The Role of Stormwater Research in BMP Design – Pathogens and Regulatory Demands

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Abstract

The U.S. Environmental Protection Agency strives to protect human health, ensure the safety of drinking and recreational waters, support economic and recreational activities, and provide healthy habitat for fish, plants, and wildlife. To accomplish these objectives, the Agency emphasizes restoring and maintaining our oceans, watersheds, and their aquatic ecosystems. Urbanization results in more impervious areas that cause larger quantities of stormwater runoff. This runoff can contribute significant amounts of pollutants (e.g., litter, oils, microorganisms, sediments, nutrients, organic matter, and heavy metals) to receiving waters.

To improve water quality in urban and suburban areas, watershed managers often incorporate structural best management practices (BMPs) to remove or reduce pollutants contained in stormwater runoff. In this project, constructed wetlands and retention ponds were evaluated for reducing microbial concentrations from urban stormwater runoff. Several studies have looked at the capabilities of these BMPs to reduce pollutant concentrations and loadings. Few studies, however, have focused on the internal mechanisms occurring in these BMPs and fewer yet on using these BMPs for treating microbial pollutants.

Preliminary results indicate both types of BMPs can lower microbial concentrations from urban stormwater runoff. Retention ponds had greater removal rates for enterococci and *E. coli* in June and September sampling events. However, further reduction may be limited by irreducible concentrations contained in the urban stormwater runoff and/or the sediments entering into or existing within the BMPs. The disparity in results may be due to light, temperature, and predation differences between the two treatments.

The Problem

The U.S. Environmental Protection Agency (U.S. EPA) strives to protect human health, ensure the safety of drinking and recreational waters, support economic and recreational activities, and provide healthy habitat for fish, plants, and wildlife. To meet these objectives, the Agency emphasizes restoring and maintaining our oceans, watersheds, and their aquatic ecosystems. Urbanization results in increased impervious areas that cause larger quantities of stormwater runoff and contribute significant amounts of debris and pollutants (e.g., litter, oils, microorganisms, sediments, nutrients, organic matter, and heavy metals) to receiving waters. To improve receiving water quality in urban and suburban areas, watershed managers often incorporate structural best management practices (BMPs) to remove debris and treat pollutants contained in stormwater runoff. The overall objective of this project is to investigate the use of constructed wetlands and retention ponds to reduce microbial concentrations from urban stormwater runoff.

BMPs are often considered as effective tools to help mitigate the impacts of urbanization on our receiving waters. With numerical requirements for meeting Total Maximum Daily Loads (TMDLs) becoming a reality, stormwater managers are counting on structural and nonstructural BMPs to help meet the regulatory restrictions on receiving water quality.

Two commonly used BMPs are constructed wetlands and retention ponds. Many studies have evaluated the capabilities of retention ponds and constructed wetlands to reduce solids and nutrient concentrations and loadings. Few studies have focused on the internal mechanisms relating to the efficacy of these BMPs and fewer yet on the application of these BMPs for treating microbial pollutants. Preliminary results from this project indicate both types of BMPs can lower microbial concentrations from urban stormwater runoff. However, further reduction may be limited by irreducible concentrations contained in the urban stormwater runoff or the sediments entering into the BMPs.

Background and Objectives

Where waters of the nation are not meeting appropriate water quality standards (WQS) after implementation of technology-based effluent limits or other pollution control programs, the Federal Clean Water Act (CWA) 1992 Amendments require that TMDLs be established for pollutants of concern.

Under this program, states must: (1) identify waters that do not meet WQS after application of existing control requirements, and prioritize those listed waters; and (2) for each water body, a TMDL must be determined for each pollutant causing a WQS violation.

TMDLs provide a framework that strengthens efforts to improve water quality. TMDLs also identify pollutant reduction goals needed to meet WQS. Therefore, a TMDL is comprised of the maximum load of a pollutant that a water body can receive and continue to be able to meet state WQS.

The goal of an ambient water quality management program, of which the TMDL program is an example, is to measure the condition of a water body and then determine whether that water body is meeting WQS. By definition, this process is dependent on the setting of appropriate WQS. Although realistic standard setting must account for watershed (hydrologic, ecological, and land use) conditions, the corresponding need to make policy decisions in setting standards must also be recognized.

As part of the 1987 amendments to the CWA, Congress added Section 402(p) to the Act to cover discharges composed entirely of stormwater. Section 402(p)(2) of the Act requires permit coverage for discharges associated with industrial activity and discharges from large and medium municipal separate storm sewer systems (MS4), i.e., systems serving a population more than 250,000 or systems serving a population between 100,000 and 250,000, respectively. These discharges are referred to as Phase I MS-4 discharges.

The U.S. EPA issued regulations on December 8, 1999 (64 FR 68722), expanding the National Pollutant Discharge Elimination System (NPDES) stormwater program to include discharges from smaller MS4s (including all systems within "urbanized areas" and other systems serving populations less than 100,000) and stormwater discharges from construction sites that disturb one to five acres, with opportunities for area-specific exclusions. This program expansion is referred to as Phase II.

The U.S. EPA also states that BMPs are appropriate controls to limit the discharge of stormwater pollutants. If it is determined that a BMP approach (including an iterative BMP approach or treatment train) is appropriate to meet the stormwater component of the TMDL, U.S. EPA recommends that the TMDL reflect this.

With pathogens listed as the highest number of reported impairments in U.S. waterbodies (7742 reported impairments, Table 1) and second for the number of TMDL allocations approved (2608 TMDLs, Table 2), this pollutant is obviously one of high concern.

Table 1: Top Six Pollutant Impairments for Determining TMDL Allocations (U.S. EPA, 2004)

General Impairment Name	Impairments Reported	Percent of Reported
PATHOGENS	7742	14.24
METALS	6581	12.11
NUTRIENTS	5600	10.30
SEDIMENT/SILTATION	5046	9.28
ORGANIC ENRICHMENT/ LOW DO	4397	8.09
FISH CONSUMPTION ADVISORIES	3194	5.88
pH	2686	4.94

Of the 2608 approved TMDL allocations, over 84% are from fecal coliforms. The reason for a greater number of fecal coliform TMDLs is that many states use fecal coliforms as the major bacterial indicator for enteric or bacterial contamination in surface waters.

To calculate the reduction in effluent pollutant concentrations for developing TMDL allocations, the effectiveness of BMPs must be well established. Much of the information on BMP effectiveness comes from current literature and the American Society of Civil Engineers (ASCE) International BMP Database. In general, information on the removal of fecal indicators from wastewater by constructed wetlands is well documented (Bavor et al., 1987; Gersberg et al., 1987; Ottová et al., 1997). Percent removal for fecal streptococci and coliforms generally exceeded 80% and 90%, respectively (Kadlec and Knight, 1996). Gersberg et al., (1987) and Garcia and Bécares (1997) concluded that extensively vegetated systems had significantly higher removal rates of indicator bacteria from wastewater compared to unvegetated systems. Both the Nationwide Urban Runoff Program (U.S. EPA, 1983) as well as others (Francy et al., 2000; Mallin et al., 2000; Selvakumar and Borst, *In Press*; Young and Thackston, 1999) have suggested that land use is an important parameter in predicting microbial concentrations in stormwater. Much of this literature reports high microbial concentrations in agricultural and urban settings. Animal manures are the likely source in agricultural areas but microbial sources in urban areas may come from cross connections between wastewater and stormwater pipes, illicit connections, combined sewer overflow or sanitary sewer overflow discharges, or many other potential sources (Burton and Pitt, 2001; Perdek et al., 2003).

Table 2: List of Approved TMDL Allocations by General Pollutant (Top Seven) since January 1, 1996 (U.S. EPA, 2004)

General Pollutant	Number of TMDLs Approved	Percent of Reported
METALS	2736	19.95
PATHOGENS	2608	19.02
NUTRIENTS	1714	12.50
SEDIMENT/SILTATION	1320	9.63
ORGANIC ENRICHMENT/LOW DO	1148	8.37
UNIONIZED AMMONIA	580	4.23
THERMAL MODIFICATIONS	552	4.03

It is important to recognize that BMPs are not a means of chemical disinfection, but rather a tool to increase those factors that promote natural inactivation or die-off of microorganisms. Therefore, determining the dominant or controlling mechanisms of stormwater bacterial and pathogen removal by these treatment systems is an important step in predicting trends in effluent concentrations to meet state WQS and developing TMDLs. Selvakumar (personal communication) examined the time-temperature relationship at the bench scale. Few quantitative studies have been carried out, however, at the pilot or field scale to determine the relative importance of various removal mechanisms by constructed wetlands and retention ponds on indicator organism concentrations. Consequently, the ability of these BMP treatments to meet water quality standards are poorly understood.

Historically, total and fecal coliforms and fecal streptococci have served as the preferred indicators. Recent efforts have led to recommendations to substitute enterococci and *E. coli* for water quality monitoring because of higher correlation with gastrointestinal illness (Gray, 2000).

The primary objectives of this ongoing study are to:

(1) Test the effects of two types of structural BMPs (retention pond and cattail wetland) on the reduction of influent concentrations of indicator microorganisms (total coliforms, fecal coliforms, *E. coli*, and enterococci) from stormwater;
(2) Evaluate the concentrations of indicator microorganisms in stormwater runoff over time as they flow through the BMP treatments; and
(3) Assess the accumulation of indicator microorganisms in sediments of each treatment practice.

This pilot study also incorporates bench-scale research (both completed and ongoing) that investigates the effects of temperature, salinity, and light on inactivation rates of bacterial indicator species.

Study Site and Experimental Design

Two rectangular mesocosms of the same size with two different stormwater BMP treatments (constructed wetland and retention pond) were constructed at the Urban Watershed Research Facility (UWRF) in Edison, New Jersey. Stormwater runoff from the Middlesex County College (9.75 acres) campus was collected from an outfall near the UWRF and stored on site (Figure 1). An aliquot of stormwater was collected for each sampling event and placed in growth media encouraging growth of the desired organisms.

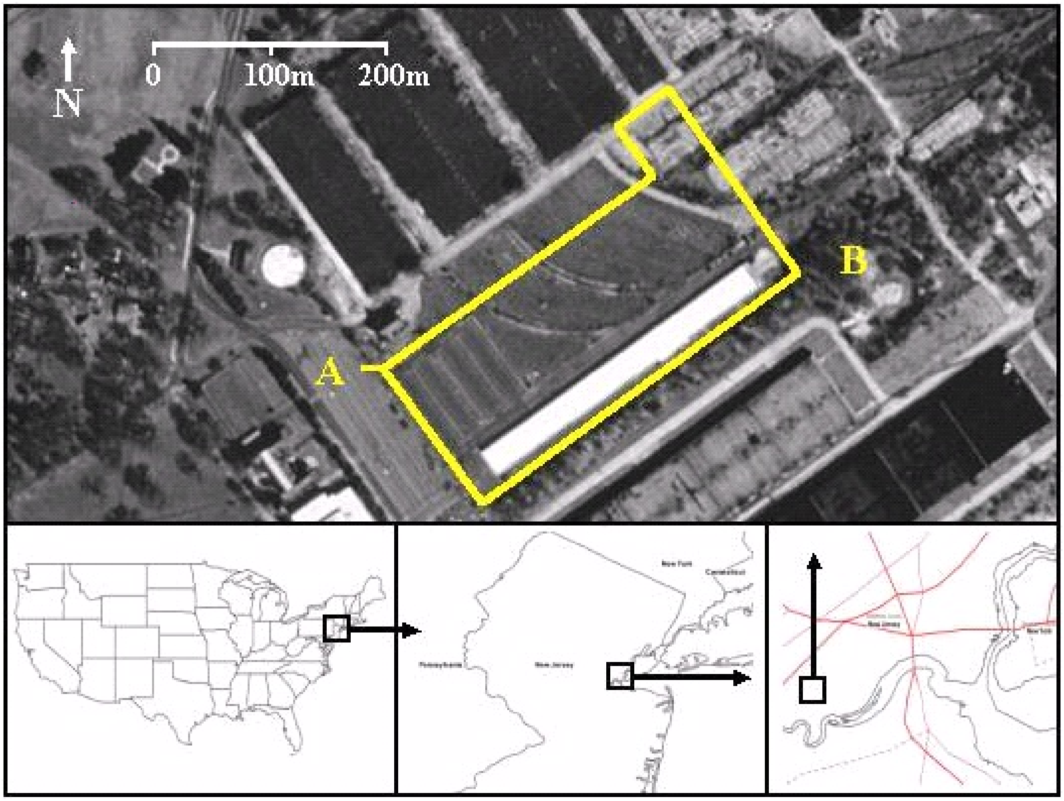

Figure 1. (A) Drainage area and (B)outfall location of the study in Edison, New Jersey.

Microorganism concentrations in this inoculated stormwater were measured along with the stored stormwater so, when combined, the microbial concentrations would represent the upper range of concentrations reported for urban stormwater runoff (U.S. EPA, 1983). The inoculated aliquot and stormwater were mixed and then distributed to the mesocosms. Water quality sondes measured temperature, dissolved oxygen (DO), pH, and turbidity. Influent and timed effluent concentrations of microbial indicator species were measured. Three of eight planned sampling events (June, September, and November) have been completed to date.

Yellow Springs Instruments (YSI Environmental Incorporated, Yellow Springs, OH 45387) data sondes were used to monitor water quality parameters on a 10-min time step before, during, and after experimental events to assess the general temporal and mesocosm-to-mesocosm water quality. The parameters measured include: DO, conductivity, temperature, pH, and turbidity. Using a Monitor Sensors (Monitor Sensors –Australia, Brendale, Queensland, Australia 4500) weather station, air temperature, relative humidity, barometric pressure, wind speed, wind direction, solar radiation, and rainfall were recorded.

The overall inactivation rates from each treatment were determined assuming the first order decay equation known as Chick's Law.

Chick's Law is defined as:

$$C_t = C_0 e^{-kt}$$

where, C_t = Concentration of microorganisms at time "t", colony forming units (CFU)/100 ml; C_o = Concentration of microorganisms at time "0", CFU/100 ml; e = natural log exponential function; k = overall inactivation rate constant; t = time, hr.

The overall inactivation rate constant is a function of the factors shown in the equation:

$$\boldsymbol{k = f\,(k_f\,, k_T, k_l, k_s\,, k_p\,, k_o\,)}$$

where, k = overall inactivation rate constant, 1/hr; k_f = inactivation due to adsorption, filtration, and sedimentation, 1/hr; k_T = inactivation due to temperature, 1/hr; k_l = inactivation due to solar radiation, 1/hr; k_s = inactivation due to salinity, 1/hr; k_p = inactivation due to predation, 1/hr; and k_o= inactivation due to other factors (such as pH, DO, conductivity), 1/hr.

The slope of a least squared linear regression of the natural logarithm of the microorganism concentrations on elapsed time was used to calculate the inactivation rate constant under the natural experimental conditions (i.e., temperature, pH, DO, solar radiation).

Preliminary Results and Discussion

Physical and chemical parameters measured in the study are listed in Table 3. Water temperatures were lower in the constructed wetland compared to the retention pond, which was likely due to shading from the macrophytic vegetation (*Typha latifolia*, with an average stem density of 39.3 stems/m^2). This temperature difference

Table 3. Average Physical and Chemical Results from the Retention Pond and Constructed Wetland Mesocosms for the Duration of the Experiment

Month	Temperature (°C)		Irradiance (Kj/m^2/day)	DO (mg/l)		pH		Turbidity (mg/l)	
	Pond	Wtlnd		Pond	Wtlnd	Pond	Wtlnd	Pond	Wtlnd
June	24.4	23.18	14.9	6.4	7.2	8.1	6.9	10.5	3.4
September	21.1	18.02	12.3	8.1	5.1	7.8	6.4	10.1	5.7
November	7.98	6.50	9.5	11.7	12.1	7.3	6.4	5.0	6.8

was larger in September than in June. DO increased in the retention pond between the two events and decreased in the constructed wetland. The pH was nearly the same between sampling events for each treatment, but was over a 1 pH unit higher in the retention pond compared to the constructed wetland. Likewise, turbidity showed little variation between sampling events, though turbidity, on average, was 60% lower in the constructed wetland compared to the retention pond. The shallower depth of free water volume and contribution of standing and dead biomass in the constructed wetland mesocosm may explain some of these differences in physical water quality parameters between the two systems.

E.coli data collected to date allowed a comparison of inactivation rates over the physical conditions in June, September, and October. Total coliforms, fecal coliforms, and enterococci were also collected in the September and November sampling dates.

There was a statistically significant decrease in microbial inactivation rates of *E.coli* in both treatments between June and September (Table 4). This difference may be due to changes in temperature and solar radiation between the sampling dates. These variables are expected to be covariants of one another.

Inactivation rates for *E.coli* were not significantly different between treatments for either sampling date. However, inactivation rates for total coliforms and enterococci were significantly lower in the constructed wetland compared to the retention pond for the September sampling event.

Table 4. Indicator Species Inactivation Rate Constants

Month	Organism	Retention Pond (hr^{-1})	Constructed Wetland (hr^{-1})
June	*E. coli*	0.165 ± 0.005	0.173 ± 0.018
September	*E. coli*	0.134 ± 0.004	0.138 ± 0.004
	Total Coliform	0.170 ± 0.009	0.121 ± 0.006
	Fecal Coliform	0.153 ± 0.006	0.148 ± 0.006
	Enterococci	0.240 ± 0.007	0.137 ± 0.004
November	*E. coli*	0.133 ± 0.007	0.152 ± 0.009
	Total Coliform	0.203 ± 0.016	0.105 ± 0.003
	Fecal Coliform	0.142 ± 0.014	0.138 ± 0.008
	Enterococci	0.199 ± 0.017	0.119 ± 0.004

When comparing these results to the literature, the inactivation rates are at the high end of other values reported for the same organisms. This may be due to the higher initial microorganism concentrations (typically $10^6 – 10^8$) used in this study.

November values in general were higher in microbial concentrations than June or September (Figure 2). Again, these differences may be explained by changes in ambient temperature, DO, or solar radiation.

Indicator species concentrations from Figure 2 show a background concentration of $10^1 – 10^4$ organisms/100 ml. Kadlec and Knight (1996) suggest that because of residual indicator bacteria populations present in wetlands, bacteria removal efficiency is a function of the inflow bacteria population size. Removal efficiency typically is higher at high inflow concentrations, but declines to low or negative efficiencies when inflow concentrations are lower than the *in situ* bacteria productions rates. This fact is lost, however, when the influent flow rates are turbulent, causing resuspension of the previously settled solids. Because these settled sediments are associated with *in situ* bacteria populations, there may be an increase in effluent concentrations of indicator bacteria with high flows, which can occur in poorly designed or aging wetland and retention pond BMPs. This may result in low or negative inactivation rates under higher flow conditions.

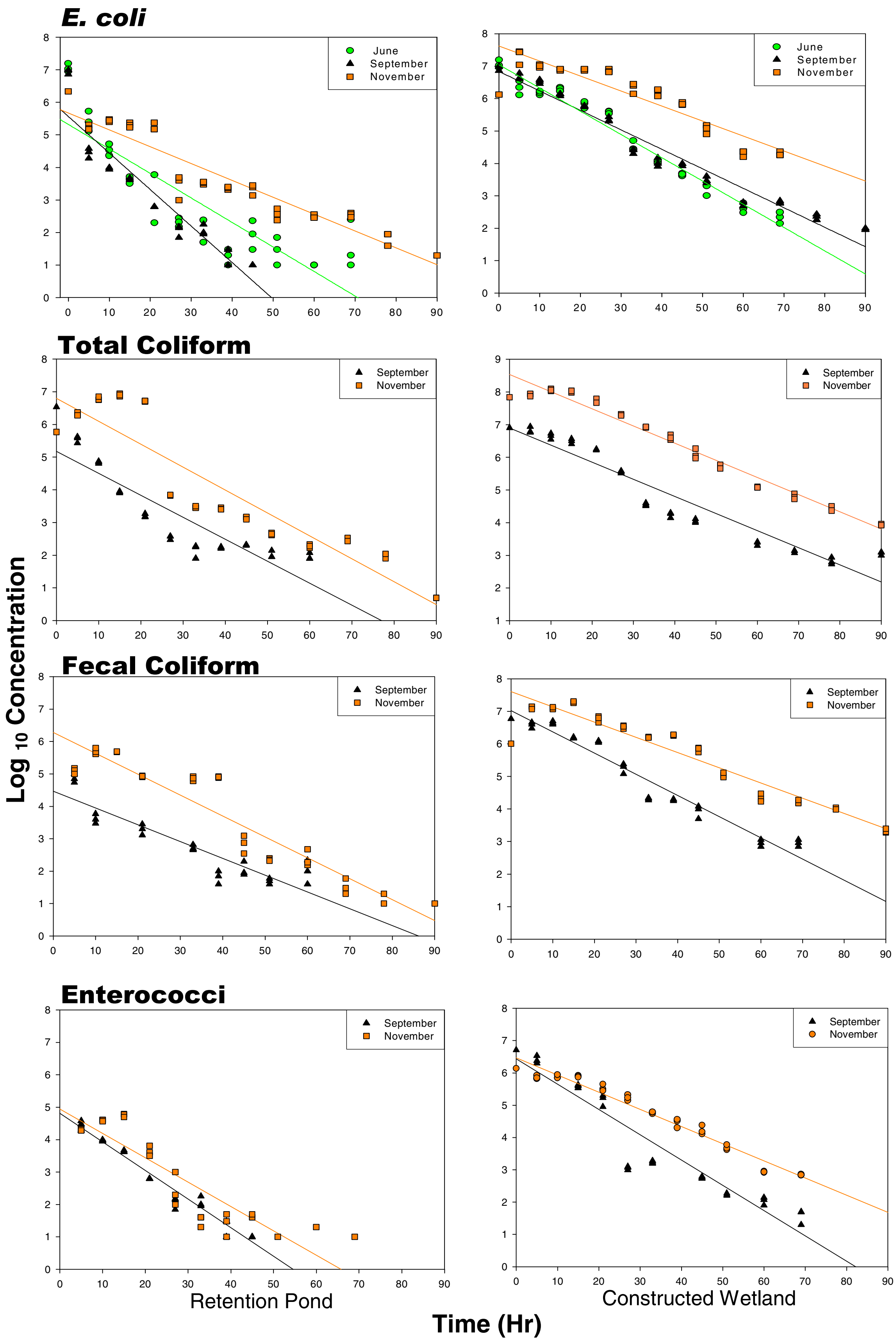

Figure 2. Effluent concentrations of indicator organisms.

Conclusions

The development of microbial inactivation models to predict effluent concentrations within constructed wetland and retention pond BMPs will aid in reducing the uncertainty and add to the accuracy of surface water quality models in determining bacterial TMDL allocations.

Structural BMPs may be effective in reducing a portion of the microbial concentrations contained in urban stormwater runoff. Low inactivation rates may occur in BMPs where inflow bacterial concentrations are lower than the *in situ* bacteria productions rates, or turbulent flow through the BMPs, causes resuspension of sediments. Placement of BMPs in urban watersheds can lead to improvements in receiving water quality by reducing the overall load to receiving waters. If stormwater managers can reduce microbial loads in water bodies using structural BMPs, verification of this stormwater management tool will help MS-4 Phase I and Phase II communities reduce microbial loading and meet requirements set out by the TMDL process. Long-term microbial load reductions will improve the overall water quality and could potentially lead to increased consumption of fish and shellfish, increased use of recreational waters, reduced beach closures, and increased protection of source water used as drinking water sources. However, the limitations of BMP effectivenessin eliminating all bacterial loading without chemical treatment must be recognized. In addition, overall effectiveness and efficiencies of BMPs hinge on proper design and maintenance of these systems.

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