that the same volume of particles from 2 to 13 microns enters and exits the pond, as seen in figure 10 in the text.

Appendix G: Storm and Background Concentrations and Confidence Intervals

6/3/2006 Storm		Fecal Coliforms (MPN/100mL)	*E. Coli* (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)		14,939	138	2,710	4,469,022	13
	raw	**19,045**	**307**	**3,557**	**4,534,667**	**13**
		24,280	684	4,668	4,600,312	14
		9,713	49	1,562	1,044,680	15
	centrifuged	**12,129**	**151**	**2,167**	**1,068,667**	**15**
		15,146	470	3,005	1,092,653	15
2 (inflow)		54,529	5,361	18,563	4,739,813	13
	raw	**70,088**	**6,743**	**24,078**	**4,830,000**	**14**
		90,087	8,482	31,230	4,920,187	14
		14,400	3,740	11,270	803,419	13
	centrifuged	**18,309**	**4,794**	**14,135**	**822,667**	**14**
		23,278	6,143	17,727	841,915	14
3 (outflow)		93,482	13,312	41,830	6,836,333	13
	raw	**121,092**	**16,837**	**54,279**	**6,874,000**	**13**
		156,856	21,295	70,432	6,911,667	13
		20,502	7,011	27,075	955,619	14
	centrifuged	**26,780**	**8,754**	**35,659**	**1,004,000**	**14**
		34,981	10,929	46,963	1,052,381	14
4 (runoff)		6,912	25	13,148	3,291,843	4
	raw	**8,632**	**101**	**16,616**	**3,447,333**	**5**
		10,780	403	20,999	3,602,824	5
		4,012	53	6,897	569,800	3
	centrifuged	**5,120**	**86**	**8,614**	**622,000**	**3**
		6,533	141	10,757	674,200	4
5 (inflow)		8,177	398	8,151	3,537,528	7
	raw	**10,195**	**686**	**10,162**	**3,618,667**	**7**
		12,712	1,183	12,671	3,699,805	7
		3,840	403	6,016	625,212	6
	centrifuged	**4,913**	**693**	**7,538**	**782,667**	**6**
		6,286	1,191	9,444	940,121	6
6 (outflow)		22,019	1,344	10,599	12,705,958	7
	raw	**28,875**	**1,898**	**13,264**	**12,830,000**	**7**
		37,867	2,681	16,600	12,954,042	7
		8,422	482	7,062	2,765,294	6
	centrifuged	**10,501**	**800**	**8,816**	**2,927,333**	**6**
		13,093	1,328	11,006	3,089,373	6
7 (NE Creek)		6,977	890	3,425	36,883,597	8
	raw	**8,712**	**1,331**	**4,415**	**37,518,667**	**8**
		10,877	1,990	5,691	38,153,737	8
		1,312	398	664	1,004,608	7
	centrifuged	**1,859**	**686**	**1,040**	**1,072,667**	**7**
		2,633	1,183	1,630	1,140,725	7

6/25/2006 Storm		Fecal Coliforms (MPN/100mL)	*E. Coli* (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)		101,536	8,671	36,894	4,460,383	11.3
	raw	**132,460**	**10,812**	**48,141**	**4,578,667**	**11.7**
		172,801	13,483	62,817	4,696,950	12.0
		97,352	12,079	31,696	1,210,295	11.7
	centrifuged	**126,505**	**15,195**	**41,610**	**1,220,667**	**11.9**
		164,389	19,115	54,624	1,231,038	12.1
2 (inflow)		106,079	4,937	52,932	3,917,078	9.4
	raw	**139,058**	**6,232**	**68,088**	**4,014,667**	**9.5**
		182,290	7,866	87,585	4,112,255	9.6
		47,038	2,979	41,830	1,053,869	9.5
	centrifuged	**60,743**	**3,880**	**54,279**	**1,062,000**	**9.6**
		78,442	5,054	70,432	1,070,131	9.7
3 (outflow)		65,410	4,155	67,480	4,156,767	10.0
	raw	**83,850**	**5,291**	**86,501**	**4,202,000**	**10.2**
		107,488	6,738	110,884	4,247,233	10.4
		71,889	3,577	52,932	998,884	9.7
	centrifuged	**92,190**	**4,598**	**68,088**	**1,027,333**	**9.9**
		118,223	5,909	87,585	1,055,783	10.1
4 (runoff)		142,952	403	47,038	3,850,844	9.8
	raw	**201,416**	**693**	**60,743**	**3,938,000**	**9.8**
		283,789	1,191	78,442	4,025,156	9.9
		153,281	280	29,409	1,046,361	9.4
	centrifuged	**224,982**	**520**	**38,687**	**1,079,333**	**9.9**
		330,221	968	50,893	1,112,306	10.3
5 (inflow)		153,281	36,894	101,536	5,654,370	11.0
	raw	**224,982**	**48,141**	**132,460**	**5,666,000**	**11.3**
		330,221	62,817	172,801	5,677,630	11.6
		167,805	51,386	79,286	1,605,216	12.2
	centrifuged	**>294,969**	**66,158**	**101,877**	**1,666,000**	**12.4**
		518,497	85,176	130,904	1,726,784	12.5
6 (outflow)		167,805	18,921	71,889	5,702,008	7.0
	raw	**>294,969**	**24,578**	**92,190**	**5,788,667**	**7.1**
		518,497	31,925	118,223	5,875,325	7.1
		167,805	34,848	51,386	1,299,673	7.7
	centrifuged	**>294,969**	**45,583**	**66,158**	**1,315,333**	**7.8**
		518,497	59,626	85,176	1,330,994	7.9
7 (NE Creek)		24,347	1,818	17,519	35,729,635	7.5
	raw	**32,039**	**2,479**	**22,619**	**36,566,667**	**7.6**
		42,161	3,380	29,204	37,403,699	7.8
		20,988	1,905	7,832	1,538,620	7.8
	centrifuged	**27,454**	**2,585**	**9,767**	**1,557,333**	**7.8**
		35,912	3,507	12,179	1,576,047	7.9
8 (Post Waterfowl)		16,018	320	1,767	100,299,013	9.8
	raw	**20,532**	**578**	**2,416**	**100,578,667**	**10.0**
		26,317	1,042	3,305	100,858,320	10.1
		6,578	49	969	902,592	9.5
	centrifuged	**8,223**	**152**	**1,430**	**1,024,000**	**9.5**
		10,279	471	2,111	1,145,408	9.6

7/25/2006 Storm		Fecal Coliforms (MPN/100mL)	*E. Coli* (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)		142,952	9,240	33,869	4,464,367	9.1
	raw	**201,416**	**11,530**	**44,354**	**4,589,333**	**9.2**
		283,789	14,386	58,085	4,714,300	9.3
		133,736	5,238	27,825	1,361,169	11.2
	centrifuged	**183,678**	**6,595**	**36,638**	**1,371,333**	**11.3**
		252,271	8,303	48,242	1,381,498	11.5
2 (inflow)		167,805	34,848	125,725	5,866,520	9.1
	raw	**>294,969**	**45,583**	**169,732**	**6,150,667**	**9.1**
		518,497	59,625	229,144	6,434,813	9.1
		142,952	17,364	97,352	822,844	10.3
	centrifuged	**201,416**	**22,403**	**126,505**	**896,667**	**10.6**
		283,789	28,905	164,389	970,489	10.8
3 (outflow)		167,805	23,136	125,725	7,023,136	8.6
	raw	**>294,969**	**30,402**	**169,732**	**7,181,333**	**8.7**
		518,497	39,950	229,144	7,339,531	8.8
		142,952	10,039	86,537	946,962	9.3
	centrifuged	**201,416**	**12,545**	**111,575**	**957,333**	**9.4**
		283,789	15,676	143,859	967,705	9.5
4 (runoff)		153,281	358	16,230	6,186,749	9.0
	raw	**224,982**	**630**	**20,826**	**6,470,000**	**9.1**
		330,221	1,111	26,722	6,753,251	9.3
		142,952	280	15,187	1,500,290	9.1
	centrifuged	**201,416**	**520**	**19,385**	**1,522,000**	**9.2**
		283,789	968	24,744	1,543,710	9.2
5 (inflow)		513,870	19,178	153,854	11,996,583	8.9
	raw	**661,588**	**26,003**	**196,582**	**12,474,000**	**9.0**
		851,770	35,256	251,175	12,951,417	9.0
		234,135	11,827	129,193	1,867,155	9.8
	centrifuged	**307,790**	**16,982**	**163,106**	**1,966,667**	**9.9**
		404,615	24,384	205,921	2,066,179	9.9
6 (outflow)		133,736	8,031	116,451	6,053,318	5.0
	raw	**183,678**	**10,014**	**154,750**	**6,112,000**	**5.1**
		252,271	12,486	205,645	6,170,682	5.3
		93,482	5,396	79,286	1,082,213	5.2
	centrifuged	**121,092**	**6,785**	**101,877**	**1,114,667**	**5.3**
		156,856	8,533	130,904	1,147,120	5.5
7 (NE Creek)		15,637	1,161	30,243	51,040,099	7.0
	raw	**20,005**	**1,672**	**39,758**	**51,337,333**	**7.2**
		25,593	2,406	52,266	51,634,568	7.4
		6,294	837	24,120	1,359,498	7.6
	centrifuged	**7,876**	**1,262**	**31,733**	**1,493,333**	**7.6**
		9,855	1,905	41,750	1,627,169	7.6
8 (Post Waterfowl)		67,480	733	27,825	114,457,087	9.2
	raw	**86,501**	**1,130**	**36,638**	**114,765,333**	**10.0**
		110,884	1,741	48,242	115,073,580	10.9
		21,452	525	20,058	1,596,846	8.7
	centrifuged	**28,095**	**858**	**26,163**	**1,670,667**	**9.1**
		36,795	1,401	34,127	1,744,488	9.4

9/5/2006 Storm		Fecal Coliforms (MPN/100mL)	*E. Coli* (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)	raw					
	centrifuged					
2 (inflow)	raw	29,409	946	4,933	2,399,723	12.6
		38,687	**1,401**	**6,226**	**2,433,333**	**12.6**
		50,893	2,076	7,860	2,466,944	12.7
	centrifuged	23,729	851	4,674	719,748	13.3
		31,206	**1,281**	**5,915**	**772,000**	**13.4**
		41,040	1,928	7,485	824,252	13.4
3 (outflow)	raw	19,586	896	4,257	3,060,902	13.4
		25,505	**1,338**	**5,414**	**3,128,667**	**13.6**
		33,214	1,998	6,885	3,196,431	13.7
	centrifuged	24,070	653	3,238	646,420	14.0
		31,667	**1,026**	**4,190**	**657,333**	**14.1**
		41,661	1,612	5,424	668,246	14.3
4 (runoff)	raw					
	centrifuged					
5 (inflow)	raw	7,222	207	2,468	1,425,745	4.8
		9,012	**414**	**3,265**	**1,479,333**	**4.9**
		11,247	827	4,320	1,532,922	4.9
	centrifuged	7,086	208	2,104	587,576	5.2
		8,845	**416**	**2,827**	**596,000**	**5.3**
		11,041	830	3,796	604,424	5.4
6 (outflow)	raw	8,859	1,088	4,947	2,221,491	6.3
		11,048	**1,581**	**6,244**	**2,238,667**	**6.3**
		13,779	2,295	7,881	2,255,842	6.4
	centrifuged	9,473	569	3,689	623,097	6.1
		11,825	**916**	**4,732**	**640,000**	**6.1**
		14,759	1,475	6,069	656,903	6.2
7 (NE Creek)	raw	**11,598**	**1,076**	**22,566**	25,613,463	9.6
		14,562	1,565	29,625	**25,942,667**	**9.7**
		18,285	2,276	38,892	26,271,870	9.9
	centrifuged	11,114	793	10,563	1,118,904	9.7
		13,932	**1,207**	**13,218**	**1,148,667**	**9.7**
		17,463	1,837	16,541	1,178,429	9.8
8 (Post Waterfowl)	raw	9,264	1,595	11,939	46,488,716	8.9
		11,559	**2,207**	**15,011**	**46,909,333**	**9.1**
		14,423	3,053	18,873	47,329,951	9.3
	centrifuged	9,033	997	11,767	2,257,739	8.4
		11,267	**1,466**	**14,785**	**2,300,667**	**8.5**
		14,055	2,155	18,576	2,343,594	8.7

9/25/2006 Storm		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)	raw					
	centrifuged					
2 (inflow)	raw	1,829	171	49	1,605,530	4.9
		2,493	**359**	**152**	**1,654,667**	**4.9**
		3,241	470	222	1,703,803	5.0
	centrifuged	901	76	49	626,010	5.0
		1,344	**203**	**152**	**638,000**	**5.1**
		1,683	284	222	649,990	5.1
3 (outflow)	raw	10,068	1,584	4,371	1,456,687	7.6
		12,582	**2,193**	**5,550**	**1,468,000**	**7.6**
		16,343	2,825	7,195	1,479,313	7.6
	centrifuged	9,033	1,767	3,476	361,721	7.5
		11,267	**2,416**	**4,477**	**371,333**	**7.6**
		14,534	3,135	5,861	380,946	7.7
4 (runoff)	raw					
	centrifuged					
5 (inflow)	raw	110,234	75,983	56,385	6,976,415	13.6
		138,135	**94,770**	**70,794**	**7,068,000**	**13.7**
		173,099	118,202	85,204	7,159,585	13.9
	centrifuged	39,493	14,989	53,940	1,423,410	12.0
		50,442	**20,889**	**67,835**	**1,433,333**	**12.1**
		510,786	29,790	81,730	1,443,256	12.2
6 (outflow)	raw	7,186	320	2,983	23795	6.7
		8,968	**578**	**3,885**	**24427**	**6.8**
		11,498	732	5,110	25059	6.8
	centrifuged	4,640	322	1,986	3,327	7.2
		5,874	**580**	**2,683**	**3,397**	**7.2**
		7,596	735	3,505	3,467	7.3
7 (NE Creek)	raw	11,178	1,930	6,393	52,593	8.5
		14,014	**2,615**	**7,997**	**54,850**	**8.7**
		18,386	3,410	10,254	57,107	8.8
	centrifuged	3,756	354	3,238	4,800	7.5
		5,287	**743**	**4,190**	**4,820**	**7.6**
		7,656	1,022	5,500	4,840	7.7
8 (Post Waterfowl)	raw	14,893	2,131	9,097	304,264	10.6
		18,982	**2,859**	**11,349**	**305,633**	**11.3**
		26,289	3,747	14,645	307,003	12.0
	centrifuged	4,298	482	4,439	4,029	9.2
		5,463	**800**	**5,633**	**4,053**	**9.3**
		7,086	1,001	7,297	4,078	9.5

10/28/2006 Storm		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)	raw					
	centrifuged					
2 (inflow)	raw	18,647	3,607	30,243	36,181,937	13.6
		25,358	**6,345**	**39,758**	**36,294,000**	**13.7**
		34,483	11,163	51,677	36,406,063	13.7
	centrifuged	7,554	490	25,256	1,591,098	12.1
		11,586	**1,518**	**33,255**	**1,734,667**	**12.3**
		17,769	4,705	43,923	1,878,235	12.5
3 (outflow)	raw	36,670	2,803	32,919	131,197,630	14.0
		47,055	**5,212**	**43,157**	**131,772,000**	**14.3**
		60,381	9,691	55,730	132,346,370	14.5
	centrifuged	20,096	2,803	28,603	1,418,730	13.4
		27,116	**5,212**	**37,647**	**1,450,000**	**13.8**
		36,589	9,691	49,161	1,481,270	14.1
4 (runoff)	raw					
	centrifuged					
5 (inflow)	raw	20,375	4,806	9,419	3,347,821	10.0
		27,454	**7,981**	**13,964**	**3,403,333**	**10.1**
		36,994	13,255	20,700	3,458,846	10.3
	centrifuged	9,527	1,058	2,772	1,278,094	10.2
		14,100	**2,544**	**5,167**	**1,301,333**	**10.2**
		20,867	6,118	9,632	1,324,573	10.2
6 (outflow)	raw	19,585	4,360	10,780	2,421,306	9.2
		26,497	**7,378**	**13,498**	**2,461,333**	**9.3**
		35,847	12,488	20,129	2,501,361	9.3
	centrifuged	12,653	3,587	9,473	1,045,488	9.3
		18,008	**6,317**	**11,825**	**1,051,333**	**9.5**
		25,629	11,126	18,065	1,057,179	9.6
7 (NE Creek)	raw	4,261	911	6,248	37,461,498	8.1
		5,418	**1,358**	**7,820**	**38,344,000**	**8.3**
		9,960	4,486	13,049	39,226,502	8.5
	centrifuged	2,708	525	2,615	1,390,324	8.1
		3,554	**858**	**3,443**	**1,424,667**	**8.2**
		7,492	3,846	7,342	1,459,009	8.2
8 (Post Waterfowl)	raw	7,405	1,007	3,514	66,660,181	8.9
		9,239	**1,479**	**4,521**	**67,032,000**	**9.2**
		14,842	4,651	8,782	67,403,819	9.4
	centrifuged	2,667	245	2,091	786,440	
		3,506	**470**	**2,810**	**813,333**	**8.9**
		7,426	3,556	6,483	840,227	

11/7/2006 Storm		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
1 (runoff)	raw	34,766	281	4,901	7,839,428	8.9
		44,771	**367**	**6,189**	**8,046,000**	**9.2**
		57,655	481	7,815	8,252,572	9.4
	centrifuged	20,244	277	3,223	3,038,292	8.9
		27,296	**363**	**4,173**	**3,150,000**	**9.0**
		36,804	475	5,403	3,261,708	9.1
2 (inflow)	raw	79,262	8,920	10,915	15,309,161	8.8
		98,834	**13,331**	**13,673**	**15,476,667**	**8.9**
		123,237	19,924	17,127	15,644,173	9.0
	centrifuged	70,343	3,607	9,677	1,666,750	9.0
		87,818	**6,345**	**12,083**	**1,731,333**	**9.1**
		109,635	11,163	15,088	1,795,917	9.3
3 (outflow)	raw	136,393	5,296	17,863	35,976,467	10.1
		172,771	**8,636**	**23,099**	**36,520,667**	**10.3**
		218,852	14,083	29,870	37,064,866	10.5
	centrifuged	181,367	3,587	13,177	2,372,523	10.4
		234,816	**6,317**	**16,655**	**2,444,667**	**10.4**
		304,015	11,126	21,052	2,516,810	10.5
4 (runoff)	raw	168,411	383	17,225	8,114,490	10.4
		216,741	**490**	**22,209**	**8,371,333**	**10.5**
		278,941	627	28,634	8,628,176	10.6
	centrifuged	141,077	335	22,566	3,753,925	10.3
		179,109	**433**	**29,625**	**3,797,333**	**10.4**
		227,395	558	38,892	3,840,741	10.4
5 (inflow)	raw	86,307	17,667	23,864	5,573,450	8.1
		107,622	**24,164**	**31,671**	**5,666,000**	**8.2**
		134,202	33,051	42,033	5,758,550	8.3
	centrifuged	95,547	13,211	10,901	2,160,182	7.9
		119,279	**18,699**	**15,827**	**2,166,667**	**8.0**
		148,906	26,467	22,978	2,173,152	8.1
6 (outflow)	raw	78,179	14,269	15,637	3,984,374	5.3
		97,489	**20,004**	**20,005**	**4,022,667**	**5.4**
		121,569	28,044	25,593	4,060,959	5.4
	centrifuged	72,638	16,230	14,650	1,290,709	5.8
		90,641	**22,411**	**18,649**	**1,297,333**	**5.9**
		113,106	30,944	23,740	1,303,957	6.0
7 (NE Creek)	raw	17,707	3,883	7,050	19,414,245	11.9
		22,881	**4,964**	**8,801**	**19,502,667**	**12.0**
		29,567	6,347	10,987	19,591,089	12.1
	centrifuged	19,586	1,304	8,157	1,204,881	11.4
		25,505	**1,849**	**10,170**	**1,219,333**	**11.5**
		33,214	2,622	12,680	1,233,786	11.7
8 (Post Waterfowl)	raw	17,364	3,052	6,185	26,051,258	13.4
		22,403	**3,968**	**7,744**	**26,149,333**	**13.4**
		28,904	5,158	9,694	26,247,409	13.5
	centrifuged	19,153	2,410	5,200	1,567,804	14.1
		24,901	**3,195**	**6,549**	**1,593,333**	**14.3**
		32,375	4,237	8,248	1,618,863	14.4

6/8/2006 Background		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
2 (inflow)		236		3	311,940	3.8
	raw	**314**		**10**	**342,667**	**3.9**
		417		40	373,394	4.0
		157		3	156,651	4.6
	centrifuged	**218**		**10**	**173,333**	**4.7**
		302		40	190,015	4.7
3 (outflow)		1,642		416	1,080,043	6.6
	raw	**2,108**		**529**	**1,368,000**	**6.6**
		2,708		674	1,655,957	6.7
		1,346		327	491,215	7.3
	centrifuged	**1,703**		**422**	**546,667**	**7.4**
		2,155		546	602,118	7.5
5 (inflow)		2,870		94	8,165,924	10.9
	raw	**3,778**		**139**	**9,572,000**	**11.0**
		4,972		207	10,978,076	11.1
		689		40	1,950,693	10.5
	centrifuged	**860**		**68**	**1,998,667**	**10.7**
		1,074		118	2,046,640	10.8
6 (outflow)		5,809		1,277	1,462,110	10.7
	raw	**7,457**		**1,611**	**1,493,333**	**10.8**
		9,571		2,033	1,524,556	10.9
		3,834		869	586,534	12.7
	centrifuged	**4,994**		**1,084**	**612,667**	**13.0**
		6,505		1,352	638,800	13.2
7 (NE Creek)		1,136		165	6,576,625	7.9
	raw	**1,425**		**228**	**6,808,000**	**7.9**
		1,788		314	7,039,375	8.0
		514		149	727,900	
	centrifuged	**648**		**208**	**754,000**	**7.1**
		816		290	780,100	
8 (Post Waterfowl)		1,959		105	12,140,585	8.3
	raw	**2,551**		**154**	**12,380,000**	**8.4**
		3,323		224	12,619,415	8.4
		762		48	497,720	6.5
	centrifuged	**950**		**80**	**540,000**	**6.7**
		1,185		133	582,280	6.8

6/19/06 Background		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
2 (inflow)	raw	536	2	4	357,252	3.8
		674	**5**	**8**	**373,333**	**3.8**
		848	13	17	389,415	3.9
	centrifuged	299	2	2	299,350	6.7
		390	**5**	**5**	**313,333**	**6.9**
		508	13	12	327,316	7.2
3 (outflow)	raw	1,289	20	56	1,555,393	7.9
		1,628	**41**	**91**	**1,582,667**	**8.0**
		2,055	82	146	1,609,941	8.1
	centrifuged	1,372	5	66	502,812	8.6
		1,738	**15**	**103**	**522,000**	**8.9**
		2,203	47	162	541,188	9.2
5 (inflow)	raw	6,794	235	70	3,761,453	5.8
		8,709	**312**	**109**	**3,878,000**	**5.8**
		11,164	415	169	3,994,547	5.9
	centrifuged	3,126	242	40	1,486,830	5.8
		4,105	**321**	**69**	**1,489,333**	**5.8**
		5,392	425	119	1,491,837	5.9
6 (outflow)	raw	5,305	48	137	3,440,770	10.8
		6,824	**80**	**193**	**3,487,333**	**10.9**
		8,778	133	272	3,533,896	11.1
	centrifuged	1,556	36	153	572,289	11.3
		1,990	**63**	**212**	**602,667**	**11.4**
		2,545	111	295	633,045	11.6
7 (NE Creek)	raw	2,715	248	140	7,917,703	9.8
		3,576	**329**	**197**	**8,745,333**	**9.8**
		4,709	434	277	9,572,964	9.9
	centrifuged	772	122	85	1,139,169	8.7
		963	**174**	**127**	**1,159,333**	**8.9**
		1,201	249	192	1,179,498	9.1
8 (NE Creek)	raw	4,852	213	146	24,837,722	8.5
		6,258	**286**	**204**	**25,218,000**	**8.7**
		8,073	384	285	25,598,278	8.8
	centrifuged	856	115	135	559,498	8.0
		1,067	**166**	**191**	**585,333**	**8.2**
		1,331	240	269	611,168	8.4

7/12/06 Background		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
2 (inflow)	raw	1,462	3	269	681,650	3.5
		2,082	**10**	**353**	**689,333**	**3.5**
		2,672	40	464	697,017	3.6
	centrifuged	939	1	206	268,317	3.4
		1,217	**5**	**278**	**280,000**	**3.6**
		1,519	36	374	291,683	3.7
3 (outflow)	raw	11,282	5	370	1,729,705	4.8
		14,915	**15**	**474**	**1,783,333**	**4.9**
		19,717	47	608	1,836,962	5.1
	centrifuged	6,794	3	281	552,896	5.0
		8,709	**10**	**367**	**1,268,240**	**5.1**
		11,164	40	481	1,983,584	5.3
5 (inflow)	raw	11,282	5	200	2,885,199	4.8
		14,915	**15**	**270**	**2,997,333**	**4.8**
		19,717	47	364	3,109,467	4.9
	centrifuged	6,794	3		1,471,149	
		8,709	**10**	**>5**	**1,480,667**	
		11,164	40		1,490,184	
6 (outflow)	raw					
	centrifuged					
7 (NE Creek)	raw	1,706	61	95	4,829,997	7.1
		2,198	**98**	**140**	**4,850,667**	**7.1**
		2,832	155	208	4,871,336	7.1
	centrifuged	916	44	61	915,082	7.4
		1,143	**75**	**97**	**934,667**	**7.4**
		1,426	126	154	954,251	7.5
8 (Post Waterfowl)	raw	2,952	86	181	16,009,368	7.4
		3,884	**129**	**247**	**16,133,333**	**7.5**
		5,109	194	337	16,257,298	7.6
	centrifuged	817	24	130	708,688	6.9
		1,018	**47**	**184**	**733,333**	**7.0**
		1,270	90	261	757,979	7.1

8/14/06 Background		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
2 (inflow)		3,720	2	94	789,569	4.0
	raw	**4,852**	**4**	**117**	**803,333**	**4.0**
		6,329	36	179	817,098	4.1
		2,952	1	73	444,353	4.3
	centrifuged	**3,884**	**3**	**100**	**451,333**	**4.4**
		5,109	105	191	458,314	4.5
3 (outflow)		2,151	17	1,003	1,153,183	5.1
	raw	**2,817**	**36**	**1,253**	**1,160,667**	**5.2**
		3,690	76	1,566	1,168,150	5.2
		2,504	5	682	432,683	10.5
	centrifuged	**3,296**	**15**	**852**	**452,667**	**10.5**
		4,340	47	1,064	472,650	10.6
5 (inflow)		9,387	3	275	9,593,680	6.8
	raw	**12,163**	**10**	**360**	**9,755,333**	**6.9**
		15,760	40	472	9,916,987	6.9
		5,809	8	128	890,125	6.7
	centrifuged	**7,457**	**20**	**182**	**918,000**	**6.8**
		9,571	54	259	945,875	6.8
6 (outflow)	raw					
	centrifuged					
7 (NE Creek)		627	3	44	6,030,836	7.6
	raw	**785**	**10**	**74**	**6,110,667**	**7.6**
		982	40	126	6,190,497	7.6
		794	1	17	1,103,513	9.4
	centrifuged	**990**	**<5**	**36**	**1,115,333**	**9.4**
		1,234	36	75	1,127,153	9.5
8 (Post Waterfowl)		2,791	168	472	7,013,612	7.7
	raw	**3,675**	**230**	**597**	**7,061,333**	**8.1**
		4,839	317	755	7,109,055	8.4
		948	90	267	754,081	9.8
	centrifuged	**1,183**	**134**	**351**	**790,000**	**9.9**
		1,476	200	461	825,919	9.9

10/25/06 Background		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	TOC (mg/L)
2 (inflow)		288	2	48	523,642	3.6
	raw	**422**	**4**	**67**	**535,333**	**3.6**
		608	87	145	547,024	3.6
		256	1	54	280,813	4.2
	centrifuged	**378**	**3**	**74**	**298,000**	**4.3**
		551	106	156	315,187	4.3
3 (outflow)		711	5	351	447,592	4.3
	raw	**887**	**15**	**452**	**453,333**	**4.3**
		1,107	47	582	459,074	4.3
		1,022	11	291	240,802	4.7
	centrifuged	**1,277**	**26**	**379**	**247,333**	**4.8**
		1,597	61	495	253,865	4.8
5 (inflow)		1,886	3	262	665,423	3.9
	raw	**2,449**	**10**	**344**	**681,333**	**4.0**
		3,181	40	453	697,244	4.1
		2,316	8	204	375,532	5.2
	centrifuged	**3,044**	**20**	**275**	**383,333**	**5.3**
		4,000	54	370	391,135	5.3
6 (outflow)		1,520	117	1,224	13,720,023	5.3
	raw	**1,940**	**168**	**1,541**	**14,208,000**	**5.4**
		2,476	242	1,940	14,695,977	5.5
		1,346	48	574	845,141	5.1
	centrifuged	**1,703**	**80**	**721**	**862,667**	**5.2**
		2,155	133	904	880,192	5.3
7 (NE Creek)		459	53	188	2,555,160	7.7
	raw	**582**	**86**	**255**	**2,581,333**	**7.8**
		737	140	347	2,607,506	7.9
		493	24	181	569,097	7.9
	centrifuged	**623**	**47**	**247**	**764,667**	**8.0**
		786	90	336	960,237	8.0
8 (Post Waterfowl)		402	17	100	2,101,601	8.0
	raw	**512**	**36**	**147**	**2,131,333**	**8.2**
		654	76	216	2,161,065	8.3
		467	14	104	436,257	9.4
	centrifuged	**592**	**31**	**152**	**457,333**	**9.5**
		749	69	222	478,410	9.5

Intrastorm 6/3/07 – 6/4/07		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	Particle Concentration d>5um (#/100mL)	TSS (mg/L)	Turbidity (NTU)	TOC (mg/L)
4 (runoff) 3:20AM 6/3/07		3,607		440	2998879	417863			5.6
	raw	**6,345**	**<10**	**743**	**3405333**	**533333**	**8.9**	**10.9**	**5.7**
		11,163		3,722	4201984	759655			5.9
		2,442	3	137	888530	81643			5.9
	centrifuged	**4,688**	**10**	**306**	**926000**	**88667**		**6.3**	**5.9**
		9,003	9,752,285	3,751	999441	102433			6.0
5-1 (inflow) 3:25AM 6/3/07		13,368	40	2,867	2549315	270572			6.1
	raw	**18,893**	**69**	**3,746**	**2754667**	**298667**	**4.7**	**4.2**	**6.2**
		26,701	13,459	7,749	3157156	353733			6.3
		6,089	32	1,684	854594	74179			6.2
	centrifuged	**9,683**	**58**	**2,315**	**962000**	**75333**		**6.3**	**6.4**
		15,399	18,218	5,804	1172515	77597			6.7
5-2 (inflow) 4:40AM 6/3/07		115,769	2,195	31,998	3920476	218310			8.4
	raw	**145,352**	**2,878**	**41,993**	**4143333**	**225333**	**3.3**	**6.3**	**8.6**
		182,494	6,576	54,341	4580133	239100			8.9
		57,176	1,397	27,825	2160505	50487			7.6
	centrifuged	**78,520**	**1,977**	**36,638**	**2555333**	**179333**		**5.1**	**7.9**
		107,831	8,052	47,957	3329197	431872			8.4
6-2 (outflow) 4:45AM 6/3/07		99,209	2,204	5,012	3920503	371423			7.1
	raw	**123,942**	**2,890**	**9,665**	**3924667**	**388667**	**2.4**	**8**	**7.2**
		154,841	6,592	18,638	3932827	422464			7.3
		89,027	1,848	3,541	1327817	88950			7.3
	centrifuged	**111,038**	**2,396**	**7,433**	**1546000**	**114667**		**3.1**	**7.4**
		138,491	5,915	15,604	1973639	165071			7.5

Intrastorm 6/3/07 – 6/4/07		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	Particle Concentration d>5um (#/100mL)	TSS (mg/L)	Turbidity (NTU)	TOC (mg/L)
5-3 (inflow) 5:40AM 6/3/07		148,484	4,311	26,527	8131014	276329			10.8
	raw	**189,207**	**5,587**	**34,939**	**8233333**	**315333**	**2.3**	**10.3**	**11.0**
		241,100	10,181	45,932	8433880	391782			11.3
		78,086	2,642	38,314	1725867	62588			11.4
	centrifuged	**97,374**	**3,480**	**49,910**	**1829333**	**85333**		**6.5**	**11.6**
		121,427	7,391	63,790	2032128	129913			12.0
6-3 (outflow) 5:45AM 6/3/07		116,622	2,270	11,748	3658956	240090			5.1
	raw	**146,470**	**2,980**	**14,760**	**4036667**	**257333**	**2.6**	**4.5**	**5.5**
		183,957	6,715	21,675	4776980	291130			6.4
		60,982	1,791	9,577	873511	50948			5.8
	centrifuged	**76,375**	**2,317**	**11,957**	**1054667**	**62667**		**3.1**	**5.9**
		95,654	5,806	18,229	1409732	85636			6.0
5-4 (inflow) 8:05AM 6/3/07		158,162	1,269	13,030	3053010	178000			10.9
	raw	**227,096**	**1,601**	**18,297**	**3185333**	**190000**	**1.6**	**10.2**	**11.5**
		326,077	4,818	30,041	3444686	213520			12.6
		29,520	529	5,012	968556	76403			12.1
	centrifuged	**42,455**	**729**	**9,665**	**1136667**	**86667**		**6.5**	**12.3**
		61,056	7,274	18,638	1466164	106783			12.6
6-4 (outflow) 8:15AM 6/3/07		122,239	1,959	34,272	4077306	309215			7.2
	raw	**196,359**	**2,551**	**49,818**	**4173333**	**330000**	**2.8**	**5.5**	**7.4**
		277,664	6,129	70,497	4361548	370738			7.6
		46,619	1,686	9,377	1204062	136179			7.2
	centrifuged	**64,652**	**2,170**	**15,877**	**1455333**	**163333**		**3.8**	**7.4**
		89,659	5,603	26,881	1947825	216555			7.8

Intrastorm 6/3/07 – 6/4/07		Fecal Coliforms (MPN/100mL)	E. Coli (MPN/100 mL	Enterococci (MPN/100mL)	Particle Concentration (#/100mL)	Particle Concentration d>5um (#/100mL)	TSS (mg/L)	Turbidity (NTU)	TOC (mg/L)
5-5 (inflow) 3:10PM 6/3/07		33,869	1,674	5,573	4006788	341729			14.9
	raw	**44,354**	**2,304**	**7,000**	**4050667**	**364000**	**3.9**	**9.4**	**15.4**
		57,158	5,788	12,004	4136669	407651			16.4
		28,603	1,715	3,989	1269556	145250			15.6
	centrifuged	**37,647**	**2,354**	**5,092**	**1396000**	**153333**		**7.4**	**15.7**
		49,161	5,857	9,533	1643830	169176			15.9
6-5 (outflow) 3:15PM 6/3/07		36,894	1,818	9,138	3732041	311689			9.4
	raw	**48,141**	**2,479**	**11,400**	**3880000**	**343333**	**5.0**	**5.7**	**9.5**
		61,677	6,029	17,539	4170001	405355			9.8
		31,106	1,055	3,726	1035070	122178			10.6
	centrifuged	**40,860**	**1,538**	**4,776**	**1501333**	**212000**		**6.4**	**10.7**
		52,991	4,732	9,118	2415209	388051			10.9
5-6 (inflow) 8:45AM 6/4/07		24,347	121	76	5379634	1585326			9.0
	raw	**32,039**	**173**	**203**	**5506667**	**1644667**	**12.5**	**9.2**	**9.1**
		42,472	4,837	4,398	5755651	1760975			9.3
		14,406	75	107	1317200	498636			8.5
	centrifuged	**18,317**	**115**	**256**	**1337333**	**520667**		**7.2**	**8.6**
		26,004	6,860	3,962	1376794	563846			8.8
6-6 (outflow) 8:50AM 6/4/07		16,164	212	1,058	5339939	727255			8.0
	raw	**20,733**	**284**	**1,542**	**5391333**	**761333**	**15.8**	**22.9**	**8.1**
		28,924	3,826	4,737	5492065	828127			8.3
		9,117	85	642	779824	177132			9.8
	centrifuged	**11,373**	**127**	**1,011**	**814000**	**192667**		**10.5**	**9.9**
		17,506	6,171	4,031	880985	223115			10.0