ABSTRACT

BAIRD, JOSHUA BRUCE. Evaluating the Hydrologic and Water Quality Performance of Infiltrating Wet Retention Ponds. (Under the direction of Dr. William F. Hunt, III).

Wet retention basins have typically been designed to temporarily capture and slowly release stormwater to mitigate peak flow rates and remove particulate-bound pollutants. However, in locations such as Fayetteville, North Carolina with Hydrologic Group A soils, wet retention basins may provide additional stormwater benefits through infiltration and evaporation. Designers must line these basins with bentonite (or other impermeable clay) to prevent infiltration and to comply with NC Department of Environmental and Natural Resources (NCDENR) design requirements. Intuitively, a pond that infiltrates influent and reduces effluent volume while still mitigating peak flows of large storms could be acceptable to NCDENR. Currently a lack of data exists to assess how well infiltrating ponds work, thus no guidance is provided for their design. Two wet retention basins were monitored in Fayetteville to assess the hydrologic and water quality performance of infiltrating wet retention basins. Monthly volume reductions were as high as 100% at both wet ponds. Peak flow rates were significantly reduced at both ponds with median peak flow rate reductions of 99%. Of the influent volume at the Bingham pond, 6% evaporated from the surface, 54% infiltrated, and 40% left as outflow. Of the influent volume at the Raeford pond, 5% evaporated from the surface, 46% infiltrated, and 49% left as outflow. At the Bingham pond, nitrate/nitrite ($NO_{2,3}$), total ammoniacal nitrogen (TAN), ortho-phosphate (ortho-P), total phosphorus (TP) and total suspended solids (TSS) concentrations were significantly reduced from inlet to outlet. The organic nitrogen (ON) concentrations were significantly higher at the outlet. The median percent reductions were 8 and 74% for TP and TSS, respectively. At

the Raeford pond, $NO_{2,3}$, total nitrogen (TN), TAN, ortho-P, TP and TSS concentrations were significantly reduced from inlet to outlet. The median percent reductions were 37, 42, and 73% for TN, TP and TSS, respectively. The effluent concentrations appeared to be on par with other non-infiltrating wet ponds monitored in North Carolina. Both ponds had significant reductions in loads for all pollutants monitored. At the Bingham pond, organic nitrogen concentrations were significantly higher at the outlet, however, the organic nitrogen load was significantly reduced with a percent reduction of 37%. Supplement design guidance was also provided, including clay liners, vegetative shelf elevations and plant selection.

Evaluating the Hydrologic and Water Quality Performance of
Infiltrating Wet Retention Ponds

by
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DEDICATION

For the preservation of our water resources and the works of His hands

BIOGRAPHY

Born August 12, 1987 to Bruce and Sharon Baird, Joshua Baird, grew up in Eastern North Carolina. Growing up Joshua enjoyed being outdoors and found a passion for the environment. To this day, Joshua enjoys being on the water and has a found a love for water skiing and scuba diving off the NC coast. After graduating from high school, Joshua was accepted to NC State University where he graduated in 2009 with a Bachelor's degree in Zoology. Following graduation, Joshua began working from a contract research organization in Research Triangle Park. In 2010, Joshua married Ruthanne Hardy. After working for three years with the contract research organization, Joshua returned to NC State to pursue his Master of Science in Biological and Agriculture Engineering under the direction of Dr. William F. Hunt, III. He is passionate about incorporating his biological background into the Biological and Agriculture Engineering Masters program. Joshua's Master's research work assessed the hydrologic and water quality performance of infiltrating wet ponds in Fayetteville, NC.

ACKNOWLEDGMENTS

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1.1 Stormwater

The hydrology of a landscape is typically determined by the amounts of precipitation, infiltration, evapotranspiration (ET), and surface runoff. The amount of rainfall is location and climate-dependent. Infiltration is determined by the underlying soil characteristics and the slope of the landscape. ET is a function of the climate, season, type of vegetation and density of vegetation. Precipitation that does not infiltrate or evapotranspire leaves the landscape as surface runoff. The amount of surface runoff depends on the balance with respect to infiltration and evapotranspiration. In a typical undeveloped forested landscape, approximately 5% of precipitation leaves the site as surface runoff on an annual basis (Figure 1.1) (Swift et al., 1987). Development alters a site's hydrology and disrupts the hydrologic balance. Development and urbanization increases impervious surfaces including rooftops, roadways, and parking lots increasing runoff and vegetation removal can substantially reduce the amount of ET from a landscape. Annual surface runoff a developed watershed, is approximately 55% of precipitation (Figure 1.2) (Environmental Protection Agency, 1993a).

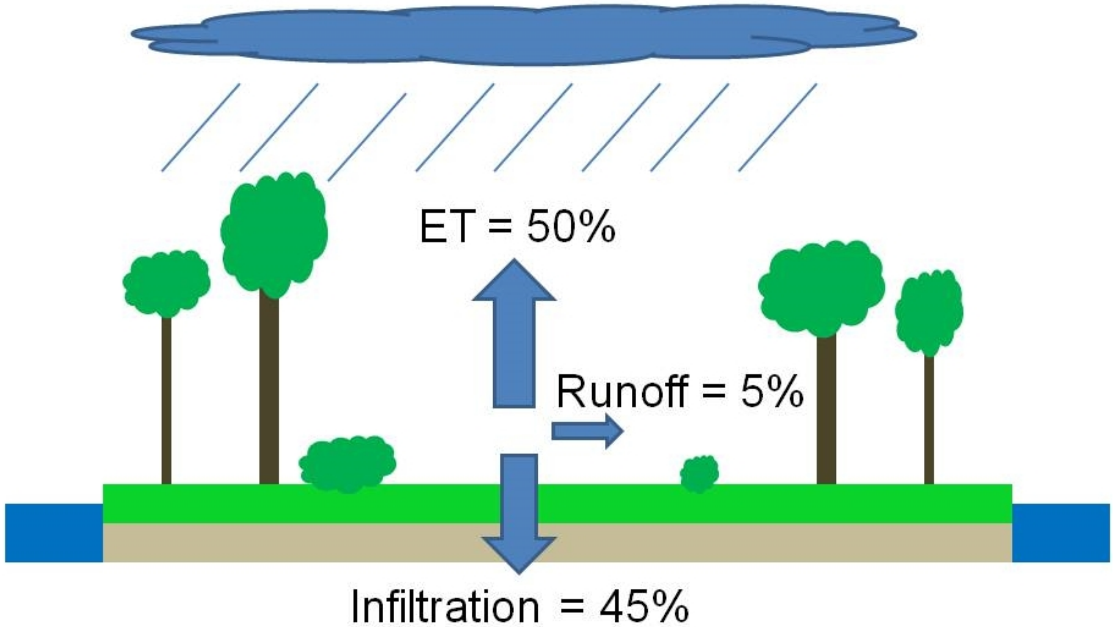


Figure 1.1: Annual rainfall allocation in forested watersheds (Swift et al., 1987)

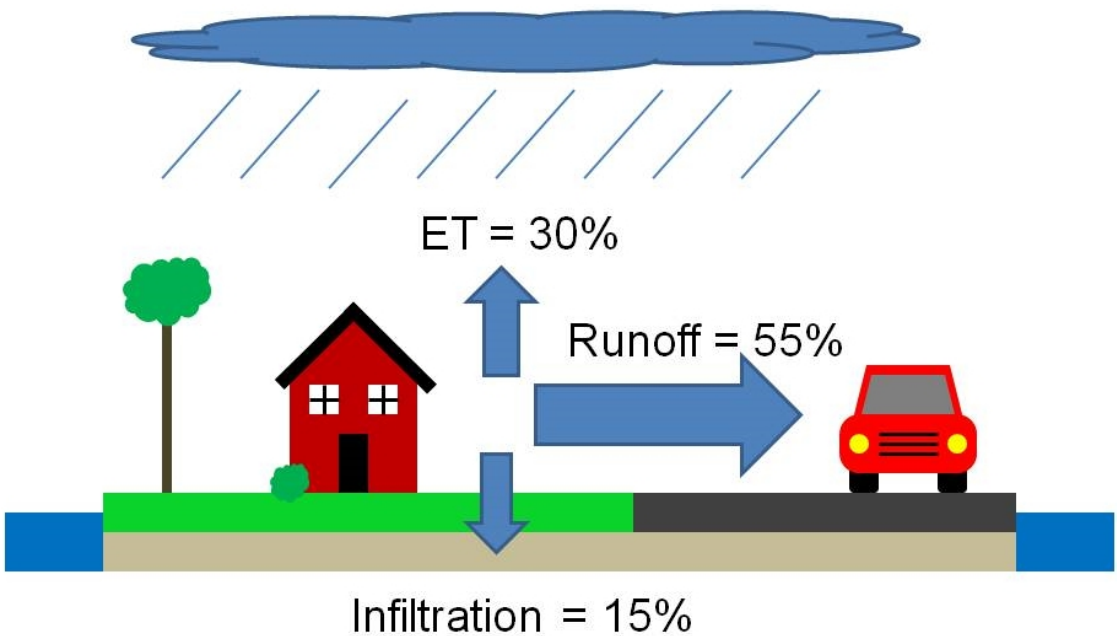


Figure 1.2: Annual rainfall allocation in developed (75-100%) watersheds (Environmental Protection Agency, 1993a)

This increase in surface runoff caused by urbanization has negative effects. Originally, urban drainage systems were designed to quickly convey stormwater away from developed areas. This strategy targeted localized urban flooding, but increased downstream peak flow rates and flooding due to shortened lag times (Leopold, 1968). Increasing impervious cover commensurately increases peak flow rates (Jennings and Jarnagin, 2002) (Figure 1.3). The energy associated with higher flow rates erodes channel banks, causing stream bank instability (Leopold, 1968; Walsh et al., 2001). Moreover, as the water flows over land, it collects and transports pollutants such as nutrients, metals, pathogens, and particulates (Figure 1.4) (Bannerman et al., 1993; Line and White, 2007). Impervious surfaces have elevated temperatures due to a shift in the energy balance and transfer heat to runoff, leading to increased thermal loads (Jones and Hunt, 2010).

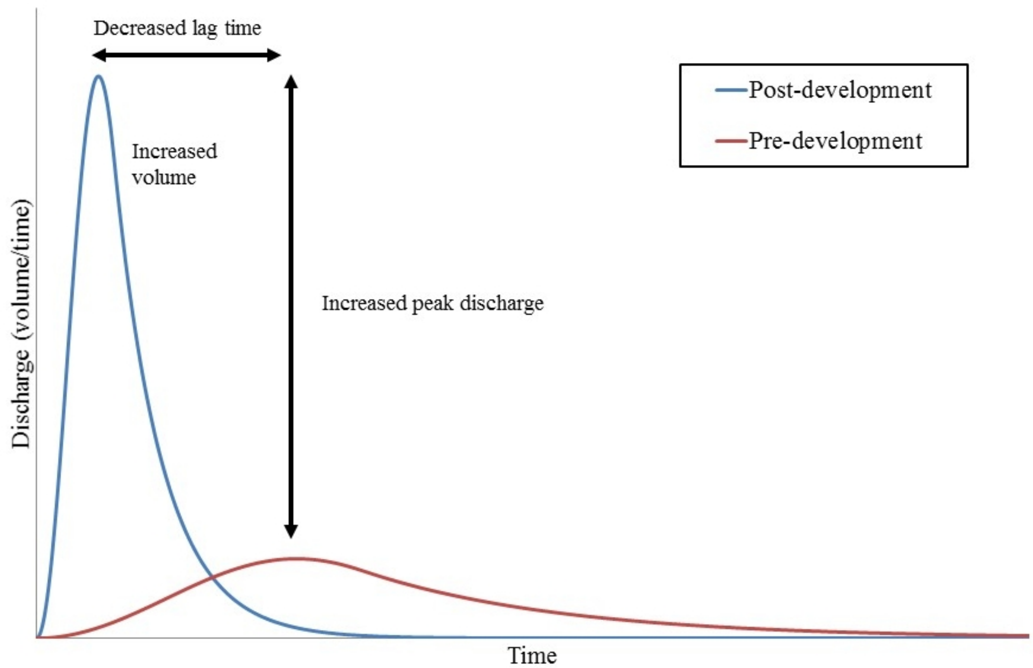


Figure 1.3: Hypothetical pre-development and post-development hydrographs


Figure 1.4: Stormwater carrying sediment and other pollutants

1.2 Stormwater Regulations

In response to the effects of stormwater, federal and state regulations have been enacted. In 1972, the Clean Water Act was established to “restore and maintain the chemical, physical, and biological integrity of the nation’s waters” (US EPA, 2014). Originally focused on point source pollution, non-point source pollution became a critical component of the legislation. Phase I of the National Pollution Discharge Elimination System (NPDES) was enacted in 1990 as part of the Clean Water Act, requiring municipalities with greater than 100,000 people with separate stormwater sewer systems to regulate stormwater runoff. Phase II of NPDES was enacted in 2003 and required all municipalities in metropolitan areas with greater than 50,000 people with separate stormwater sewer systems to regulate stormwater runoff (US EPA, 2005).

There are also stormwater regulations at the state level to protect certain water resources. Coastal communities and communities within the Tar-Pamlico River basin, Neuse River basin, Jordan Lake watershed and others have specific regulations aimed at reducing nutrients to waterways (NCDENR, 2009).

1.3 Wet Retention Ponds

To mitigate stormwater’s adverse impacts and comply with regulations, engineers and designers use a wide variety of stormwater control measures (SCMs). SCMs employ a variety of pollutant removal mechanisms and can improve the hydrologic condition downstream. One of the most common practices in North Carolina is the wet retention pond (referred to as “wet ponds” hereafter) (Figure 1.5).

Figure 1.5: Wet retention pond with forebay in foreground

Originally designed to control flooding during major storms, wet ponds were later adopted to improve stormwater quality (Hvitved-Jacobsen et al., 1990). Wet ponds are basins that receive runoff from a watershed. They are designed to have a permanent presence (or pool) of water. The basin has additional capacity above the permanent pool to store and slowly release a design storm. Pond elevations and release of water are controlled by an outlet structure, including a point of overflow and below that, a drawdown orifice. The latter sets the permanent pool and controls slow release of the treated stormwater. Wet ponds are designed with a forebay to collect sediment and allow for its easy removal (Figure 1.5 and Figure 1.6). Wet ponds may also contain a vegetated shelf along the pond's edge (Figure 1.6).

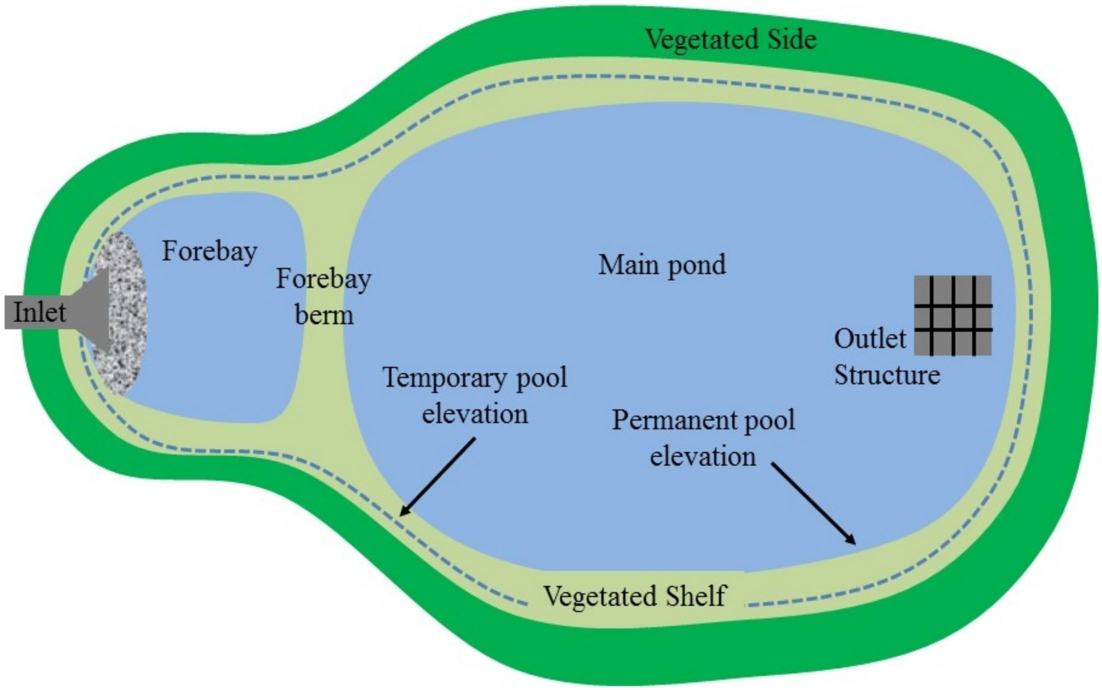


Figure 1.6: Plan view of basic wet pond design elements

1.4 Pollutant Removal Credits

Based on research and an understanding of SCM pollutant removal mechanisms, the State of North Carolina awards total suspended solids (TSS), total phosphorus (TP), and total nitrogen (TN) removal credits to SCMs. These removal credits are used by designers and engineers to determine the best SCM for a site to satisfy regulatory requirements. The state of

North Carolina awards wet ponds with 85% TSS removal, 25% TN removal and 40% TP removal (Table 1.1) (NCDENR, 2009). The state does acknowledge peak runoff attenuation, but no runoff reduction. The SCM is considered a flow-through system with no reduction to influent volume. For a wet pond to receive pollutant removal credits it must be designed and function as outlined in the North Carolina Department of Environmental and Natural Resources (NC DENR) Best Management Practices Manual (NCDENR, 2009). For wet ponds, the water-quality design storage is required to be above the normal pool, and the pond must discharge the water-quality treatment volume completely over a period of 2 to 5 days (NCDENR, 2009).

Table 1.1: Regulatory credits awarded to wet ponds by the State of North Carolina (NCDENR, 2009)

Pollutant Removal	
Total Suspended Solids	85%
Total Nitrogen	25%
Total Phosphorus	40%
Water Quantity	
Peak Runoff Attenuation	yes
Runoff Volume Reduction	no

1.5 Infiltrating Wet Retention Ponds

Due to sandy soils and water table fluctuations in the sandhills of North Carolina, many wet ponds do not maintain a permanent pool of water (at the intended elevation) year-round due to infiltration (Figure 1.7). However, because these practices retain some water for more than 48 hours, they likewise do not comply with the NC DENR design guidance for infiltration basins (NCDENR, 2009). Infiltrating wet ponds are in a NCDENR “no man’s land.” Infiltrating wet ponds lack performance assessment and design guidance. Government officials struggle to determine how much pollutant removal credit should be awarded to this SCM. Currently, pond designers are asked to line these devices with bentonite clay (or other impermeable liner) (Figure 1.8) so that the wet pond retains water and provides a 2-5 day drawdown (NCDENR, 2009). However, lining wet ponds can be costly, and installation can be difficult with varying results. Furthermore, infiltration is an accepted mechanism in other SCMs such as bioretention, permeable pavement and infiltration basins. Thus, a wet pond that partially infiltrates is potentially an acceptable practice. It is possible that an infiltrating wet pond over sandy soils will not only reduce peak flow rates, but also substantially reduce volumes. A comprehensive peer-reviewed study on the hydrology and water quality performance of infiltrating wet ponds has not been completed to date.

Figure 1.7: Example of a wet pond that is infiltrating and not holding a permanent pool of water

Figure 1.8: Example of bentonite/clay liner above permeable soil

1.6 Literature Review

1.6.1 Effect of Wet Ponds on Hydrology

Wet ponds are designed to control peak discharges, but typically do not substantially reduce runoff volume. Hancock et al. (2010) evaluated the hydrology of five wet ponds within the Chesapeake Bay watershed over a four-year period. Four of the five ponds failed to meet the regulatory requirement of a 24-hour inflow-to-outflow centroid lag time for the one-year, 24-hour design storm event. The researchers reasoned this to be due to an oversimplified calculation for the outlet structure orifice. Hancock et al. (2010) also found that the peak inflows were higher than what the pond was designed for and concluded that these wet retention ponds failed to meet the regulatory goals of this type of SCM. Another study found that wet ponds have minimal peak flow attenuation for smaller, more common storms, but did improve the hydrology for larger, less frequent storms (Ferrara and Witkowski, 1983).

Emerson et al. (2005) evaluated the effectiveness of wet ponds as a network on a watershed scale. By modeling six measured storm events, they found that watershed-wide peak flow rates were only reduced by an average of 0.3%. For one particular downstream location, there was no apparent difference in watershed hydrographs between watersheds with and without wet ponds. The authors concluded that design and management begins at the site level, but the effectiveness should be viewed from a watershed-wide scale (Emerson et al., 2005).

1.6.2 Effects of Wet ponds on Water Quality

The mechanisms by which wet ponds remove pollutants include sedimentation, biodegradation, adsorption, and plant uptake, with the key pollutant removal mechanism being sedimentation (Nix et al., 1988). By reducing the energy of incoming stormwater and providing time for particles to settle, wet ponds remove suspended solids with sorbed pollutants. Ferrara and Witkowski (1983) found wet ponds effective in removing TP, and solids; however, total kjeldahl nitrogen (TKN) concentrations increased. The extent to which pollutants were removed was thought to be primarily due to sedimentation. The effectiveness of sedimentation depended on the particle size distribution. Pollutant removal was higher for more intense storms which carried larger sized particles that quickly settled under gravity (Ferrara and Witkowski, 1983).

Mallin et al. (2002) evaluated monthly inflow and outflow for three wet ponds in Wilmington, North Carolina, for 29 months. One wet pond was characterized by high length-to-width ratio and had high removal rates of TN, ammonium, TP, orthophosphate (ortho-P), and fecal coliform bacteria. In another pond, inflow entered at the middle and lower sections which led to significant reductions in turbidity and fecal coliform bacteria. Removal efficacy of nutrients was likely reduced due to stormwater short-circuiting most of the pond. A third pond was located on a golf course and had significant increases in nitrate, ammonium, TP, and ortho-P. A strong correlation existed between the concentrations of TSS and phosphorus, indicating phosphorus was solid-borne. Wet ponds’ efficacy can be increased by having a high length-to-width ratio and planting aquatic macrophyte plant species (Mallin et al., 2002).

Wu et al. (1996) studied three wet ponds in the Piedmont of North Carolina to evaluate pollutant removal rates as a function of wet pond surface to drainage area ratios. Pollutants monitored included TSS, TKN, ammonia nitrogen (NH_3-N), TP, ortho-P and dissolved metals (lead, zinc, copper, and iron). Wu et al., (1996) found that the surface area to drainage ratio could be a predictor in determining the performance of a wet pond, recommending a ratio of 1-2% to meet target water quality standards.

Comings et al. (2000) studied two wet ponds in Bellevue, Washington, and found that both ponds removed TSS. TP removal rates were 46% and 19%, while those of soluble phosphorous were 62% and 3%. Krometis et al. (2009) concluded that wet ponds were most effective if located close to the upland drainage areas where contaminants are first collected (Krometis et al., 2009). Wet ponds can also effectively remove polycyclic aromatic hydrocarbons (PAHs) (Istenic et al., 2011). Jones and Hunt (2010) conducted a study in Western North Carolina to determine the effects of wet ponds and constructed stormwater wetlands on the temperature of stormwater. The inflow temperatures during summer months were found to be significantly higher than the 21°C threshold for trout and temperatures were also consistently higher at the wet pond outlet that at the inlet.

Winston et al. (2013) evaluated a floating hydroponic system with wetland vegetation growing within as retrofit to wet ponds. These floating treatment wetlands contained a medium for vegetation to grow and remove nutrients including those soluble nutrients that do not settle from pond water. When compared with the pre-retrofit monitoring, a wet pond with

18% water surface area coverage showed a statistically significant improvement post-retrofit for TP and TSS removal. However, a wet pond with 9% water surface area coverage showed no statistically significant improvement when compared to the pre-retrofit monitoring. The increased capture efficacy of the wet pond with 18% surface area coverage was thought to be due to wetland plants stilling water and promoting increased sedimentation.

The pollutant removal efficiencies of wet ponds have been documented in literature. Table 1.2 highlights mean effluent pollutant concentrations from some wet ponds that have been monitored in North Carolina and Washington. The concentrations are reported as the amount of nitrogen or phosphorus in each form.

Table 1.2: Mean effluent concentrations (in mg/L) from monitored wet ponds

Location	Reference	TKN	NO_x	TN	TAN	Ortho-P	TP	TSS
Pond A	Comings et al. (2000)	NA	NA	NA	NA	0.01	0.08	8.9
Pond C	Comings et al. (2000)	NA	NA	NA	NA	0.01	0.05	2.9
DOT (pre-retrofit)	Winston et al. (2013)	0.97	0.08	1.05	0.11	0.12	0.17	30
Museum (pre-retrofit)	Winston et al. (2013)	0.35	0.06	0.41	0.05	0.07	0.11	24
Ann McCrary	Mallin et al. (2002)	NA	NA	0.65	0.06	0.03	0.05	4
Silver Stream	Mallin et al. (2002)	NA	NA	0.51	0.04	0.02	0.06	6
Echo Farms Golf	Mallin et al. (2002)	NA	NA	0.62	0.08	0.04	0.07	4
Lakeside	Wu et al. (1996)	0.59	NA	NA	NA	NA	0.08	7
Waterford	Wu et al. (1996)	0.73	NA	NA	NA	NA	0.11	44
Runaway Bay	Wu et al. (1996)	0.63	NA	NA	NA	NA	0.08	22

1.6.3 Ecosystem Services

Additionally, wet ponds can provide ecosystem services, including biodiversity, carbon sequestration, aesthetics, recreation and education opportunities. Wet ponds have the potential to create an aquatic habitat within an urban landscape. Wet ponds with vegetated littoral shelves can contribute to carbon sequestration and increased predatory insect presence (Moore and Hunt, 2012). Wet ponds located within highway corridors can contribute to the biodiversity of the area and habitat connectivity (Le Viol et al., 2012).

On the negative side, semi-aquatic and aquatic wildlife species can be exposed to increased pollutants in wet ponds. These aquatic habitats are threatened by chemical and physical environmental stressors. Also, wet ponds located near airports with heavy traffic pose a hazard to aviation safety due to the number of avian species attracted by wet ponds (Fox et al., 2013). Due to the permanent pool of water, unmaintained wet ponds can be an optimum breeding habitat for mosquitoes and contain several different species of said pest (Hunt et al., 2006).

2 Objectives

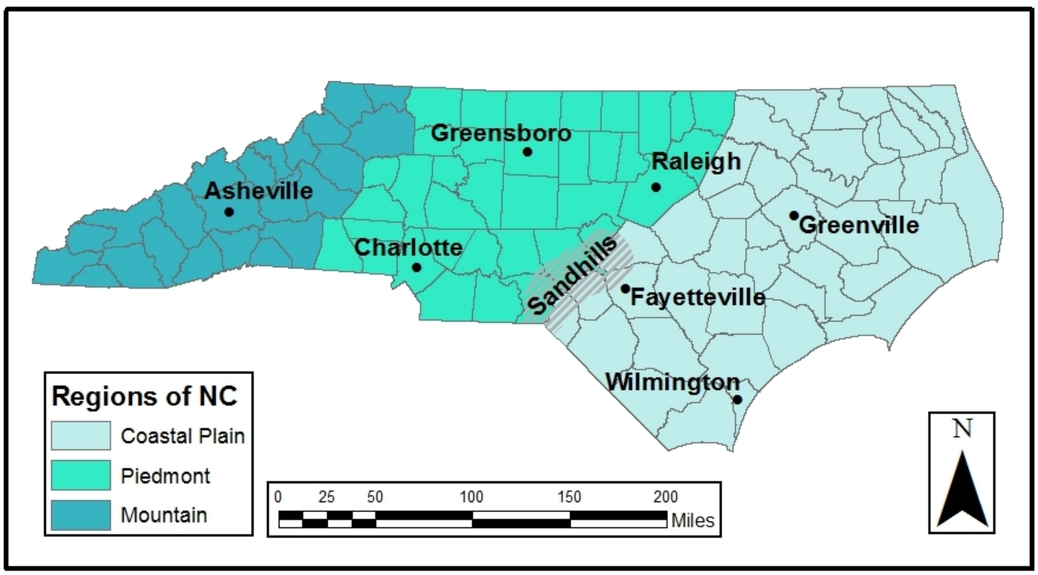
The review of literature established the need to study wet ponds that infiltrate. The primary goal of this research is to assess the hydrologic and water quality performance of wet ponds that infiltrate, thus not reliably maintaining a permanent pool of water and thereby not meeting current standards.

The first objective was to assess the effects of infiltration on monthly, seasonal and annual water budgets. The water budget considered the components of rainfall on the pond, surface inflow, outflow, evaporation and infiltration. The second objective was to assess how well infiltrating wet ponds removed pollutants. The final objective was to develop design guidance to help engineers and designers maximize the performance and pollutant crediting of wet ponds that infiltrate.

3 Materials and Methods

3.1 Site Descriptions

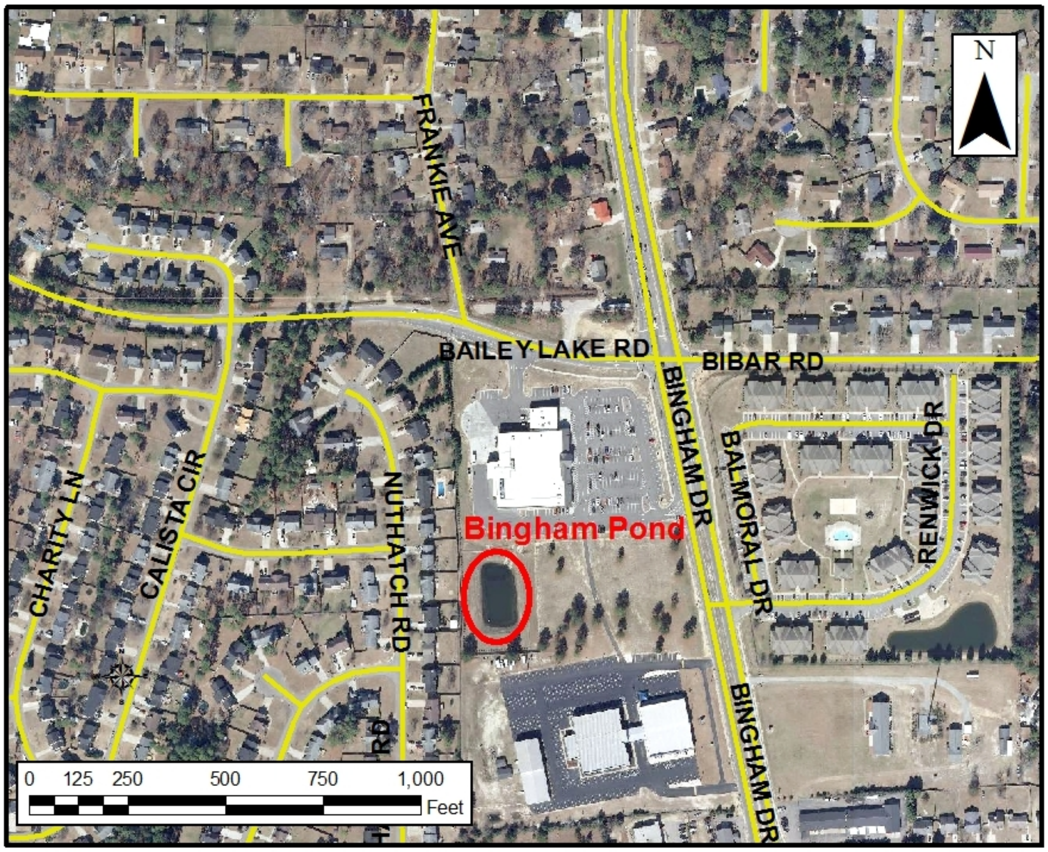
The project site was located in Fayetteville, North Carolina (population 204,000, (U.S. Census Bureau, 2014)), the border of the Coastal Plain and Sandhills region of North Carolina (Figure 3.1). Normal mean temperatures range from 6 °C in January to 27 °C in July, and the average rainfall is 1186 mm (State Climate Office of North Carolina, 2014).



Data from NC DOT and ArcGIS Online

Figure 3.1: Location of Fayetteville, NC

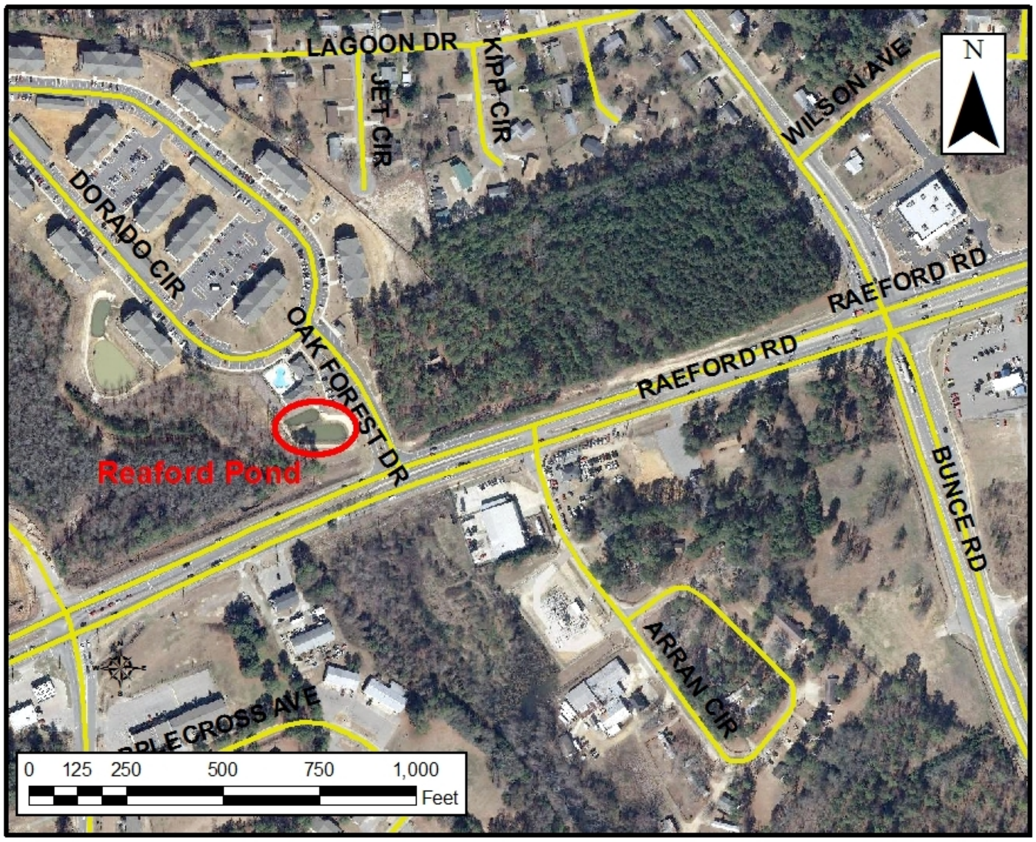
Two existing wet retention ponds were identified in December of 2012 for monitoring during 2013 and 2014. The ponds were selected based on monitoring feasibility and geographic proximity, which was important to reduce climatic variation between the two sites. The two wet ponds selected located within the Cape Fear river basin were 2.95-km apart. One wet pond (hereafter referred to as Bingham pond) was installed at a shopping center at the corner of Bingham Drive and Bailey Lake road (Figure 3.2) (Appendix A). The shopping center consisted of a grocery store and several smaller retail businesses. The 2.37-ha drainage area to the pond was 77% impervious (parking lot and rooftop) with 0.55-ha of pervious vegetated shoulders and medians. The surface area of the pond at permanent pool elevation was 0.12-ha, with a forebay comprising approximately 20% of the pond's surface area. The outlet structure was a 3-m diameter circular riser with a 5-cm diameter drawdown orifice. The Cumberland County, NC soil survey indicated that the underlying soils are Autryville loamy sand (Soil Survey Staff, 2012). Pre-construction infiltration testing showed infiltration rates of 356-mm/hr and 399-mm/hr below the basin. A 25-cm clay liner was installed, however, the clay liner did not hold water at the normal pool for 48-hours. The contractor applied 1089-kg of bentonite on top of the clay liner and the city inspector allowed the pond operation. The pond was fringed by a vegetated shelf covered with native grasses.



Data from NC oneMap and Cumberland County GIS

Figure 3.2: Aerial view of Bingham Pond and surrounding areas

The other wet pond (hereafter referred to as Raeford pond) was built at an apartment complex located on Raeford road (Figure 3.3) (Appendix A). The 1.94-ha drainage area comprises impervious parking area, rooftops and vegetated areas around each building unit and is 44% impervious. The surface area of the pond at the permanent pool elevation was 0.08-ha with a forebay surface area approximately 20% of the main pond's surface area. The outlet structure was a square riser, 1.5-m x 1.5-m, with a 3.8-cm diameter low-flow orifice. The Cumberland County soil survey indicated that the underlying soils were Candor sand (Soil Survey Staff, 2012). Both wet ponds were frequented by Canada geese (*Branta* *anadensis*), and mallard ducks (*Anas platyrhychos*). Table 3.1 summarizes the site characteristics.



Data from NC OneMap and Cumberland County GIS

Figure 3.3: Aerial view of Raeford Pond and surrounding area

Table 3.1: Summary of site characteristics

	Bingham pond	Raeford pond
Coordinates	35°0’58”N 78°59’11”W	35°2’30”N 78°59’43”W
Date construction was completed	Mar-11	Jun-12
Surface area at permanent pool (ha)	0.12	0.08
Forebay Area (%)	20	20
Underlying Soil/HSG	Autryville loamy sand/A	Candor sand/A
Drainage Area (ha)	2.37	1.94
Impervious Area (ha)	1.82	0.85
% Impervious	77	44
Loading Ratio (area)	20:1	24:1
Depth to SHWT (m)	>1	<1
Pre-construction infiltration rates (mm/hr)	356/399	NA
Outlet Structure	3 m diameter round riser	1.5 x1.5 m square riser
Drawdown Orifice (cm)	5	3.8
Temp. water quality ponding depth (m)	0.45	0.9

HSG – Hydrologic Soil Group
SHWT – Seasonal High Water Table

3.2 Methods

3.2.1 Design

To monitor the water quality and hydrology at each pond, monitoring equipment was installed at each inlet and outlet in May 2013. At the Bingham pond, inflow entered via a 90-cm reinforced concrete pipe (RCP). The invert of the pipe was below the top of the outlet structure and therefore, a compound weir could not be used for flow measurements at the inlet because of the potential for submergence. Therefore, an ISCO 750 area velocity meter (AVM) was used to measure inflow and provide input to an ISCO 6712 automated sampler for flow-paced composite samples (Table 3.2) (Figure 3.4). The level of water within the

RCP and velocity of water were recorded at a two-minute interval. All sampling equipment was powered by a marine deep cycle 12-volt battery that maintained a charge via a 5-watt solar panel. At the outlet, an ISCO 6712 automated sampler was installed with an ISCO 730 bubbler module measuring flow via a compound weir fitted inside the riser. The compound weir had a 15.2-cm – 45° v-notch below a 70.1-cm high rectangular weir with a 61-cm crest length (Figure 3.4). The stage of water above the weir was recorded at a two minute interval. The sample intake strainers were affixed either to the bottom of the RCP or to the inside bottom of the outlet structure in an area of well-mixed flow.

Figure 3.4: Clockwise from top: AVM module at Bingham inlet, compound weir at Bingham outlet, and ISCO 6712 sampler and deep cycle battery in housing

At the Raeford pond, inflow entered via a 60-cm RCP (hereafter referred to as inlet 1) and a 38-cm RCP (hereafter referred to as inlet 2). ISCO 6712 automated samplers and ISCO 730 bubbler flow modules with appropriately sized compound weirs were placed at both inlet 1 and the outlet. At inlet 1, the compound weir consisted of 10.2-cm - 60° v-notch below a 30.5-cm high rectangular weir with a 120-cm crest length. The outlet compound weir contained a 15.2-cm – 30° v-notch below a 45.7-cm high rectangular weir with a 61-cm crest length (Figure 3.5). The invert of inlet 2 was below the top of the outlet structure and therefore, an ISCO 6712 sampler and associated ISCO 750 area velocity meter were installed at inlet 2 (Figure 3.5). As with the Bingham site all hydrology data were recorded at a two minute intervals.

Figure 3.5: Clockwise from top: Compound weir at Raeford inlet 1, Raeford inlet 1 during a storm event, AVM module at Raeford inlet 2, compound weir at Raeford outlet

Rainfall data were collected at both sites with a manual rain gauge and a tipping bucket rain gauge (Davis Instruments Rain Collector Model 7852 - 0.25 mm/tip) connected to an ISCO sampler (Figure 3.6). The manual gauge and tipping bucket were mounted on wooden posts in an area free of trees and overhead obstructions.

Figure 3.6: Tipping bucket rain gauge, manual rain gauge, and 5-watt solar panel at Raeford pond

Water surface evaporation was estimated at both sites via an atmometer (ETgage Model E) with a #30 turfgrass reference evapotranspiration (ET) cover and connected to a Hobo Onset Event logger (Figure 3.7). Each hundredth of an inch (0.25 mm) of ET was time-stamped by the Hobo Onset Event logger. The atmometer was placed as close as possible to the water surface of the pond, while still avoiding inundation. The turfgrass reference ET was multiplied by a coefficient of 1.05 to obtain the estimated surface water evaporation (Allen et al., 1998).

Figure 3.7: From left to right: Etgage Model E atmometer, Hobo Onset Event logger

A HOBO U20 water level logger was placed in a stilling well of 8 cm PVC tube attached to the outlet structure at both sites to monitor pond stage (Figure 3.8). The water level loggers were corrected with a third Hobo U20 water level logger to account for barometric pressure. Both ponds were surveyed using a total station, and data were imported to CAD. Stage-storage relationships were developed for each pond that provided a total volume as a function of depth (Appendix B).

Figure 3.8: From left to right: PVC well attached to Raeford outlet structure, Hobo U20 water level logger

Table 3.2: Summary of monitoring Equipment

Location	Structure	Flow Monitoring Device	Rain Gauge	Water Level	Evap
Bingham Inlet	NA	ISCO 750 Area Velocity Meter	NA	NA	NA
Bingham Outlet	15.2 cm 45° v-notch - 61 cm rectangular weir	ISCO 730 Bubbler Module	Manual and Tipping bucket	Hobo U20	ETgage Model E
Raeford Inlet 1	10.2 cm 60° v-notch - 1.2 m rectangular weir	ISCO 730 Bubbler Module	Manual and Tipping bucket	NA	NA
Raeford Inlet 2	NA	ISCO 750 Area Velocity Meter	NA	NA	NA
Raeford Outlet	15.2 cm 30° v-notch - 61 cm rectangular weir	ISCO 730 Bubbler Module	NA	Hobo U20	ETgage Model E

During each site visit all monitoring equipment was checked to ensure that it was clear of debris and functioning properly. The ISCO 730 bubbler flow modules were calibrated by adding water behind the weir up to the invert and zeroing out the level. Hydrologic and rainfall data were downloaded using an ISCO Rapid Transfer Device (RTD). Bubbler and AVM modules desiccant was replaced when it became apparently saturated.

Composite water quality samples were taken with the automated samplers using flow pacing. Samplers were programmed to suction 250-mL aliquots per specified runoff volume. The runoff volume ranged from site to site and depended on the catchment area. The samples were deposited and stored in one of 24 - 1 L plastic bottles within each sampler that were configured to collect samples from rainfall events ranging from 3-mm to 51-mm.

Samples were removed from the field as soon as possible while ensuring that at least 80% of the outflow hydrograph was sampled. All individual 1 L bottles were poured into a 24-L Nalgene bottle to create a composited sample, which was agitated to completely mix the sample and re-suspend all particles. A 1 L plastic bottle (for TSS) and a pre-acidified 125-mL plastic bottle (for nutrients) were filled with the composited sample. Approximately 20-mL of the composited sample was filtered through a 0.45-µm filter into a glass bottle for ortho-phosphate analysis. After mixing and filtering the samples were placed on ice and transferred to North Carolina Center for Applied Aquatic Ecology (CAAE) in Raleigh, NC, for analysis. There, the samples were analyzed for TSS, TKN, total ammoniacal nitrogen (TAN), nitrate-nitrite-nitrogen ($NO_{2,3}$-N), TP, and ortho-P. TN was calculated by the sum of TKN and $NO_{2,3}$-N. Organic nitrogen (ON) was calculated as the difference between TKN and TAN. Particle Bound Phosphorous (PBP) was estimated as the difference between TP and ortho-P. Table 3.3 contains a summary of the laboratory analytical methods used. The water quality sample concentrations provided by the CAAE were considered event mean concentrations (EMCs) since the samples were flow paced and composited, therefore, representative of the pollutant concentrations over a particular storm. In order to determine an influent concentration at the Raeford site, a volume weighted average was taken of the water quality parameter concentration at both inlets. This technique provided one influent concentration for each water quality parameter to compare to an effluent concentration.

Table 3.3: Laboratory analytical methods and reporting limits

Pollutant	Pollutant Name	Analytical Method	Reporting Limit	Unit
$NO_{2,3}$-N	Nitrate - Nitrite Nitrogen	SM 4500 NO3 F[a]	0.0056	mg/L
TKN	Total Kjeldahl Nitrogen	EPA Method 351.2[b]	0.28	mg/L
TAN	Total Ammoniacal Nitrogen	SM 4500 NH3 G[a]	0.007	mg/L
ON	Organic Nitrogen	=TKN - TAN	NA	mg/L
TN	Total Nitrogen	=TKN + $NO_{2,3}$-N	NA	mg/L
Ortho-P	Orthophosphate	SM 4500 P F[a]	0.006	mg/L
TP	Total Phosphorus	SM 4500 P F[a]	0.01	mg/L
PBP	Particle Bound Phosphorus	=TP - Ortho-P	NA	mg/L
TSS	Total Suspended Solids	SM 2540 D[a]	1	mg/L

[a]Eaton et al., 1995
[b]US EPA, 1993

3.2.2 Monitoring Challenges

Throughout the monitoring period there were several challenges. It was difficult to keep all monitoring stations functioning for an entire year, particularly during winter months when cold temperatures reduced the performance of the 12-volt batteries. There were a few occurrences where the battery life was insufficient to collect samples throughout the entirety of a storm event. Because of the redundancy of the monitoring design, many data could be calculated if missed. For instance, if an inlet sampler were down during a storm event, the influent volume could be estimated from the differences in stage measurements collected with the Hobo water level logger.

The second challenge was keeping the weirs and AVM modules clear of debris, litter and, particularly, sediment (Figure 3.9 and Figure 3.10). With each site visit, the weirs and AVM modules were cleared of debris, and sediment was removed by shovel to ensure that the next storm's water quality and quantity parameters were not affected by the prior storm.

Figure 3.9: Sediment accumulating behind the weir at Raeford inlet 1.

Figure 3.10: Post storm event sediment removed from behind weir

Freezing temperatures and snow presented additional challenges. When subjected to freezing temperatures, the water at the weir invert would freeze, making it impossible to measure the water level. Snow storms were not accurately measured. Three storm events (1/21/14, 1/29/14, and 2/13/14) that included freezing temperatures and/or snow were omitted from the entire water budget. The water budget analysis was re-started once the pond had completely de-watered from the freezing or snow event.

The final challenge was improper placement of the Hobo water level logger in the Bingham pond. As the monitoring began, it became obvious that the pond's stage dropped to that below the water level logger, thus creating missing stage data. During this time period if a water level was required for a calculation, a conservative approach was used and the water level was assumed to be at the lowest stage the logger could read. In reality, the stage was lower which would mean less volume in the pond and in turn a greater amount of infiltration.

This problem was quickly fixed by simply moving the water level logger towards the center of the pond to a deeper location.

3.2.3 Data Analysis

Flow and rainfall data were analyzed with FLOWLINK version 5.0 software. Rainfall intensities and total rainfall depths from the tipping bucket rain gauges were adjusted by a factor developed from the difference between the tipping bucket and manual rain gauges. Storm events considered for analysis had a minimum antecedent dry period of six hours and rainfall depths of at least 2.5-mm. HOBOware Pro version 3.3.1 software was used to process the water level data and compensate for the barometric data, and BoxCar Pro version 4.3 software was used to extract the ET data. Data were exported from FLOWLINK, HOBOware, and BoxCar Pro for additional analysis. Recorded water levels from FLOWLINK were converted to flow rates using developed stage-discharge weir equations. Peak 5-minute rainfall intensity, peak flow rate reduction and volume reduction were calculated for each storm. Water level readings from the HOBO logger were converted to a stage with the normal pool or draw-down orifice as the elevation datum (elev=0). With this reference elevation, a pond stage with a positive value means the water level was above the low-flow orifice and still discharging. A pond stage with negative value infers the water level was below the draw-down orifice and no water was leaving the device via the outlet structure. Equations and calculations can be found in Appendix C.

Because these wet ponds did not completely de-water prior to the next storm event in periods of frequent rainfall, analyzing per storm event volume reduction was difficult. Instead, the hydrology was analyzed over monthly, seasonal, and annual time frames. The following parameters comprise the water balance of a pond: rainfall incident onto the pond, inflow, outflow, evaporation from the surface, and infiltration, as calculated by:

$$V_i + \sum_{i=1}^{n} (V_{in} + P - V_{out} - E - F)_i = V_f \tag{3.1}$$

where:

V_i – Initial volume (m^3)
V_{in} – Influent volume (m^3)
P – Precipitation volume (m^3)
V_{out} – Effluent volume (m^3)
E – Evaporated volume (m^3)
F – Infiltrated volume (m^3)
V_f – Final volume (m^3)

All water budget components were measured by the monitoring design except for infiltration which was determined from Equation 3.1. An infiltration rate was calculated using Equation 3.2 and was considered as the draw-down rate of the pond when the water level was below normal pool.

$$F_{rate} = F \div SA \div T \tag{3.2}$$

Where:

F_{rate} – Infiltration rate (m/hr)
F – Infiltrated volume (m^3)
SA – Surface area (m^2)
T – Time (hr)

Individual storm pollutant loadings and annual pollutant loadings were determined for each of the water quality parameters as outlined in Appendix E.

R 3.1.1 (R Core Team, 2014) was used to statistically compare hydrology and water quality parameters. Paired data sets were first tested for normality via visually inspecting Quintile-Quintile plots and three goodness-of-fit tests: Shapiro-Wilk, Anderson-Darling, and Lilliefors. Normally distributed data were tested for significance using the student's t-test. Data that were non-normal were first log transformed and re-analyzed for normality. Resulting log-normal data were analyzed via the student's t-test. Non-normal data after log transformation were analyzed for significance using the Wilcoxon signed rank test. Data were analyzed for significance at the $\alpha=0.05$ level. Paired inflow and outflow values were compared for peak discharge, water quality concentrations, and water quality loading. Example R code is included in Appendix G. The effect of rainfall, average monthly water level and antecedent dry period on monthly volume reduction was analyzed using simple and multiple linear regression. The relationship among 5-min peak intensity, total rainfall, and antecedent dry period on each water quality parameter was also analyzed using simple and multiple linear regression.

4 Results and Discussion

4.1 Results

4.1.1 Precipitation

The Bingham site was monitored for hydrology and water quality from May 15, 2013 through May 31, 2014. During this period a total of 77 hydrologic events were recorded ranging from 3-mm to 102-mm (Table 4.1). The Raeford site was monitored for hydrology and water quality from July 29, 2013 through August 9, 2014. During this period a total of 66 hydrologic events were recorded ranging from 3-mm to 102-mm. One complete year of rainfall at the Bingham site and Raeford site totaled 1330-mm and 1067-mm, respectively (Table 4.2). The 30-year normal precipitation for the Fayetteville area is 1186 mm (State Climate Office of North Carolina, 2014). During the monitoring period, April was approximately two fold wetter than normal and September and October were approximately three to four fold drier than normal. It is important to note that the months of June and July in Table 4.2 are not from the same year. The June and July precipitation totals for the Bingham site are from 2013; whereas, the June and July totals at the Raeford site are from 2014. This explains a large portion of the variation in rainfall totals between the two sites despite their close proximity.

Table 4.1: Summary of hydrologic events

	Bingham	Raeford
Number of hydrologic events	77	66
Mean storm rainfall (mm)	18	18
Median storm rainfall (mm)	11	11
Minimum storm rainfall (mm)	3	3
Maximum storm rainfall (mm)	102	102

Table 4.2: 30-Year Normal and recorded monthly precipitation at each wet pond

Month	30-yr Normal*	Bingham	Raeford
Jan	106	117	114
Feb	87	47	53
Mar	111	117	138
Apr	78	156	176
May	84	57	64
Jun**	106	300	115
Jul**	132	187	44
Aug	132	117	118
Sep	121	37	28
Oct	77	13	19
Nov	72	69	65
Dec	81	115	132
Year	1186	1330	1067

*(State Climate Office of North Carolina, 2014)
**Rainfall totals at Bingham site from 2013 and rainfall totals from Raeford site from 2014

4.1.2 Hydrology

As previously stated, analyzing volume reduction of a wet pond on a storm-by-storm basis was difficult because storms may overlap one another. Table 4.3 and Table 4.4 show the water budgets at the Bingham site and Raeford site, respectively. Using Equation 3.1, a infiltrated volume was calculated for each month. Calculations use the water levels at the beginning and end of each month. The rainfall onto the pond, initial volume (function of initial water level), final water level, and final volume (function of final water level) are not shown in the tables, but were used in calculating the volume of water that infiltrated. The volume reduction shown was computed from the influent and effluent volumes. The largest monthly volume reductions at the Bingham site and Raeford site were both 100% (no water left the outlet structure). The lowest monthly volume reductions at the Bingham and Raeford sites were 10.3% and -14.9%, respectively.

Table 4.3: Bingham pond monthly water budget (rainfall on pond, initial volume and final volume used for calculations but excluded from table)

Month	Rainfall (mm)	Initial WL (m)	Influent Vol (m^3)	Effluent Vol (m^3)	Evap (m^3)	Infiltrat Vol (m^3)	Vol Reduction (%)
June	300	-0.16	3989	2075	123	1734	48.0
July	187	0.19	2989	2683	158	655	10.3
August	117	-0.03	1526	540	154	1143	64.6
September	37	-0.19	446	0	132	359	100.0
October	13	-0.19	211	0	80	380	100.0
November	69	-0.43	805	84	67	437	89.6
December	115	-0.12	1414	423	47	981	70.1
January	117	-0.03	1751	872	55	1137	50.2
February	47	-0.14	751	4	62	865	99.5
March	117	-0.19	2448	720	101	1619	70.6
April	156	0.03	2428	1056	156	1290	56.5
May	57	0.24	1099	441	170	1417	59.8

Table 4.4: Raeford pond monthly water budget (rainfall on pond, initial volume and final volume used for calculations but excluded from table)

Month	Rainfall (mm)	Initial WL (m)	Influent Vol (m^3)	Effluent Vol (m^3)	Evap (m^3)	Infiltrat Vol (m^3)	Vol Reduction (%)
August	118	0	1765	950	99	655	46.2
September	28	-0.03	403	54	85	566	86.7
October	19	-0.15	77	0	52	337	100.0
November	65	-0.49	684	64	43	673	90.6
December	132	-0.01	1855	1091	31	902	41.2
January	114	0.25	1581	1816	36	526	-14.9
February	53	-0.20	390	164	40	592	58.1
March	138	-0.11	1654	881	65	820	46.7
April	176	0.16	2303	1665	100	1287	27.7
May	64	0.61	1296	1107	109	471	14.6
June	115	-0.28	1582	723	81	687	54.3
July	44	0.01	343	42	105	451	87.7

Another way to evaluate the water budget of each pond is to analyze it on a seasonal basis. All parameters are summed or calculated for each season of the year: spring (Mar 20 – Jun 20), summer (Jun 21 – Sep 21), fall (Sep 22 – Dec 20) and winter (Dec 21 – Mar 19). Seasonal water budgets for the Bingham and Raeford ponds can be found in Table 4.5 and Table 4.6, respectively. The largest volume reduction at the Bingham site was 83.6% and occurred in the fall, while the smallest volume reduction was 35.5% and occurred during the summer. The largest volume reduction at the Raeford site was 60.4% and occurred in the summer, while the smallest volume reduction was 21.6% and occurred in the fall.

Table 4.5: Bingham pond seasonal water budget (rainfall on pond, initial volume, final water level, and final volume used for calculations but excluded from table)

Season	Rainfall (mm)	Initial WL (m)	Influent Vol (m^3)	Effluent Vol (m^3)	Evap (m^3)	Infiltrat Vol (m^3)	Vol Reduction (%)
Spring	434	0.05	7227	3304	444	4095	54.3
Summer	467	-0.03	5894	3802	441	2392	35.5
Fall	144	-0.19	1891	311	213	1539	83.6
Winter	285	-0.18	4845	1480	194	3255	69.4

Table 4.6: Raeford pond seasonal water budget (rainfall on pond, initial volume, final water level and final volume used for calculations but excluded from table)

Season	Rainfall (mm)	Initial WL (m)	Influent Vol (m^3)	Effluent Vol (m^3)	Evap (m3)	Infiltrat Vol (m^3)	Vol Reduction (%)
Spring	230	0.32	3012	1515	299	1926	49.7
Summer	155	-0.34	1720	682	162	754	60.4
Fall	319	-0.01	3885	3046	127	866	21.6
Winter	362	0.10	5315	3766	290	1330	29.1

Despite the difficulty in measuring storm volume reductions there was a subset of storms in which the stage was at or below the draw-down orifice when the event started and the pond had time to de-water before the following storm event. These storms were “solo storms” and did not overlap. A volume reduction of these solo storms was examined on a storm basis, and there was a statistically significant difference in the influent and effluent volumes. At the Bingham site 52 of the 77 hydrologic events were solo (68%) and at the Raeford site 40 of the 66 hydrologic events were solo (61%). The median and mean volume reductions for solo storms at the Bingham and Raeford sites are shown in Table 4.7. Since the effluent peak flow rate occurred either during or shortly after the storm event, peak flow rate attenuation could be assessed on a storm basis for all hydrologic events. The differences between influent peak flow rate and effluent peak flow rate were significantly (α=0.05 different at both sites (Table 4.7). These values include storm events with no outflow that therefore have a volume reduction and peak flow rate reduction of 100%. Even for large storm events, both wet ponds were able to mitigate the peak flows. At the Bingham site, storm events with depths of 42 mm, 42 mm, 49 mm, 57 mm, and 76 mm had peak flow reductions of 100%, 99.2%, 97.9%, 98.6% and 100%, respectively. At the Raeford site, storm events with depths of 34 mm, 40 mm, 46 mm, and 50 mm had peak flow rate reductions of 98.5%, 98.0%, 93.1% and 70.1%.

Table 4.7: Summary of hydrologic parameters during monitoring period

	Bingham	Raeford
Median Peak Flow Reduction*	99.2%	98.7%
Mean Peak Flow Reduction*	94.9%	79.7%
Median Volume Reduction**	100.0%	100.0%
Mean Volume Reduction**	87.4%	84.9%
Median Antecedent Dry Period (days)	2.4	3.9
Mean Antecedent Dry Period (days)	4.1	5.1

*Values include storm events with no outflow that have a volume reduction and peak flow rate reduction of 100%.
** Only solo storms (Bingham n=52, Raeford n=40). Solo storms considered those that began when the stage was below the draw-down orifice and the pond had time to de-water prior to the following event

4.1.3 Water Quality

During the monitoring period, there were a total of 23 water quality events collected at the Bingham site. Rainfall depths ranged from 4 to 76 mm with a mean 5-min peak intensity of 36 mm/hr. Four of these events were not paired inlet/outlet samples, but inlet-only samples, when there was no outflow from the device. These four inlet samples were used to calculate mean and median influent values, but were not used for the paired statistical tests. Of the remaining water quality events, there were a total of 19 paired nutrient samples and 17 paired TSS samples.

At the Raeford pond there were a total of 20 water quality events, ranging from 5 mm to 102 mm. The mean 5-min peak rainfall intensity was 37 mm/hr. As with the Bingham site, four of these water quality events were not paired inlet/outlet samples, but inlet-only samples. Of the water quality events collected, there were a total of 16 paired inlet/outlet water quality events. A summary of the water quality events is found in Table 4.8 and the seasonal distribution of the events is found in Table 4.9.

Table 4.8: Summary of water quality events

	Bingham	Raeford
Number of water quality events*	23	20
Mean rainfall (mm)*	24	28
Median rainfall (mm)*	16	21
Minimum rainfall (mm)*	4	5
Maximum rainfall (mm)*	76	102
Mean - 5-min peak rainfall intensity (mm/hr)*	36	37
Median - 5-min peak rainfall intensity (mm/hr)*	21	31
Minimum - 5-min peak rainfall intensity (mm/hr)*	3	7
Maximum - 5-min peak rainfall intensity (mm/hr)*	135	133

*Includes 4 storms at each location where only the inlets were sampled. These 4 storm events were not paired samples

Table 4.9: Seasonal distribution of sampling events

Site	Spring	Summer	Fall	Winter
Bingham*	9	5	4	5
Raeford*	6	6	3	5

*Includes 4 storms at each location where only the inlets were sampled. These 4 storm events were not paired samples

Table 4.10 shows the median and mean, inlet and outlet concentrations and percent concentration reductions at the Bingham site. Statistical analysis showed there were significant differences in the inlet and outlet concentrations for all variables except for TKN, TN, and PBP. Table 4.11 shows the distribution of each water quality variable, the test of significance used, the associated p-value and whether there was a significant difference.

Table 4.10: Bingham mean and median nutrient and TSS concentrations and mean EMC percent concentration reduction at each sampling location (n=23 inlet, n=19 outlet, n=22 inlet TSS, n=18 outlet TSS)

	Median Values		Mean Values			
Variable	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)	Percent median conc. reduction (%)	Percent mean conc. reduction (%)
TKN	0.55	0.55	0.74	0.63	-1	15
$NO_{2,3}$	0.19	0.05	0.19	0.06	71	66
TN	0.74	0.57	0.93	0.69	24	26
TAN	0.16	0.04	0.20	0.05	74	73
ON	0.42	0.54	0.54	0.57	-27	-6
$O\text{-}PO_4^{3-}$	0.008	0.003	0.013	0.004	65	71
PBP	0.049	0.051	0.07	0.05	-5	32
TP	0.06	0.05	0.08	0.05	9	38
TSS	44	12	55	13	74	77

Table 4.11: Statistical analysis results for nutrients and TSS concentrations at the Bingham site

Variable	n	Distribution	Test of Significance	p-value	Significant Difference*?
TKN	19	Log-Normal	Student's t	0.5926	no
$NO_{2,3}$	19	Normal	Student's t	0.0006	**yes**
TN	19	Log-Normal	Student's t	0.2550	no
TAN	19	Log-Normal	Student's t	<0.0001	**yes**
ON	19	Log-Normal	Student's t	0.0173	**yes**
$O\text{-}PO_4^{3-}$	19	Log-Normal	Student's t	0.0002	**yes**
PBP	19	Not-Normal	Signed Rank	0.0949	no
TP	19	Log-Normal	Student's t	0.0484	**yes**
TSS	17	Log-Normal	Student's t	<0.0001	**yes**

* Data analyzed for significance at the α=0.05 level

Table 4.12 shows the median and mean, inlet and outlet concentrations and percent concentration reductions at the Raeford site. Statistical analysis showed there were significant differences in the inlet and outlet concentrations for all variables except for TKN, ON, and PBP. Table 4.13 shows the distribution of each water quality variable, the test of significance used, the associated p-value and whether there was a significant difference.

Table 4.12: Raeford mean and median nutrient and TSS concentrations and mean EMC percent concentration reduction at each sampling location (n=20 inlet, n=16 outlet)

	Median Values		Mean Values			
Variable	Inlet (mg/L)	Outlet (mg/L)	Inlet (mg/L)	Outlet (mg/L)	Percent median conc. reduction (%)	Percent mean conc. reduction (%)
TKN	1.00	0.72	1.06	0.85	28	20
$NO_{2,3}$	0.24	0.10	0.25	0.11	58	57
TN	1.26	0.79	1.31	0.96	37	27
TAN	0.23	0.08	0.25	0.09	65	64
ON	0.74	0.63	0.81	0.76	15	6
$O\text{-}PO_4^{3-}$	0.064	0.027	0.072	0.033	58	55
PBP	0.12	0.10	0.13	0.11	15	11
TP	0.23	0.13	0.20	0.15	42	28
TSS	50	14	56	24	73	58

Table 4.13: Statistical analysis results for nutrients and TSS concentrations at the Raeford site

Variable	n	Distribution	Test of Significance	p-value	Significant Difference*?
TKN	16	Not Normal	Signed Rank	0.0934	no
$NO_{2,3}$	16	Normal	Student's t	<0.0001	**yes**
TN	16	Normal	Student's t	0.0132	**yes**
TAN	16	Log-Normal	Student's t	<0.0001	**yes**
ON	16	Normal	Student's t	0.9166	no
$O\text{-}PO_4^{3-}$	16	Normal	Student's t	0.0004	**yes**
PBP	16	Log-Normal	Student's t	0.3478	no
TP	16	Normal	Student's t	0.0038	**yes**
TSS	16	Log-Normal	Student's t	<0.0001	**yes**

* Data analyzed for significance at the α=0.05 level

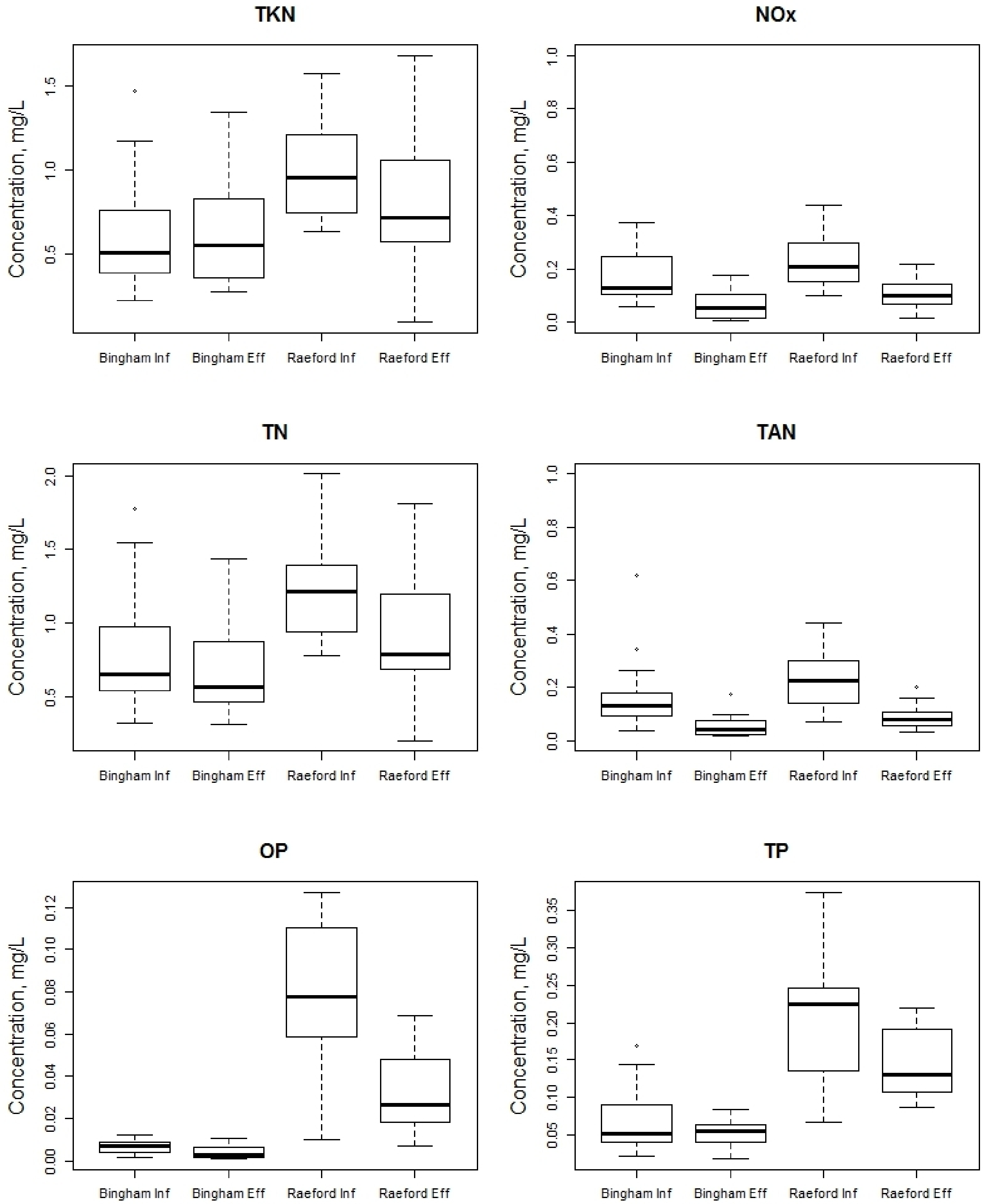


Figure 4.1: Nutrient concentrations at each monitoring station

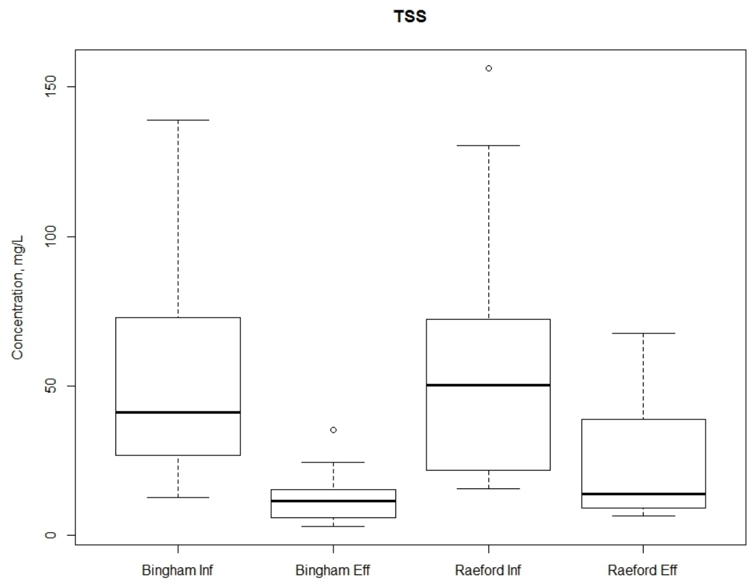


Figure 4.2: TSS concentrations at each monitoring station

4.1.4 Loading

As described in Appendix E, loads were calculated for each water quality variable based on the water quality results and the hydrologic results. Table 4.14 shows the summation of loads for the storm events that were sampled. This includes only events that had outflow and this summation therefore underpredicts annual performance. The variable with the lowest reduction was ON while the variable with the highest reduction was TSS. There was a significant difference in the influent loads and effluent loads for all water quality variables (Table 4.15).

Table 4.14: Summary of percent load reductions at the Bingham site (n=19 all nutrients, n=17 TSS – only the storms with both inflow and outflow sampled)

Variable	∑ Inlet Loading (kg)	∑ Outlet Loading (kg)	Percent Reduction (%)
TKN	4.1	2.2	45
NO2,3	1.1	0.4	68
TN	5.2	2.6	50
TAN	1.1	0.3	70
ON	3.0	1.9	37
OP	0.05	0.02	62
PBP	0.5	0.2	60
TP	0.6	0.2	61
TSS	451	66	85

Table 4.15: Statistical analysis results for nutrients and TSS loadings at the Bingham site

Variable	n	Distribution	Test of Significance	p-value	Significant Difference*?
TKN	19	Log-Normal	Student's t	<0.0001	**yes**
$NO_{2,3}$	19	Not Normal	Signed Rank	<0.0001	**yes**
TN	19	Not Normal	Signed Rank	<0.0001	**yes**
TAN	19	Log-Normal	Student's t	<0.0001	**yes**
ON	19	Log-Normal	Student's t	0.0011	**yes**
OP	19	Not Normal	Signed Rank	<0.0001	**yes**
PBP	19	Log-Normal	Student's t	<0.0001	**yes**
TP	19	Log-Normal	Student's t	<0.0001	**yes**
TSS	17	Log-Normal	Student's t	<0.0001	**yes**

* Data analyzed for significance at the α=0.05 level

Table 4.16 shows the summation of loads for the storm events that were sampled at the Raeford site. As with the Bingham site, these were only storm events with inflow and outflow. The variable with the lowest percent reduction was ON while the variable with the highest reduction was TSS. A significant difference existed between the influent loads and effluent loads for all water quality variables (Table 4.17).

Table 4.16: Summary of percent load reductions at the Raeford site (n=16 - only the storms with both inflow and outflow sampled)

Variable	∑ Inlet Loading (kg)	∑ Outlet Loading (kg)	Percent Reduction (%)
TKN	7.3	4.0	45
NO2,3	1.7	0.7	57
TN	9.0	4.8	47
TAN	1.6	0.6	62
ON	5.7	3.4	40
OP	0.7	0.2	68
PBP	1.0	0.6	41
TP	1.6	0.8	49
TSS	504	167	67

Table 4.17: Statistical analysis results for nutrients and TSS loadings at the Raeford site

Variable	n	Distribution	Test of Significance	p-value	Significant Difference*?
TKN	16	Not Normal	Signed Rank	0.0003	**yes**
$NO_{2,3}$	16	Log-Normal	Student's t	0.0001	**yes**
TN	16	Not Normal	Signed Rank	0.0002	**yes**
TAN	16	Log-Normal	Student's t	<0.0001	**yes**
ON	16	Not Normal	Signed Rank	0.0029	**yes**
OP	16	Not Normal	Signed Rank	<0.0001	**yes**
PBP	16	Not Normal	Signed Rank	0.0034	**yes**
TP	16	Not Normal	Signed Rank	0.0034	**yes**
TSS	16	Not Normal	Signed Rank	<0.0001	**yes**

* Data analyzed for significance at the α=0.05 level

4.1.5 pH

During the latter part of the monitoring period, pH readings were taken of the inlet and outlet samples. The only reliable pH results were those from the Raeford pond. The results are listed in Table 4.18. The pond water was tested in three locations from the inlet to the outlet and had a pH of 6.9 at all 3 locations.

Table 4.18: pH results from Raeford pond (n=1)

	Raeford	
Inlet 1	Inlet 2	Outlet
6.4	6.6	7.3

4.2 Discussion

4.2.1 Hydrology

As engineers and developers strive to mimic pre-development hydrology and reduce adverse effects on downstream receiving bodies, volume reduction is an important factor in assessing the performance of any SCM. Both of the monitored infiltrating wet ponds were able to infiltrate substantial volumes of water. Both wet ponds had substantial volume reductions on a monthly and seasonal basis, mainly due to infiltration.

One anomaly in the data merits discussion. In January, 2014, the Raeford pond appeared to produce 14.9% more outflow than inflow. At the beginning of January the pond was still drawing down from a large rain event on December 29, and consequently the pond stage was 0.25 m above the normal pool. The December 29 storm event's influent volume occurred in December and was recorded in December. However, only a fraction of the effluent volume left the pond during December; the balance of the effluent volume drained during the onset of January. When volume reductions are calculated on a monthly basis, it is based on the total inflow volume and total outflow volume during that month. So, the volume reduction for December (41.2%) is likely higher than expected because part of the effluent volume for the storms in later December is not being accounted for. Likewise the volume "reduction" for January (-14.9%) is lower than expected because of the volume of water remaining in the pond from December's storms.

Accordingly, at the Raeford pond, the volume reduction for January, May, and, to some extent, April may be lower than expected. Conversely, the volume reduction reported for December, April and, to some extent, March may be higher than expected. At the Bingham site, the volume reductions for July and May are lower than expected, while the volume reductions for June and April are higher than expected. This monthly over/under prediction could be corrected by taking the initial and final volumes into account when determining volume reductions. As the time interval increases, the effect of differing initial and final water levels is not as substantial due to a larger data set, as demonstrated when examining the volume reduction on a seasonal basis (Table 4.5 and Table 4.6).

Figure 4.3 and Figure 4.4 demonstrate that the ability of the ponds to reduce volume was strongly dependent upon the amount of rainfall. The previously explained potentially skewed volume reductions are evident here (July at Bingham, and January and May at Raeford). In months when there was little rainfall such as in September and October, the infiltrating wet ponds were able to completely or almost completely eliminate all outflow.

Monthly volume reduction and rainfall were inversely proportional and as rainfall increased the monthly volume reduction decreased (Figure 4.5). A significant relationship was found at the Bingham site (regression slope p-value=0.007) and the Raeford site (regression slope p-value=0.027) between the total monthly precipitation and the volume reduction. Despite a few months with potentially skewed volume reductions, there was still a significant relationship at both sites.

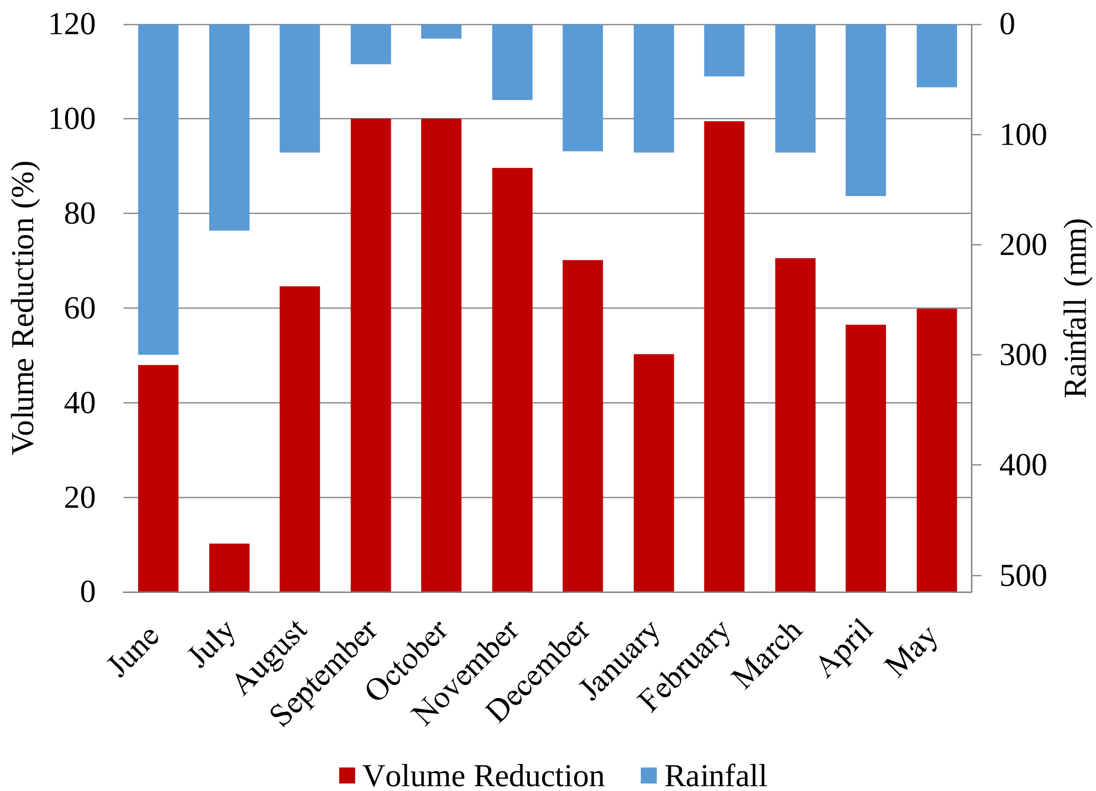


Figure 4.3: Monthly volume reduction and rainfall at the Bingham site

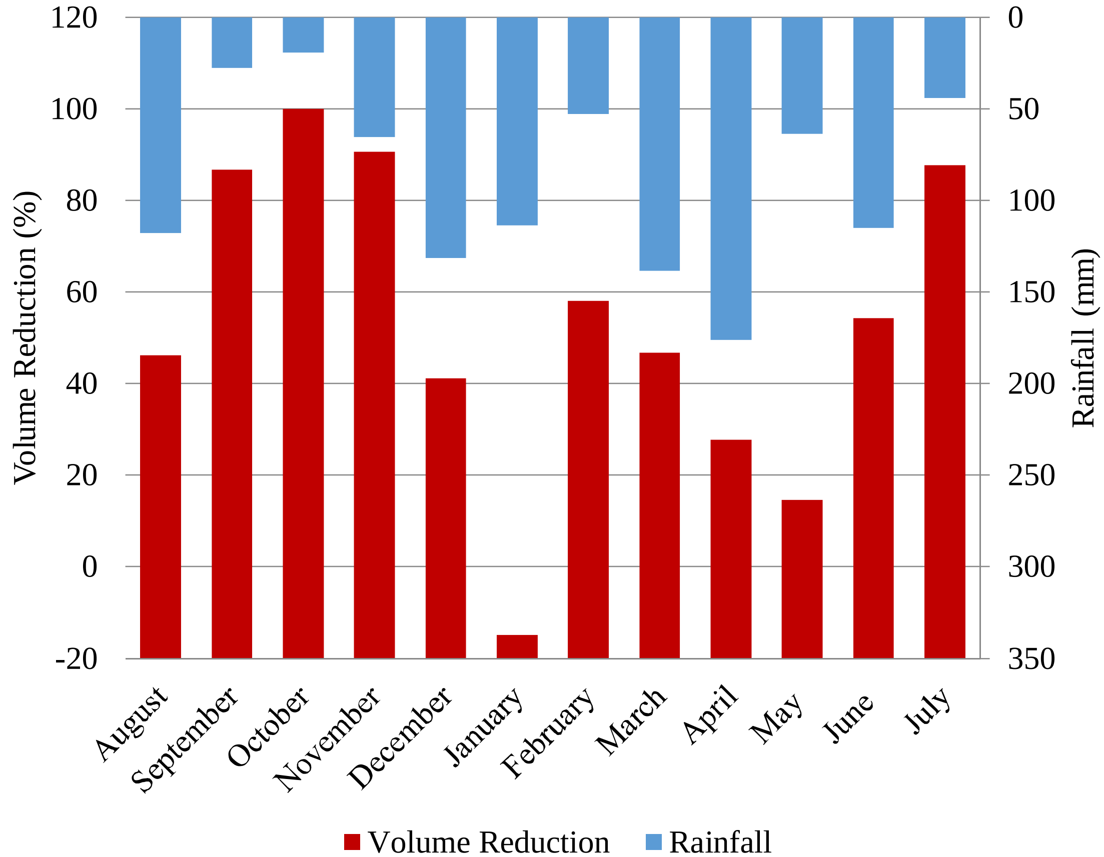


Figure 4.4: Monthly volume reduction and rainfall at the Raeford site

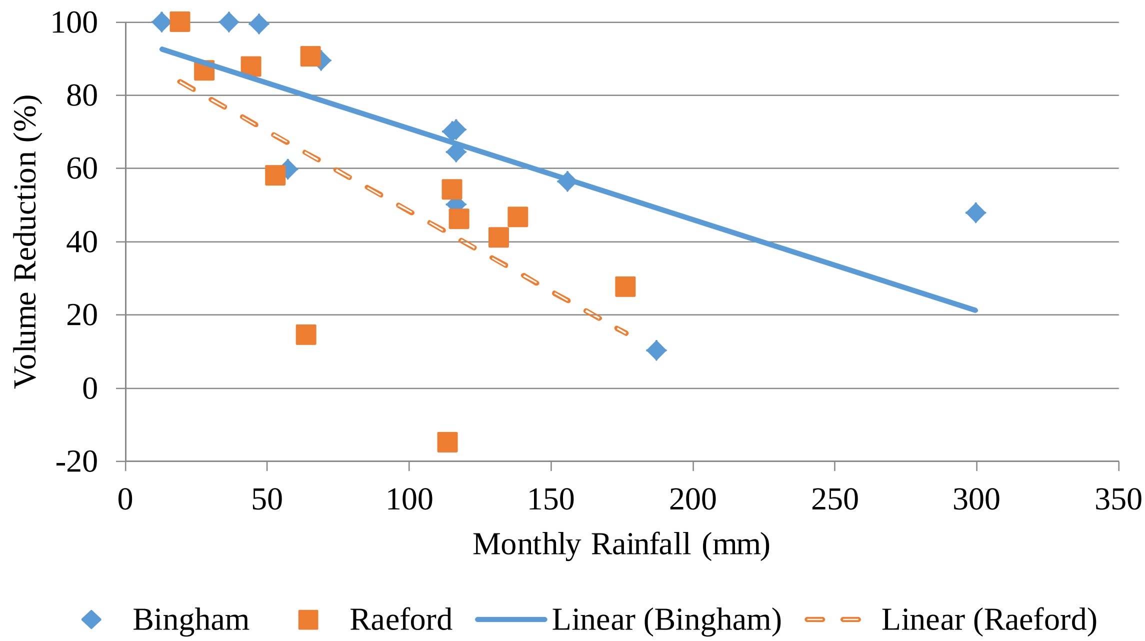


Figure 4.5: Monthly volume reduction versus total monthly rainfall and fitted lines (Bingham r^2 = 0.54, Raeford r^2 = 0.40)

A monthly average of the two-minute interval water level readings was plotted against the monthly volume reductions. A significant relationship was found at the Bingham site (regression slope p-value=0.024) and the Raeford site (regressions slope p-value=0.009) between the monthly volume reduction and average monthly water level (Figure 4.6).

The ability of the pond to reduce a specific storm event's outflow depends on the stage of the pond when the storm begins. If the pond stage is below the low-flow orifice, a volume of water is captured before any outflow occurs via the outlet structure (Figure 4.7). Figure 4.8 - hydrograph from a 44-mm event at the Bingham pond demonstrates this principle. The wet pond was able to capture the incoming flow during the first hours of the storm event. Eventually sufficient runoff caused outflow; however, discharge was minimal. The wet pond captured 83% of the influent volume. The more the pond stage persist below normal pool, the greater the monthly volume reduction. Standard wet ponds may be intended solely for peak flow attenuation; however, infiltrating wet ponds offer a unique opportunity for volume reduction by bringing the water level below normal pool prior to the next storm event.

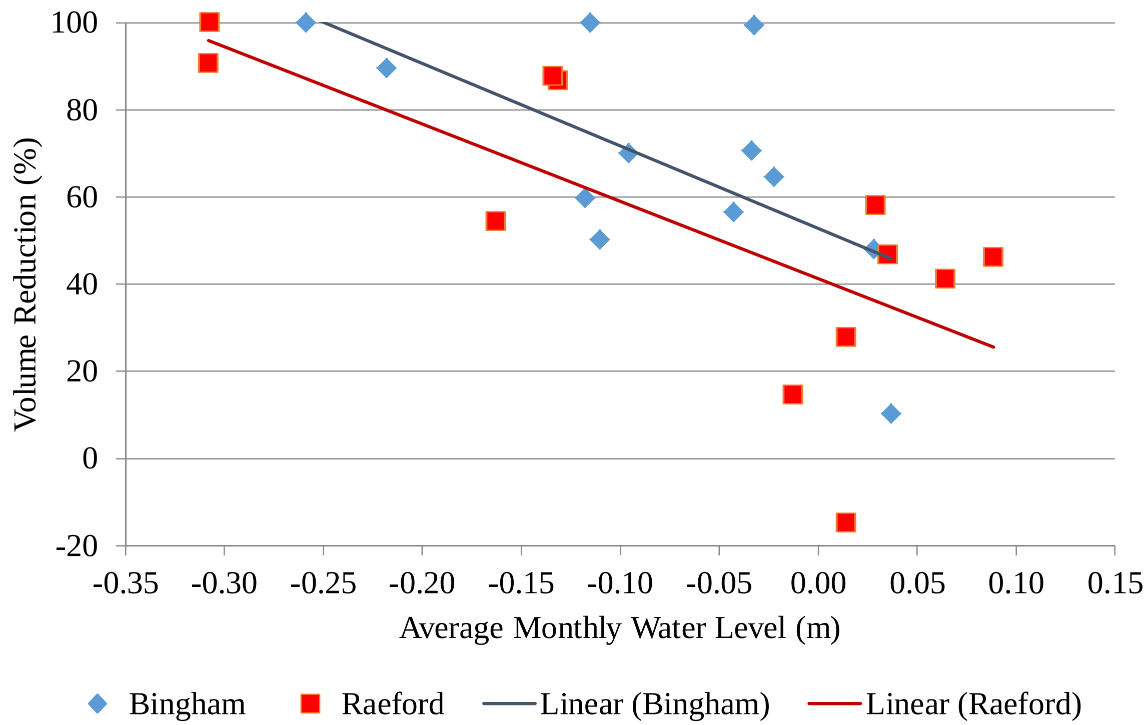


Figure 4.6: Monthly volume reduction versus average monthly water level and fitted lines (Bingham $r^2 = 0.41$, Raeford $r^2 = 0.51$)

Figure 4.7: Storage volume before outflow occurs denoted by red arrow

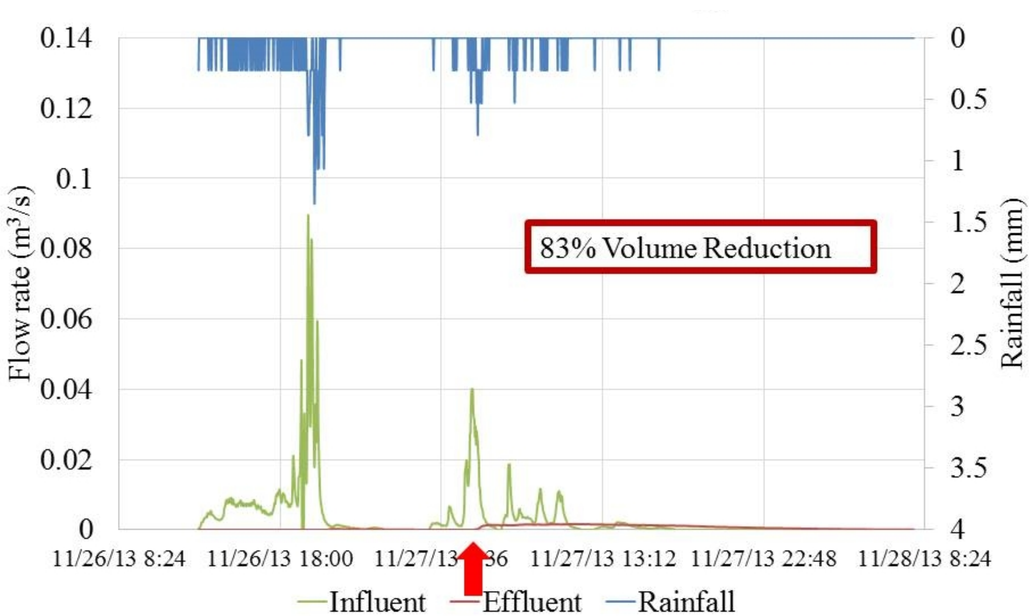


Figure 4.8: Hydrograph from 44 mm event at Bingham pond – red arrow denotes where outflow begins

Figure 4.9 and Figure 4.10 illustrate the fate of water leaving the wet pond on a monthly basis. At both sites, evaporation from the surface of the water was minimal. The majority of the runoff either infiltrated or became outflow. The monthly outflow volume differed the most of all components and was likely a function of rainfall depth. Variations in hydrologic fate from month-to-month were likely due to one of two factors. First, differences in the average water level produced differences in the head driving infiltration. Second, as the average water level of the pond changed, the wetted area also changed. When the water level of the pond was higher, there was a larger footprint of wetted area for infiltration to occur.

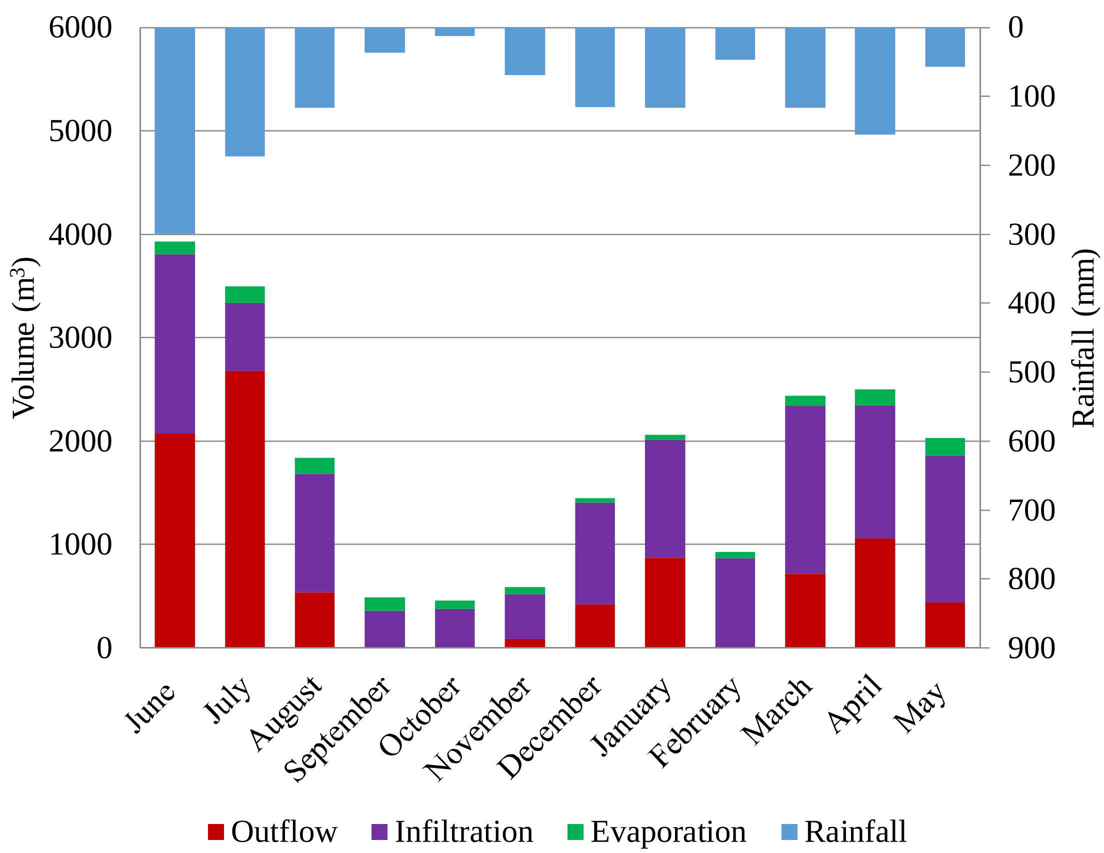


Figure 4.9: Fate of runoff at the Bingham pond

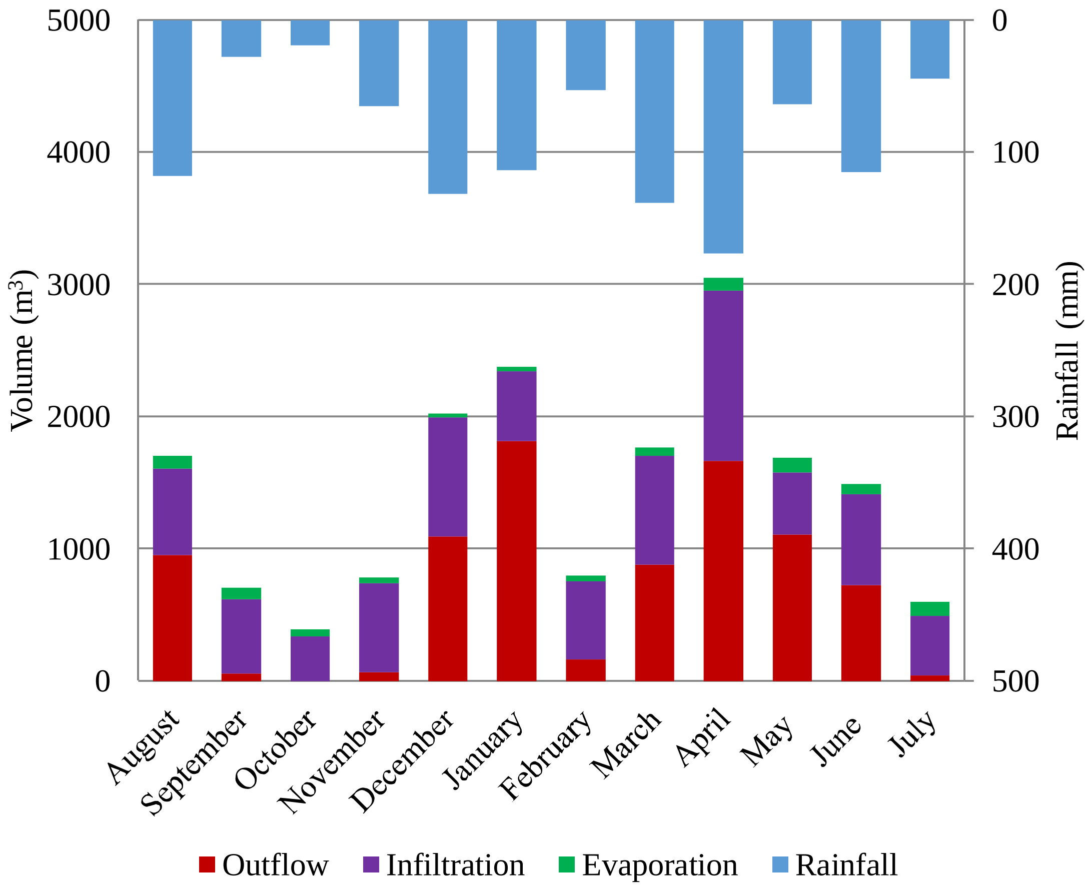


Figure 4.10: Fate of runoff at the Raeford pond

Figure 4.11 shows the annual fate of runoff from each pond. At the Bingham site, 40% of the water left via the outlet, 54% infiltrated and 6% evaporated from the pond surface. At the Raeford site, 49% of the water outflowed, 46% infiltrated and 5% evaporated. The modest differences between the two wet ponds could be attributed to the different surface areas, loading ratios and/or underlying soils. The percentages for infiltration and runoff remain substantially different from those of an undeveloped site. For example, a stated LID target of 5% total runoff (Swift et al., 1987), remains clearly out of reach.

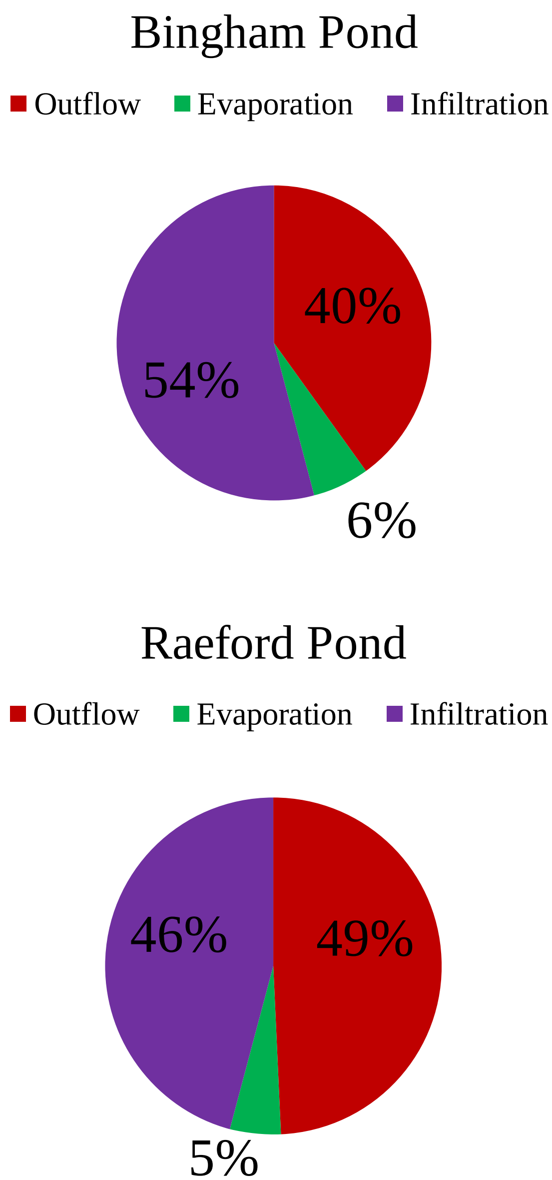


Figure 4.11: Fate of runoff at the Bingham and Raeford ponds

The differences in the percentage of infiltration and evaporation between ponds could be attributed to the difference in surface areas. With a relatively larger pond surface area, there is an increased wetted area for both evaporation and infiltration to occur. The Bingham pond with a surface area 0.12-ha was able to infiltrate 54% and evaporate 6% of the water while the Raeford pond with a surface area of 0.08-ha infiltrated 46% and evaporated 5% of the volume.

The loading ratios (area) of the ponds were also different and could have attributed to the differences in runoff fates. The loading ratio (watershed area : normal pool area) of the Bingham pond was 20:1 and the loading ratio at the Raeford pond was 24:1. However, it is difficult to draw conclusions from loading ratios when the sites have different percent imperviousness. The impermeable area loading ratios were 15:1 and 11:1 at the Bingham and Raeford ponds respectively.

Despite a 25-cm clay liner and 1089-kg (0.9 kg/m^2) of bentonite, there were sill significant volume reductions at the Bingham pond (Appendix A). The clay liner was installed around the entire pond to an elevation of the temporary pool. If no liner were installed, it is likely there would be no outflow and, therefore, a volume reduction of 100% year round. The device would likely have functioned as an infiltration basin due to the high infiltration rates of the underlying soil. The volume reductions that were observed in this study were most likely the result of a hole in the liner or water penetrating the clay and bentonite.

To quantify an infiltration rate for each pond, two techniques were used. For the first, the total volume of water infiltrated during a specific time span (month, season, etc.) was divided by the surface area of the pond at the normal pool elevation and the amount of time within that span (month, season, etc.) (Equation 3.2). The resulting value was in unit length per time. Table 4.19 shows the calculated average monthly infiltration rates for each infiltrating wet pond. These rates are solely based on the volume of water that infiltrated the ground. Infiltration rates of these SCMs would not meet NC DENR's requirement for infiltration devices (13 mm/hr, (NCDENR, 2009)). Because, (1) these infiltrating wet ponds do not infiltrate fast enough to be considered infiltration SCMs, and (2) they do not maintain a normal pool, infiltrating wet ponds are in a SCM no man's land and they need design requirements of their own.

Table 4.19: Calculated infiltration rates in mm/hr at the Bingham and Raeford wet ponds

	Infiltration Rate (mm/hr)	
Month	Bingham	Raeford
Jan	1.3	0.3
Feb	1.0	0.3
Mar	1.9	1.0
Apr	1.5	0.4
May	1.6	1.6
Jun	2.0	1.1
Jul	0.7	0.8
Aug	1.3	1.4
Sep	0.4	0.6
Oct	0.4	0.5
Nov	0.5	0.5
Dec	1.1	1.0
Avg	1.1	0.8

Another way to estimate the infiltration rate was to examine the draw down rate of the pond when the elevation was below the normal pool or low-flow orifice during times of no rain. Figure 4.12 shows the stage of water in the Bingham pond from October 18 to October 28. During this 10-day period there was no rain and the water level was below the low-flow orifice (negative water level). The draw-down rate pictured below was due to infiltration *and* evaporation. The water loss slope was determined to be 0.013 m/day or 0.56 mm/hr. To isolate the infiltration rate, the rate of evaporation would need to be subtracted from the 0.56 mm/hr overall rate. An evaporation rate for the month of October can be determined by taking the measured monthly sum of evaporation (6.3 cm) and dividing it by the number of days (31) in October, leading to an estimate of 0.002 m/day or 0.09 mm/hr. The infiltration rate was calculated to be 0.47 mm/hr, which is consistent with the value in Table 4.19 for the monthly average infiltration rate during October at the Bingham pond (0.4 mm/hr). This modest difference may be due to comparing a 10-day time period versus a monthly average. One rate was determined based on monthly water budgets measured by ISCO samplers measuring influent and effluent volumes, while the second method was determined by analyzing the water surface draw down slope from HOBO water level loggers.

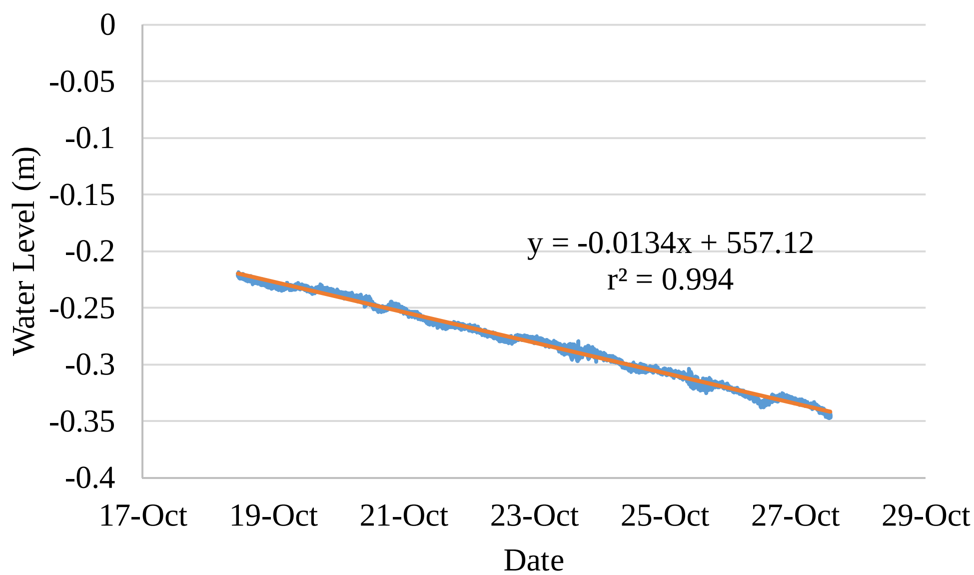


Figure 4.12: Water level at the Bingham pond from October 18-28

Both monitored wet ponds mitigated peak flows very well (Table 4.7) with median peak flow reductions of 99.2% and 98.7% at the Bingham pond and Raeford pond, respectively. This is attributed to the low-flow orifice design that slowly released the captured water. At the beginning of many storms, the water level was below the invert of the low-flow orifice, thus limiting the number of storms reaching the top of the outlet structure. During the monitoring period the water level reached the top of the outlet structure during 8 storm events at both the Bingham and Raeford ponds. When the water level breaches the top of the outlet structure the SCMs ability to reduce the outflow rate becomes limited. Because infiltrating wet ponds typically can store a large volume below low-flow orifice, these SCMs likely reduce peak outflow rates for larger storms better than a standard wet pond where the water level is maintained at the normal pool. However, a comprehensive study comparing an infiltrating wet pond to a standard wet pond would need to be performed before drawing any conclusions.

4.2.2 Water Quality

Both wet ponds reduced the TSS concentrations from inlet to outlet (74% and 73%, Bingham and Raeford, respectively). By reducing the energy of incoming stormwater, the wet ponds enable sediment and attached pollutants to settle. The rate at which sedimentation occurs is based upon settling velocities that are highly dependent on the particle size distribution of the incoming stormwater. With a high sand content comprising this regions underlying soil, sedimentation will occur more rapidly than that of clay particles in other areas with higher clay fractions. One potential concern with infiltrating wet ponds is that the water level would become too low to dissipate inflow energy, resulting in re-suspension of sediment. The significant TSS reductions shown for these two infiltrating wet ponds alleviate this concern. A significant positive relationship existed between the 5-min peak rainfall intensity and the storm's influent TSS concentration at both locations, likely due to higher intensity rainfall events eroding more sediment. The Raeford pond appeared to have substantial amounts of sediment eroding from the banks during events in addition to inflow TSS (Figure 4.13). Bank stabilization is key and the appropriate plants must be selected.

Figure 4.13: Sediment coming off the banks of the Raeford pond

Both ponds significantly reduced inflow TP concentrations with percent median concentration reductions of 9% and 42% at the Bingham and Raeford ponds, respectively. Bingham influent TP concentrations were less than the Raeford influent (Figure 4.1). This difference is likely due to the extensive landscaping at the Raeford site with phosphorus perhaps coming from the fertilized soil. The influent Ortho-P concentrations at the Bingham site were lower than those at the Raeford site. Both ponds significantly reduced ortho-P despite the fact that wet ponds possess few mechanisms for removing dissolved constituents. There were two potential mechanisms for this reduction. The first was the uptake of this dissolved or "reactive" phosphate by plants along the shelves or banks of each pond. A second was that dissolved phosphorus was adsorbing to sediment and then settling in the pond. The extent to which each of these mechanisms occurred is unknown. The adsorption of phosphorus to sediment would have likely occurred pre-SCM when the water was mixing in the storm drain network. Particle bound phosphorus concentrations at the inlets and outlets were not significantly different at either pond. It was expected that the PBP phosphorus would be reduced as sediment settles out of the water column. One potential mechanism to explain this lack of reduction was that the dissolved ortho-P was actually sorbing to sediment in the pond as previously mentioned. There could be some settling of PBP and some ortho-P sorbing to smaller clay particles that remain suspended. This would account for a decrease in ortho-P, but no change in the PBP concentrations. At the Raeford wet pond, a significant positive relationship existed between the influent TP and the influent TSS (regression slope $p\text{-value}<0.0001$), indicating that sediment likely contained bound phosphorus (Figure 4.15). However, the relationship at the Bingham pond was not significant. As with influent TSS concentrations, a significant direct relationship existed between the 5-min peak rainfall intensity and the storm's influent TP concentration at both locations. Both wet ponds were able to decrease the TP concentrations via sedimentation. As with TSS, this ability may differ from location to location depending on the nearby watershed and site.

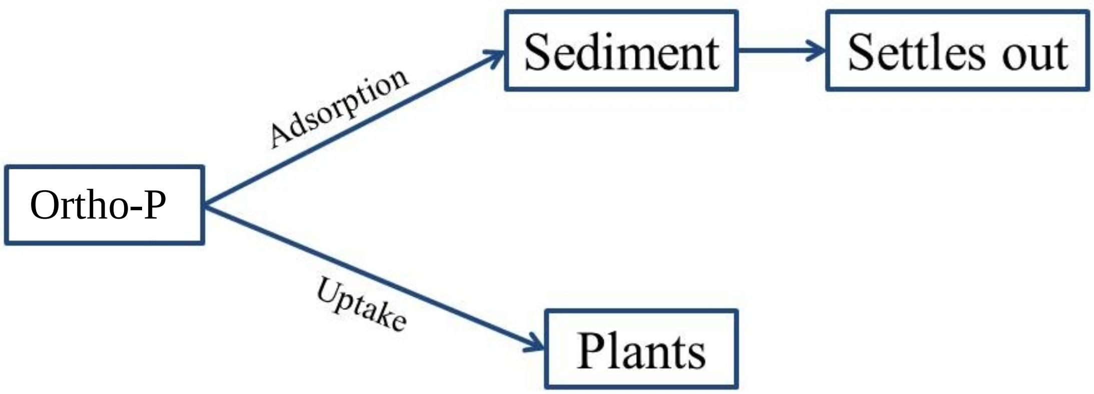


Figure 4.14: Potential pathways for ortho-P removal

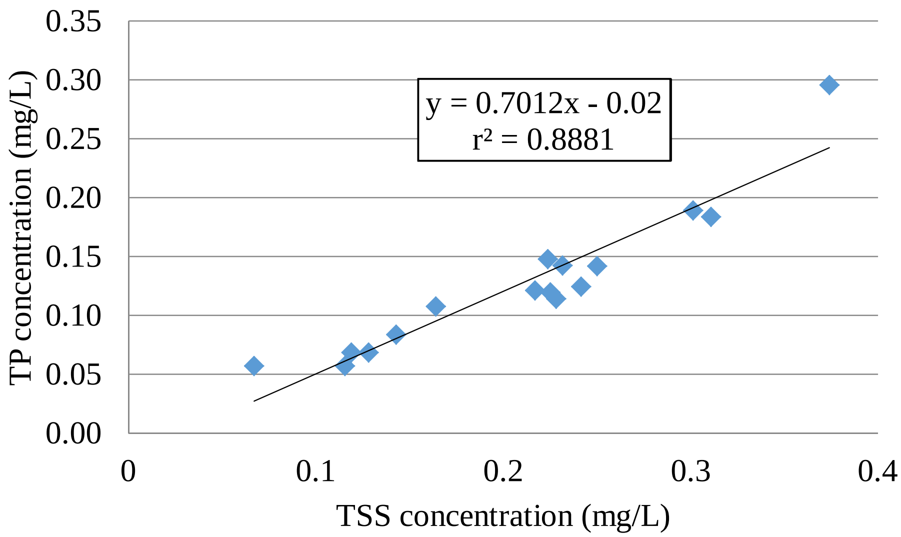


Figure 4.15: TP concentrations versus TSS concentrations at the Raeford site

The Bingham pond's effluent TP concentrations were typically lower than the effluent goal of 0.11 mg/L suggested by McNett et al. (2010) which considered the health of streams as assessed by benthic macro invertebrates. The Raeford pond's effluent TP concentrations did not meet the same goal.

Only the Raeford pond significantly reduced inflow TN concentrations. Typically, influent $NO_{2,3}$-N comes from the application of commercial fertilizers and atmospheric deposition (Bannerman et al., 1993). Both ponds significantly reduced the $NO_{2,3}$-N concentrations with percent median concentration reductions exceeding 58%. The reduction in $NO_{2,3}$-N is suspected to be due to denitrification in anaerobic zones at the bottom of the pond (Figure 4.16) where nitrate and nitrite would be converted to nitrogen gas (Knowles, 1982). It is also possible that some of the $NO_{2,3}$-N was taken up by plants along the shelves and banks (Lenhart et al., 2012).

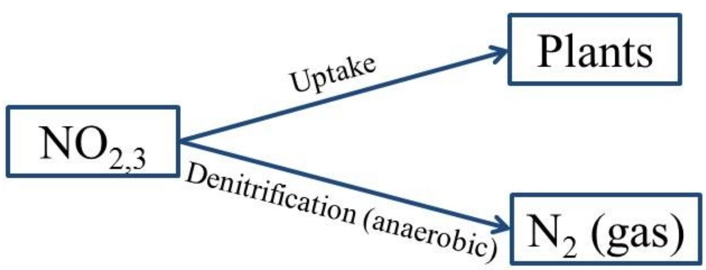


Figure 4.16: Potential pathways for NO_x removal

Inflow TAN concentrations were significantly reduced at both locations. The sources of TAN in urban watersheds include animal wastes, and atmospheric deposition on rooftops, driveways and roads (Bannerman et al., 1993). The concentration reductions from inlet to outlet were likely due to one of three mechanisms (Figure 4.17): (1) adsorption of NH_4^+ ions to the negative sediment particles; (2) NH_4^+ ions are transformed into nitrate via nitrification in the upper aerobic zone of the pond, and then are reduced by denitrification; and (3) uptake by plants located around the perimeter of the pond could also sequester NH_4^+.

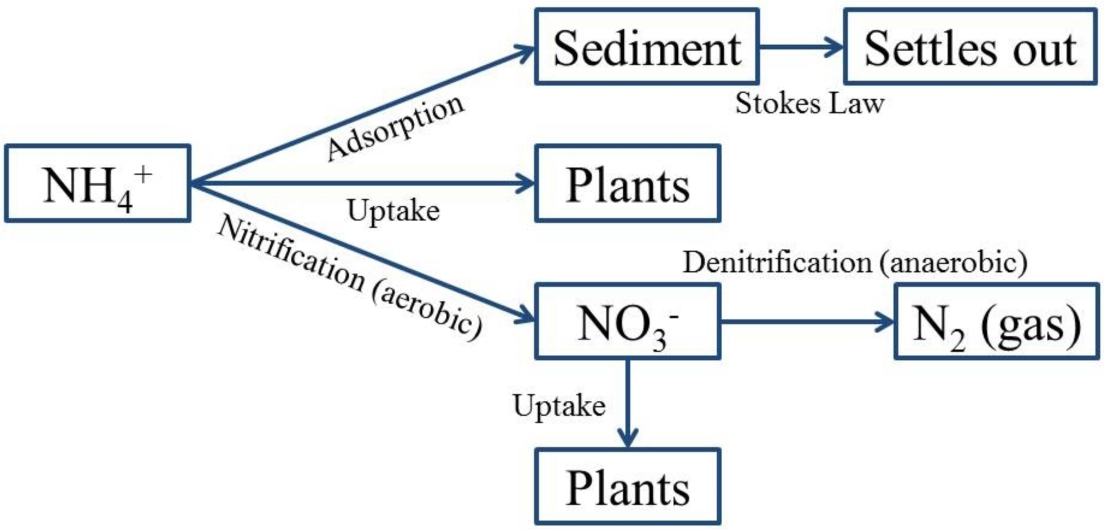


Figure 4.17: Potential pathways for NH_4^+ removal

The Bingham pond increased ON while the ON concentrations between inflow and outflow at the Raeford pond were unchanged. The sole pathway for ON removal in a wet pond is mineralization to NH_4^+, and based on the results, this did not occur quickly enough to reduce ON concentrations. At the Bingham site, grass clippings, leaf litter, and droppings (manure) from ducks and geese were evident. At the Bingham pond, the landscaping crews cut the grasses to the edge of the pond, and the mowers would discharge the clippings onto the pond itself, increasing the amount of organic matter and nitrogen in the pond (Figure 4.18).


Figure 4.18: Grass clipping and other organic matter along the edge of the Bingham pond

Because TAN was significantly reduced, the lack of TKN and TN treatment at both ponds were likely due to the ON fraction of TKN. Both the Bingham pond and the Raeford pond met the suggested TN effluent concentration of 0.99 mg/L suggested by McNett et al. (2010).

The effluent nutrient and TSS concentrations were not substantially different from those leaving other monitored non-infiltrating wet ponds (Figure 4.19, Figure 4.20, and Figure 4.21).

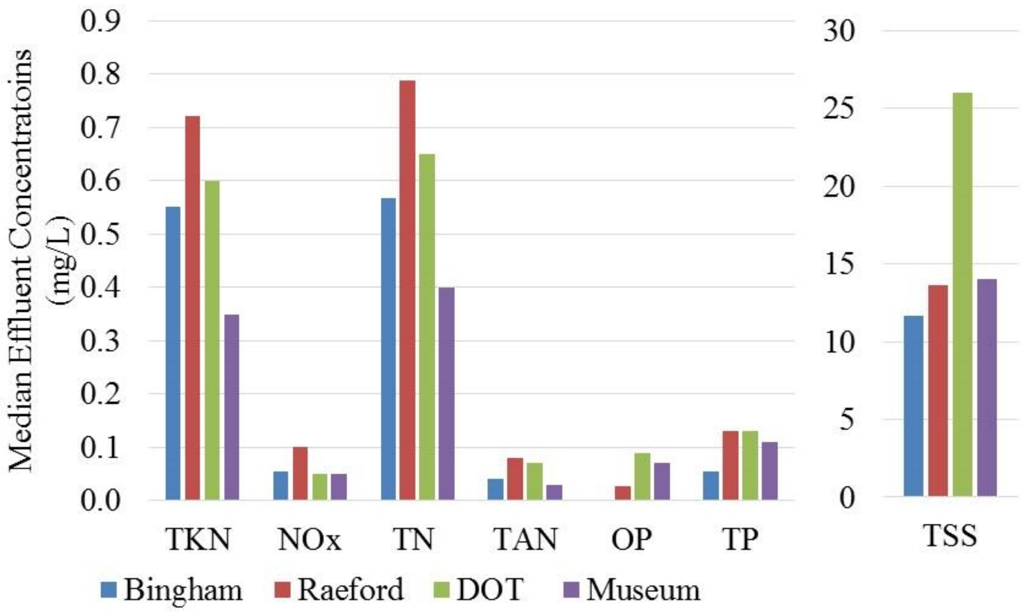


Figure 4.19: Median effluent concentrations compared to Winston et al., 2013

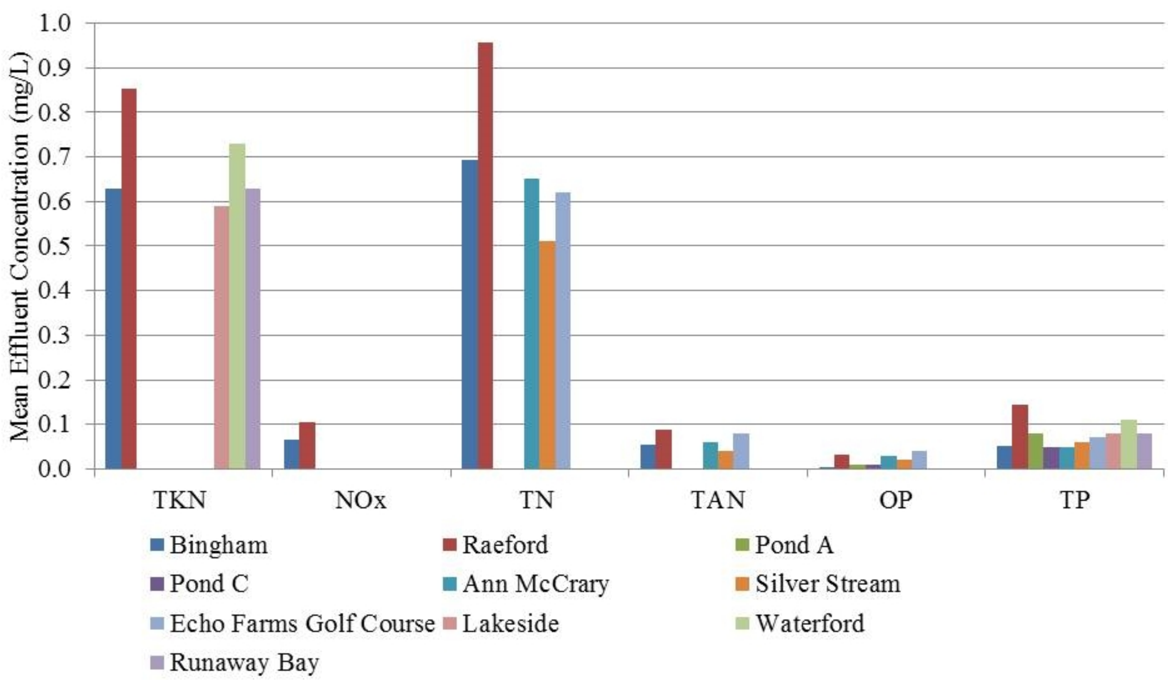


Figure 4.20: Mean effluent nutrient concentrations compared to other wet pond studies (Comings et al., 2000; Mallin et al., 2002; Wu et al., 1996)

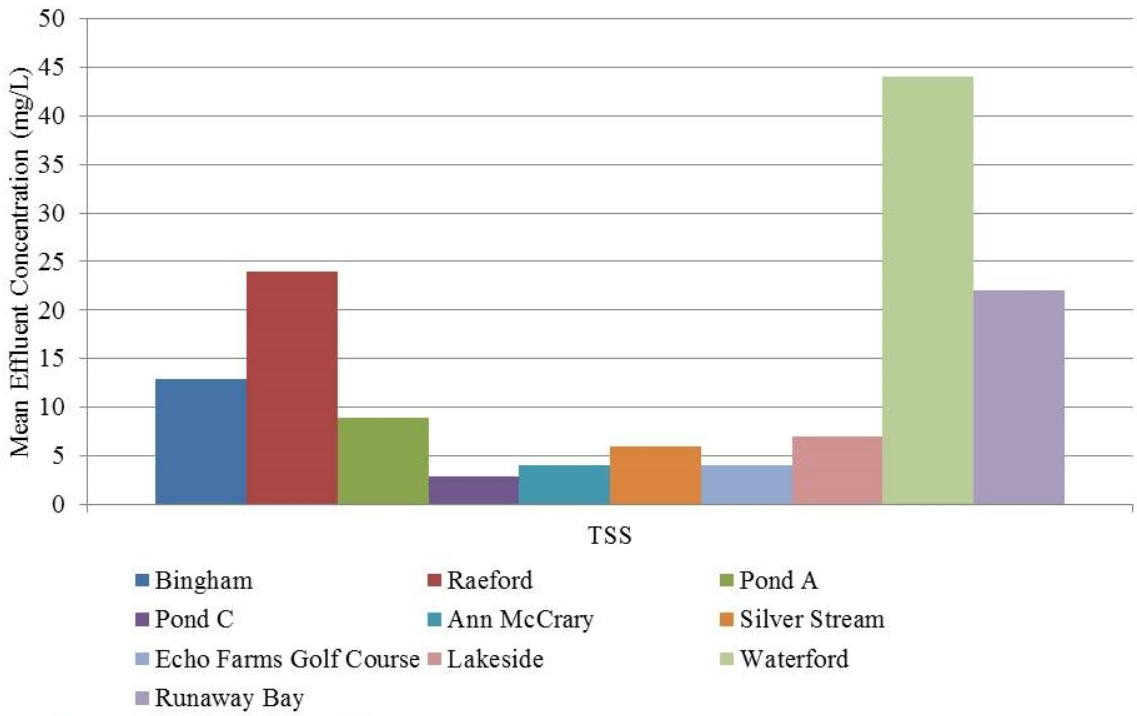


Figure 4.21: Mean effluent TSS concentrations compared to other wet pond studies (Comings et al., 2000; Mallin et al., 2002; Wu et al., 1996)

4.2.3 Loading

The water quality concentrations reported are an intensive property. Loadings are an extensive property that account for the change in pollutant concentrations as well as any decrease in volume leaving the facility. Both are important metrics in analyzing SCMs. When water quality concentrations are combined with the volume reductions, infiltrating wet ponds reduce pollutant loads substantially. The ponds' abilities to reduce inflow volumes are key. For example, despite the Bingham pond discharging higher ON concentrations, the pond still reduced loads. A similar result was found for the Raeford pond.

The Raeford pond met the pollutant removal credit metric for TP of 40% (NCDENR, 2009) based on concentrations alone; however, the Bingham pond did not. When considering loads, both ponds were able to surpass this metric. The Raeford pond also met the pollutant removal credit metric for TN of 25% based on concentrations alone; however, the Bingham pond did not. When factoring in the volume reductions, the median TN load reductions were 50% and 47% at the Bingham and Raeford sites, respectively. The TSS median load reductions at the Bingham pond did surpass the pollutant removal credit metric of 85%; however, the Raeford site fell short at only 67%.

The calculated loadings for the water quality events were scaled up to a yearly basis based on the total volume sampled and the total volume over a period of one year (Appendix E) (Table 4.20 and Table 4.21). Comparing the results to annual mass export rates from an undeveloped site in the Piedmont of North Carolina (Line and White, 2007), the Bingham pond had considerably lower export rates post-SCM than those of undeveloped conditions for all constituents except TAN. At the Raeford site, the export rates post-SCM were lower than those reported for North Carolina undeveloped except TAN and TP.

Table 4.20: Calculated annual loadings at the Bingham site

Variable	Annual Influent loading (kg/yr)	Annual Effluent loading (kg/yr)	Annual Influent loading (kg/ha/yr)	Annual Effluent loading (kg/ha/yr)	Percent Reduction (%)	NC undeveloped* (kg/ha/yr)
TKN	11.1	4.8	4.7	2.0	57	5.3
$NO_{2,3}$	2.8	0.8	1.2	0.3	74	1.0
TN	13.9	5.5	5.9	2.3	60	6.3
TAN	2.9	0.7	1.2	0.3	77	0.2
ON	8.2	4.1	3.5	1.7	50	-
OP	0.2	0.04	0.07	0.02	74	-
PBP	1.3	0.4	0.5	0.2	66	-
TP	1.5	0.5	0.6	0.2	68	0.5
TSS	1109.0	140.8	468.5	59.5	87	349

*(Line and White, 2007)

Table 4.21: Calculated annual loadings at the Raeford site

Variable	Annual Influent loading (kg/yr)	Annual Effluent loading (kg/yr)	Annual Influent loading (kg/ha/yr)	Annual Effluent loading (kg/ha/yr)	Percent Reduction (%)	NC undeveloped* (kg/ha/yr)
TKN	14.5	7.9	7.5	4.1	46	5.3
$NO_{2,3}$	3.3	1.4	1.7	0.7	58	1.0
TN	17.8	9.3	9.2	4.8	48	6.3
TAN	3.3	1.2	1.7	0.6	62	0.2
ON	11.4	6.7	5.9	3.4	42	-
OP	1.3	0.4	0.7	0.2	68	-
PBP	2.0	1.1	1.0	0.6	41	-
TP	3.1	1.6	1.6	0.8	49	0.5
TSS	980.8	325.2	505.8	167.7	67	349

*(Line and White, 2007)

4.2.4 Aesthetics

As with any SCM, aesthetics and public acceptance of the SCM is important. How an SCM looks and “fits” into the landscape should be considered. Unfortunately, there is no set of established metrics to analyze the attractiveness of an SCM. Standard (non-infiltrating) wet ponds can have a pleasant appearance when incorporated into a landscape correctly (Figure 4.22). However, infiltrating wet ponds may be considered an eye-sore to the general public. When the water level recedes below the normal pool, bare soil is exposed (Figure 4.23). Due to this fact, it is crucial for infiltrating wet ponds to have the proper vegetation selection.

Figure 4.22: Wet pond in Singapore that fits into the landscape and is aesthetically pleasing (photo credit: Laura Merriman)

Figure 4.23: Infiltrating wet pond with bare banks, exposed soil, and that is not aesthetically pleasing

4.2.5 Mosquitoes

Because wet ponds contain standing water for extending periods of time, these practices can become breeding grounds for mosquitoes (Hunt et al., 2006). A comprehensive mosquito study was performed at both ponds in August of 2014. A cup of pond water was grab sampled every 4-5 m along the edge of the pond (Figure 4.24). The sample was checked for number and type of mosquito larvae. At the conclusion of the study there were no mosquito larvae present at either pond. Several mosquito larvae predators were found in abundance at both ponds. At the Bingham pond there were substantial tadpoles (*Rana temporaria*), whirly gig beetles (*Gyrinus natator*), and damsel flies (*Ischnura heterosticta*). At the Raeford pond there were a substantial number of back swimmers (Family:

Notonectidae). Neither pond contained mosquitofish (*Gambusia*). The fact that both wet ponds were not shaded and had little vegetation around the perimeter likely aided in keeping mosquito populations to a minimum (Hunt et al., 2006).

Figure 4.24: Sampling for mosquitoes along the pond perimeter

5 Further Considerations and Research

5.1 Design Consideration

5.1.1 Liners, Sizing, and Aquatic Shelves

Infiltrating wet ponds do not function as a standard wet pond. Standard, non-infiltrating, wet ponds are designed specifically for peak flow attenuation and water quality treatment. They are not intended to reduce total outflow, and are often being designed to restrict infiltration. Infiltrating wet ponds are also not infiltration basins as they do maintain a (often shallow) pool of water even in drier conditions. Infiltrating wet ponds are "in between" practices, containing aspects of both wet ponds and infiltrations basins.

For an infiltrating wet pond to be designed for peak flow attenuation, water quality treatment, and volume reduction, there are certain design elements that would differ from those of a standard wet pond. First and foremost, an infiltrating wet pond would not be designed with a clay or bentonite liner that encompasses the entire basin. If the goal is to allow as much water as possible to infiltrate, there would be no need for a liner to restrict infiltration. However, infiltrating wet ponds should not go completely dry, even during droughts. A series of small pools should retain water year-round, serving as a habitat for mosquito predators (Hunt III et al., 2006). Moreover, standing water is important to prevent re-suspension of sediment. To create sustainable wet pools over sandy soils, small portions, such as the forebay, of the pond may need to be lined (Figure 5.1). This would allow infiltration to occur in the majority of the basin, yet still maintain some water in the forebay for energy dissipation and habitat for mosquito predators. There is no reason for the average depth of infiltrating wet ponds (1 m to 2.5 m) to change from current design guidelines.

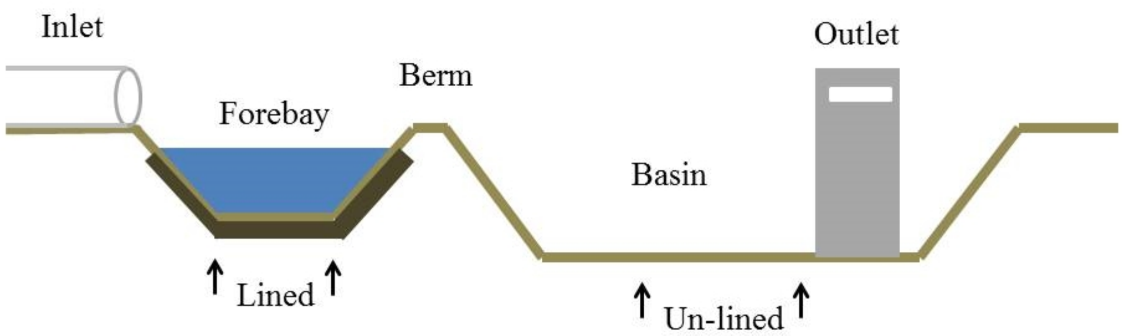


Figure 5.1: Liner installed beneath forebay

As noted previously, infiltration can also be increased by having a larger surface area of the pond. A larger pond surface area also provides a larger evaporation surface. However, increasing the amount of land area or footprint of a SCM is costly, as it reduces developable space.

To design a wet pond for infiltration, identifying the location of the seasonal high water table (SHWT) is critical. For infiltration to occur, the wet pond's normal pool elevation must be higher than that of the SHWT. Currently design guidance by NCDENR suggests that the permanent pool elevation should be within ±15 cm of the SHWT.

Wet ponds that infiltrate should be designed with a vegetated shelf such as that of any wet pond. The vegetated shelf should have a slope not exceeding 3:l, due to safety (NCDENR, 2009). Shallow depths within a wet pond are important because this is the zone in which nitrification and denitrification occur (NCDENR, 2009). The shelf should be well established with plants, because vegetation improves the water quality performance of the pond, stabilizes the shelf and embankment and also helps improve the aesthetics of the pond. Plants selected must survive under the wide range of moisture conditions along the shelf. Infiltrating wet pond vegetated shelves should be placed at a lower elevation than those of a standard wet pond. If the shelf is placed lower into the water, the plants will have more access to water. Currently, the inside edge of the shelf is located 15-cm below the normal pool, and the outside edge is located 15-cm above the normal pool. For instance, installing the shelf at an elevation where the inside edge is 30-cm deep may increase the plants' chance of survival by increasing the amount of time the plant has access to water. Specific planting recommendations can be found in section 5.1.2.

Another important design parameter of wet ponds is size of the low-flow draw down orifice. The low-flow draw down orifice in a standard wet pond is designed by using the orifice equation to determine a specific diameter needed to release the water quality volume within 2-5 days. If an infiltrating wet pond's low-flow orifice is sized as it would be for a standard wet pond, the water-quality volume will draw down in less time than designed because of infiltration. Accounting for infiltration will lead to an orifice diameter that is smaller than that of a standard wet pond. In doing this, the hydrologic and potentially the water-quality function provided the wet pond may be slightly improved. However, with a smaller orifice size there is a greater risk of the orifice clogging with trash or debris. The clogging risks may out-weigh the slight benefit to water quality.

5.1.2 Plant Selection

Vegetation is important for wet ponds. Plants stabilize the pond shelf and decrease erosion. The root systems of the plants hold the soil in place while the leaves and canopy of the plants reduce some erosive forces of intense rainfall (Bochet et al., 1998; Bochet et al., 2006; Zhou et al., 2008). Plants reduce nutrient concentrations via uptake (Lenhart et al., 2012). Because of stormwater-borne nutrients, properly selected plants along the shelves of wet ponds are able to thrive and do not require fertilization once established. Plants provide an environment for nitrification and denitrification (Knowles, 1982). Vegetation improves the aesthetics of a wet pond by adding additional color and life to the landscape. With an infiltrating wet pond, plants are even more important because they stabilize the bank and provide aesthetics when the pond water level is low. Moreover, since plants evapotranspire (Lott and Hunt, 2001; Pauliukonis and Schneider, 2001) they may contribute to volume reductions.

Plant selection is based on (1) the amount of time a plant is expected to be inundated and (2) duration of drought conditions. Because of fluctuating water levels, the palette of plants for infiltrating wet ponds is more limited than that of standard wet ponds. Plants in an infiltrating wet pond experience rapid changes in the soil moisture content and length of time they are inundated.

A variety of plants should be selected for wet pond aquatic shelves, which decreases the chance of creating a monoculture. A minimum of 3 different species should be selected (NCDENR, 2009). Plants must be tolerant of dry conditions and inundation. Inundation of water will typically not last more than 3 days; however, the dry conditions could persist for at least a month. Most plants will handle the temporary inundation better than the extended dry conditions (Naumburg et al., 2005); thus, it is important to select plants that are drought tolerant. One naturally occurring landscape that mimics a hydrologic pattern of a wet pond shelf is river banks in the North Carolina Coastal Plain. These areas are typically very sandy, and moisture conditions change rapidly (Wells, 1928). Vegetation becomes inundated when the river level rises, but then experiences low moisture conditions during droughts. Plants that naturally grow in these areas may be successful on the shelf of an infiltrating wet pond.

Recommended plants can be divided in two groups: shrubs /perennials and grasses (Table 5.1). The red star hibiscus, goldenrod, and silky dogwood produce colorful flowers that add to the aesthetics of the wet ponds.

Table 5.1: Plant recommendations for infiltrating wet pond shelves

Shrubs/Perennials		
Common name	Scientific name	Comments
Beautyberry	*Callicarpa americana*	pink berries
Chokeberry	*Aronia arbutifolia*	dark berries
Red star hibiscus	*Hibiscus coccineus*	red flowers; may be confused with marijuana
Goldenrod	*Solidago*	yellow flowers
Buttonbush	*Cephalanthus occidentalis*	white to pale yellow flower
Possumhaw	*Viburnum nudum*	pink and blue berries
Silky dogwood	*Cornus amomum*	white flowers
Virginia Sweetspire	*Itea virginica*	white flowers

Grasses		
Common name	*Scientific name*	Comments
Sweet grass*	*Muhlenbergia filipes*	*filipes* variant best
Switchgrass	*Panicum virgatum*	Shanandoah variant also acceptable
River oats	*Chasmanthium latifolium*	oat-like seed-heads
Little bluestem	*Schizachyrium scoparium*	color ranges from blue tint to red
Indiangrass	*Sorghastrum nutans*	golden seed head

*Many nurseries in North Carolina carry different varieties of sweet grass; however, it is important to get the *filipes* variant as it is better adapted to varying conditions.
(C. Glen, Personal Communication, Sep. 24, 2014; B. Lord, Personal Communication, November 24, 2014)

The shrubs/perennials are recommended by NCDENR (2009) to should be planted at a density of 8 shrubs per 18 m^2; grasses at a minimum density of 50 plants per 18 m^2. This spacing allows the plants to properly grow without interfering with one another (C. Glen, Personal Communication, Sep. 24, 2014). Plant establishment is critical. Ideally, planting should be done in the autumn or spring (NCDENR, 2009), with spring preferable due to wetter conditions and the potentially higher water level within the pond. If vegetation is planted in the autumn, it may require initial watering to aid in establishment.

Vegetation should be planted on the upper bank, the area from the outer edge of the shelf to the existing ground (Figure 1.6). This includes the top of the dam and berms. This zone typically has high slopes (and highly erosive), making stabilization critical. Turf grass should be planted to stabilize the embankment and make access for maintenance purposes easier. For these locations, centipede grass is recommended (NCDENR, 2009). Trees and woody shrubs should not be planted on the dam and berms because high winds could topple them, jeopardizing the integrity of the embankment.

It is not recommended to plant Cattails (*Typha* spp.) as they tend to overtake other vegetation and create a monoculture (Hunt et al., 2006). Cattails tend to provide a habitat that shelters mosquitoes from their predators (Knight et al., 2003). If cattails do colonize at least 15% of a wet pond that is located near a neighborhood or residential area, the cattails should be removed (NCDENR, 2009).

Despite the often shallow water levels of infiltrating wet ponds, plants should not be placed in the deep area of the basin. Plants in this area are not practical due to the potential for high depths of water and prolonged inundation. However, this area could sustain plants via floating treatment wetlands (Winston et al., 2013).

5.1.3 Maintenance

As with any other SCM, infiltrating wet ponds should be maintained on a regular basis with a similar maintenance schedule to that of a standard wet pond (NCDENR, 2009). With an infiltrating wet pond, vegetation health should be regularly monitored because the vegetation will be subjected to greater water level fluctuations than in a standard wet pond. The banks and perimeter of the pond should be monitored for erosion or areas of bare soil. As the water level drops, there is a greater chance of bare soil exposure which can lead to erosion and/or erosive gullies forming. If this occurs, correct with vegetation to stabilize the bank and reduce any further sediment input into the wet pond (NCDENR, 2009).

5.2 Further Research

As this is the first study on infiltrating wet ponds, many areas still need further research. One way to improve upon this research would be to directly monitor two wet ponds, one that infiltrates and one that does not. This study showed there can be significant reductions in volume, nutrients and TSS from infiltration wet ponds; however, there was no direct comparison to a non-infiltrating wet pond. A study of an infiltrating wet ponds with herein design recommendations would also be beneficial.

Another area of potential research would be to automate a wet pond with real time controls similar to DeBusk (2013). In theory, the system would read NOAA precipitation forecast values and release water only when the forecast for rain in the next couple of days is above a certain threshold. With this design and controls, captured water could be detained as long as possible to optimize sedimentation, plant uptake and plant nourishment, but still be able to capture the next storm event.

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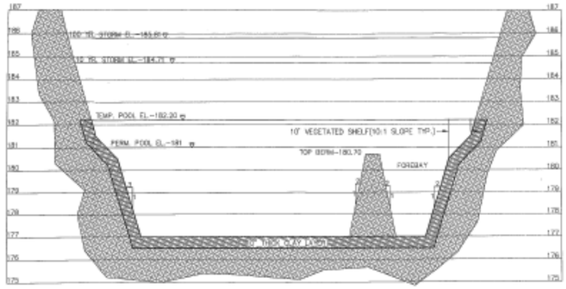
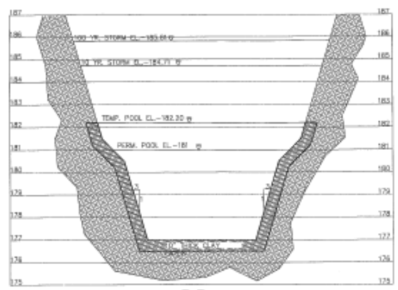
APPENDICES

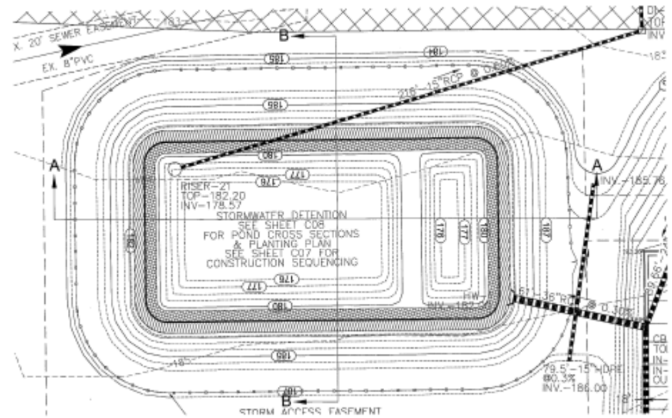
Appendix A: Detailed Pond Drawings



A-A
SCALE: 1"=20' HOR.
1"=2' VER



B-B
SCALE: 1"=20' HOR.
1"=2' VER



POND PLANTING PLAN
SCALE: 1"=20' HOR.
1"=2' VER

PLANTING SCHEDULE

SHALLOW LAND

SHALLOW WATER

SHALLOW LAND COMMUNITY (NORMAL POOL TO 6" ABOVE) = 2,393 S.F.								1 PLANT/9 S.F. (36" O.C.) = 266 PLANTS
PLANT TYPE	QTY	KEY	BOTANICAL NAME	COMMON NAME	ROOT	CALIPER	HEIGHT	NOTES
HERBACEOUS	80		Asclepias incarnata	Swamp Milkweed	CONT.	4" Pot		36" O.C.
	80		Carex stricta	Tussock Sedge	CONT.	4" Pot		36" O.C.
	80		Lobelia cardinalis	Cardinal Flower	CONT.	4" Pot		36" O.C.
SHRUBS	9		Aronia arbutifolia	Red Chokeberry	CONT.	3 Gal.	18"-24"	36" O.C.
	9		Cephalanthus occidentalis	Buttonbush	CONT.	3 Gal.	18"-24"	36" O.C.
	8		Ilex glabra	Inkberry	CONT.	3 Gal.	18"-24"	36" O.C.

NOTE: ONLY HERBACEOUS SPECIES SHALL BE LOCATED ON FOREBAY BERM.

SHALLOW WATER COMMUNITY (NORMAL POOL TO 6" BELOW) = 2,236 S.F.								1 PLANT/9 S.F. (36" O.C.) = 249 PLANTS
PLANT TYPE	QTY	KEY	BOTANICAL NAME	COMMON NAME	ROOT	CALIPER	HEIGHT	NOTES
HERBACEOUS	51		Iris versicolor	Blue Flag Iris	CONT.	4" Pot		36" O.C.
	75		Juncus effusus	Soft Rush	CONT.	4" Pot		36" O.C.
	75		Pontedaria cordata	Pickerelweed	CONT.	4" Pot		36" O.C.
	24		Saururus cernuus	Lizard's tail	CONT.	4" Pot		36" O.C.
	24		Schoenoplectus tabernaemontani	Softstem Bulrush	CONT.	4" Pot		36" O.C.

[redacted]

Figure A.1: Bingham Pond Drawing

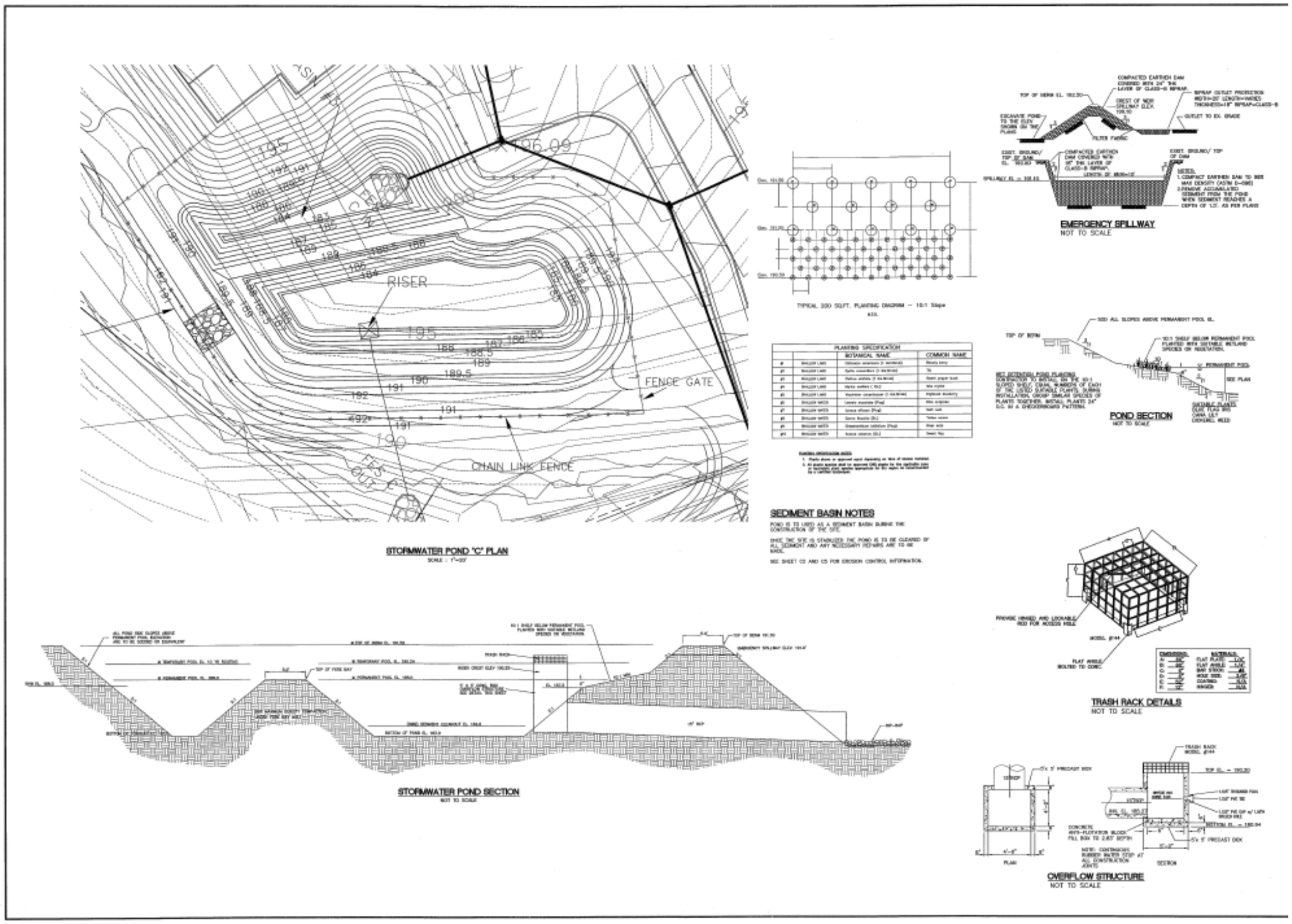


Figure A.2: Raeford Pond Drawing

Appendix B: Stage-Storage Measurements

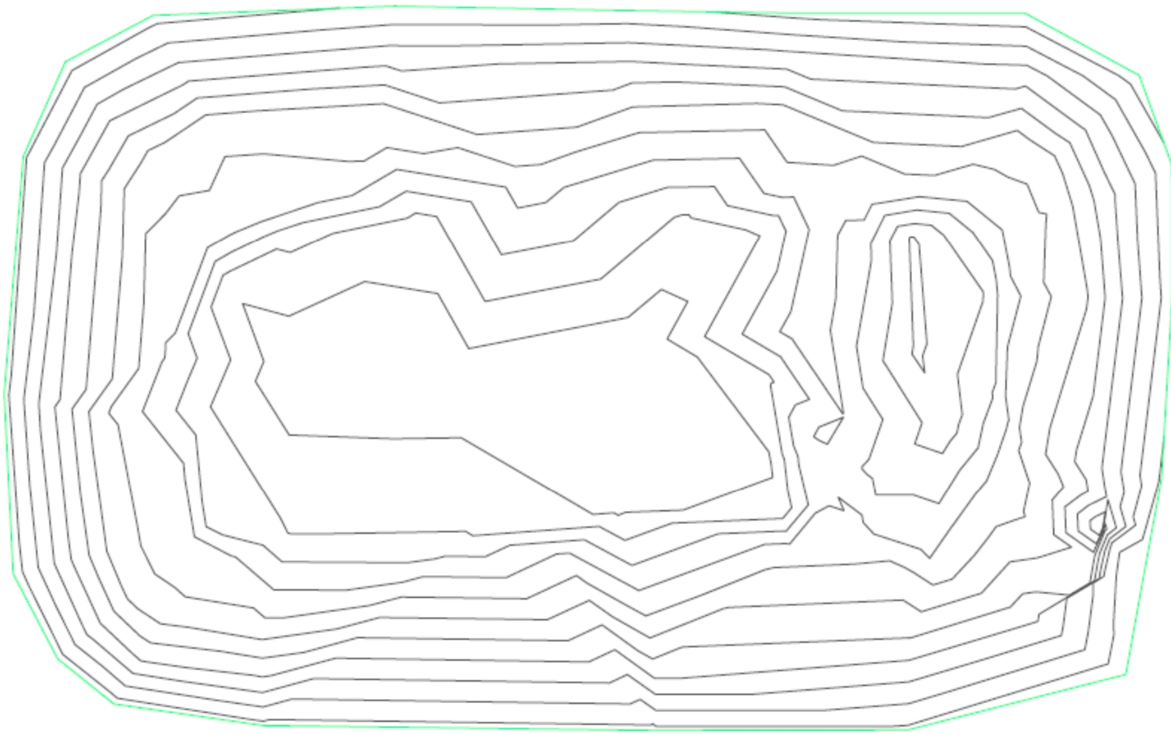


Figure B.1: Bingham one foot contours

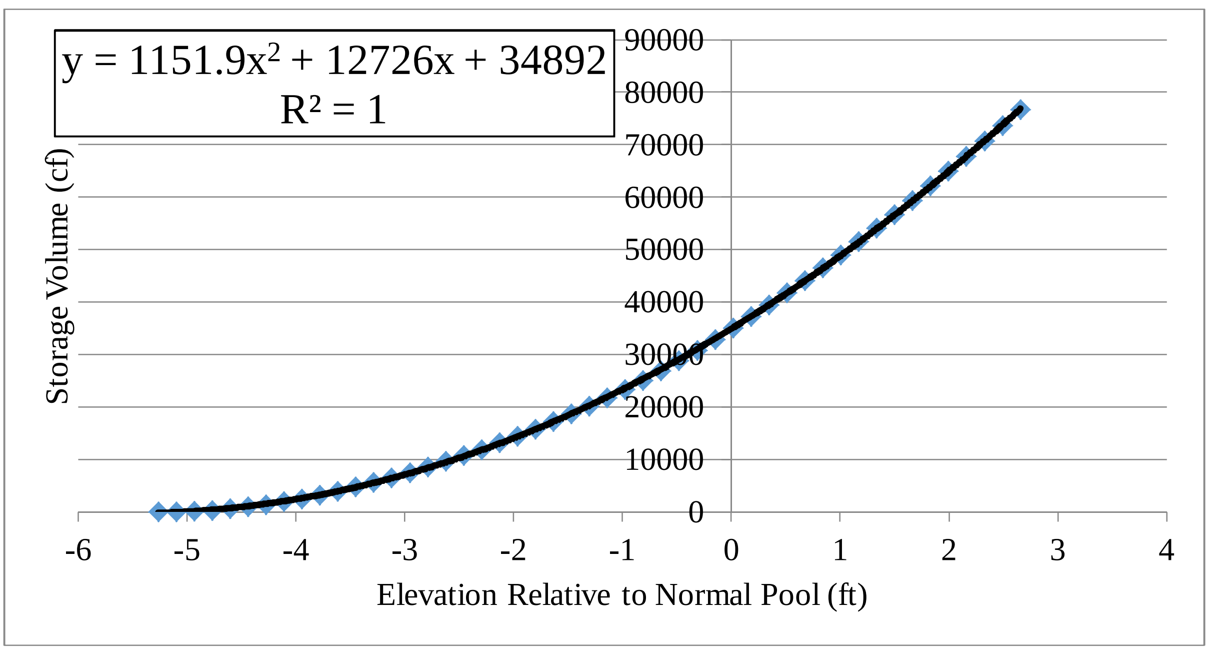


Figure B.2: Bingham Stage-Storage Relationship

Figure B.3: Raeford one foot contours

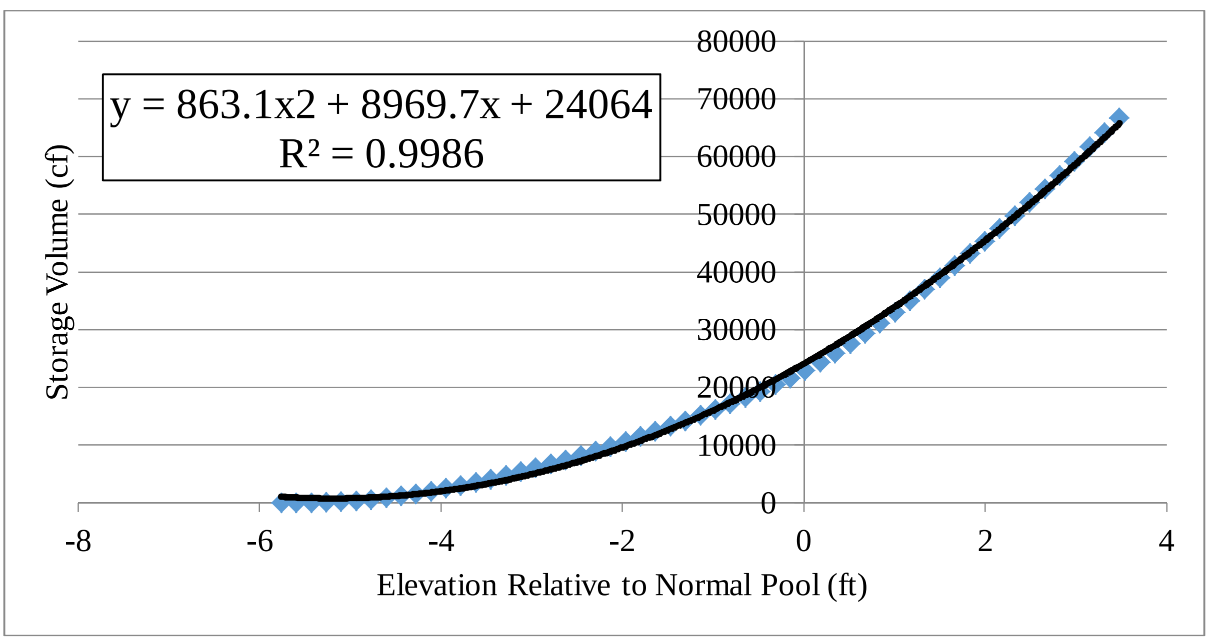


Figure B.4: Raeford Stage-Storage Relationship

Appendix C: Detailed Percent Reductions Calculations

Peak flow rate reduction

$$\left(\frac{Q_{peak,\ inf} - Q_{peak,\ eff}}{Q_{peak,\ inf}}\right) * 100$$

Where:
$Q_{peak,\ inf}$ – Peak influent flow rate
$Q_{peak,\ eff}$ – Peak effluent flow rate

Volume reduction

$$\left(\frac{V_{inf} - V_{eff}}{V_{inf}}\right) * 100$$

Where:
V_{inf} – Influent volume
V_{eff} – Effluent volume

Concentration reduction

$$\left(\frac{EMC_{inf} - EMC_{eff}}{EMC_{inf}}\right) * 100$$

Where:
EMC_{inf} – Influent concentration
EMC_{eff} – Effluent concentration

Loading reduction

$$\left(\frac{Load_{inf} - Load_{eff}}{Load_{inf}}\right) * 100$$

Where:
$Load_{inf}$ – Influent loading
$Load_{eff}$ – Effluent loading

Appendix D: Raw Data - Event Mean Concentrations

Table D.1: Bingham EMCs

		TKN (mg/L)		NH_3-N (mg/L)		$NO_{2,3}$-N (mg/L)		TN (mg/L)		TP (mg/L)		Ortho-P (mg/L)		TSS (mg/L)	
Storm	Rain (mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
5/19/13	18	0.76	1.01	0.34	0.08	0.23	0.08	1.00	1.09	0.05	0.08	0.010	0.008	25	12
5/23/13	6	1.17	0.88	0.62	0.05	0.37	0.06	1.55	0.94	0.07	0.06	0.008	0.004	86	18
6/3/13	8	2.12		0.38		0.25		2.37		0.19		0.038		45	
6/10/13	29	0.46	0.35	0.05	0.02	0.10	0.05	0.56	0.40	0.17	0.05	0.008	0.003	113	11
6/13/13	13	0.87	0.48	0.24	0.02	0.24	0.01	1.11	0.49	0.07	0.04	0.006	0.002	56	7
6/18/13	8	1.47	0.85	0.13	0.03	0.30	0.01	1.77	0.86	0.10	0.06	0.010	0.004		26
6/23/13	25	0.62	0.75	0.16	0.02	0.12	0.01	0.74	0.76	0.06	0.08	0.011	0.007	73	24
6/24/13	12	0.38	0.55	0.10	0.02	0.19	0.02	0.56	0.57	0.03	0.04	0.002	0.001	31	12
6/25/13	14	0.51	0.81	0.11	0.03	0.31	0.01	0.82	0.82	0.05	0.05	0.003	0.001	33	12
6/26/13	16	0.45	0.74	0.19	0.02	0.26	0.01	0.72	0.74	0.03	0.05	0.002	0.002	27	23
8/21/13	18	0.40	0.42	0.13	0.06	0.12	0.05	0.53	0.46	0.05	0.04	0.004	0.010	30	3
10/7/13	8	1.43		0.22		0.15		1.58		0.26		0.110		44	
11/26/13	42	0.30	0.34	0.06	0.04	0.11	0.13	0.40	0.47	0.05	0.06	0.005	0.001	62	7
12/9/13	16	0.76	1.35	0.16	0.08	0.20	0.09	0.96	1.44	0.14	0.08	0.008	0.006	71	
12/14/13	39	0.50	0.97	0.07	0.08	0.07	0.11	0.56	1.08	0.08	0.06	0.004	0.002	118	6
1/10/14	70	0.55	0.46	0.09	0.06	0.06	0.05	0.60	0.51	0.11	0.05	0.009	0.007	64	15
2/5/14	4	0.69		0.21		0.28		0.96		0.05		0.013		39	
3/3/14	10	1.25		0.59		0.38		1.63		0.10		0.025		59	
3/6/14	39	0.25	0.38	0.10	0.10	0.10	0.13	0.36	0.51	0.03	0.02	0.007	0.001	20	7
3/17/14	15	0.35	0.30	0.14	0.07	0.13	0.11	0.48	0.41	0.04	0.02	0.007	0.002	20	3
3/28/14	37	0.53	0.31	0.16	0.04	0.12	0.11	0.65	0.42	0.04	0.02	0.003	0.003	41	5
4/18/14	25	0.23	0.28	0.04	0.02	0.10	0.03	0.32	0.31	0.02	0.03	0.004	0.001	12	5
4/29/14	76	1.01	0.72	0.26	0.18	0.25	0.17	1.26	0.89	0.14	0.08	0.012	0.008	139	35

Table D.2: Raeford nitrogen species EMCs

Storm date	Rainfall (mm)	TKN (mg/L)			NH_3-N (mg/L)			$NO_{2,3}$ (mg/L)			TN (mg/L)		
		Inlet 1	Inlet 2	Eff	Inlet 1	Inlet 2	Eff	Inlet 1	Inlet 2	Eff	Inlet 1	Inlet 2	Eff
8/21/13	20	1.06	1.25	0.79	0.18	0.09	0.07	0.13	0.09	0.02	1.19	1.34	0.81
9/21/13	19	0.86	0.78	1.68	0.14	0.12	0.04	0.27	0.22	0.05	1.13	1.00	1.73
10/7/13	6	1.13	2.24		0.13	0.51		0.15	0.09		1.28	2.33	
12/9/13	20	1.00	2.59	0.10	0.33	0.18	0.10	0.21	0.20	0.10	1.21	2.79	0.20
12/14/13	40	1.08	0.78	0.66	0.21	0.06	0.10	0.15	0.05	0.10	1.23	0.83	0.76
1/14/14	5	0.64		0.56	0.14		0.06	0.29		0.08	0.93		0.64
2/4/14	14	1.22	1.15	0.55	0.35	0.25	0.07	0.36	0.15	0.09	1.58	1.30	0.65
3/3/14	9	1.34	1.72		0.82	1.02		0.44	0.25		1.78	1.97	
3/6/14	46	0.77	0.45	0.60	0.26	0.15	0.10	0.26	0.11	0.15	1.02	0.56	0.75
3/17/14	22	0.78	0.67	0.54	0.26	0.13	0.09	0.25	0.09	0.15	1.04	0.76	0.69
3/28/14	34	0.93	2.35	0.65	0.25	0.41	0.06	0.32	0.10	0.12	1.25	2.44	0.77
4/15/14	10	1.71	1.42		0.14	0.13		0.41	0.21		2.12	1.63	
4/15/14	21	1.22	1.16	0.89	0.07	0.07	0.03	0.19	0.08	0.10	1.41	1.25	0.99
4/18/14	31	0.69	0.59	0.61	0.10	0.18	0.05	0.17	0.08	0.06	0.86	0.67	0.68
4/29/14	81	0.92		1.06	0.17	0.35	0.20	0.27		0.22	1.20		1.28
6/17/14	28	1.82	1.19	1.64	0.45	0.43	0.12	0.52	0.31	0.16	2.33	1.50	1.81
6/27/14	24	1.48	0.83	1.06	0.38	0.24	0.16	0.24	0.15	0.05	1.72	0.97	1.11
7/10/14	21	1.37	1.04	1.43	0.33	0.16	0.03	0.40	0.28	0.07	1.76	1.33	1.50
8/2/14	6	0.77	0.83		0.16	0.21		0.32	0.35		1.09	1.18	
8/9/14	102	0.77	0.71	0.80	0.17	0.12	0.13	0.15	0.14	0.14	0.92	0.85	0.94

Table D.3: Raeford phosphorus species and TSS EMCs

		TP (mg/L)			Ortho-P (mg/L)			TSS (mg/L)		
Storm date	Rainfall (mm)	Inlet 1	Inlet 2	Effluent	Inlet 1	Inlet 2	Effluent	Inlet 1	Inlet 2	Effluent
8/21/13	20	0.32	0.39	0.14	0.18	0.05	0.02	53	190	25
9/21/13	19	0.26	0.12	0.22	0.11	0.03	0.01	76	49	61
10/7/13	6	0.26	0.22		0.04	0.02		131	116	
12/9/13	20	0.24	1.05	0.12	0.12	0.19	0.04	41	1265	12
12/14/13	40	0.34	0.27	0.17	0.12	0.10	0.06	187	73	15
1/14/14	5	0.07		0.15	0.01		0.07	19		9
2/4/14	14	0.24	0.18	0.12	0.09	0.01	0.03	34	160	9
3/3/14	9	0.12	0.11		0.06	0.03		25	56	
3/6/14	46	0.15	0.06	0.10	0.06	0.03	0.03	24	19	9
3/17/14	22	0.14	0.11	0.09	0.07	0.04	0.02	15	21	6
3/28/14	34	0.13	0.36	0.10	0.06	0.07	0.02	18	109	10
4/15/14	10	0.28	0.19		0.07	0.03		60	46	
4/15/14	21	0.24	0.18	0.12	0.10	0.03	0.02	46	73	16
4/18/14	31	0.15	0.07	0.09	0.08	0.02	0.02	10	24	7
4/29/14	81	0.22		0.21	0.10	0.03	0.04	58	119	67
6/17/14	28	0.37	0.22	0.22	0.18	0.05	0.01	54	44	37
6/27/14	24	0.27	0.17	0.12	0.14	0.07	0.01	73	35	12
7/10/14	21	0.19	0.11	0.19	0.07	0.03	0.05	43	15	48
8/2/14	6	0.06	0.05		0.01	0.01		10	12	
8/9/14	102	0.23	0.22	0.19	0.12	0.07	0.07	53	123	40

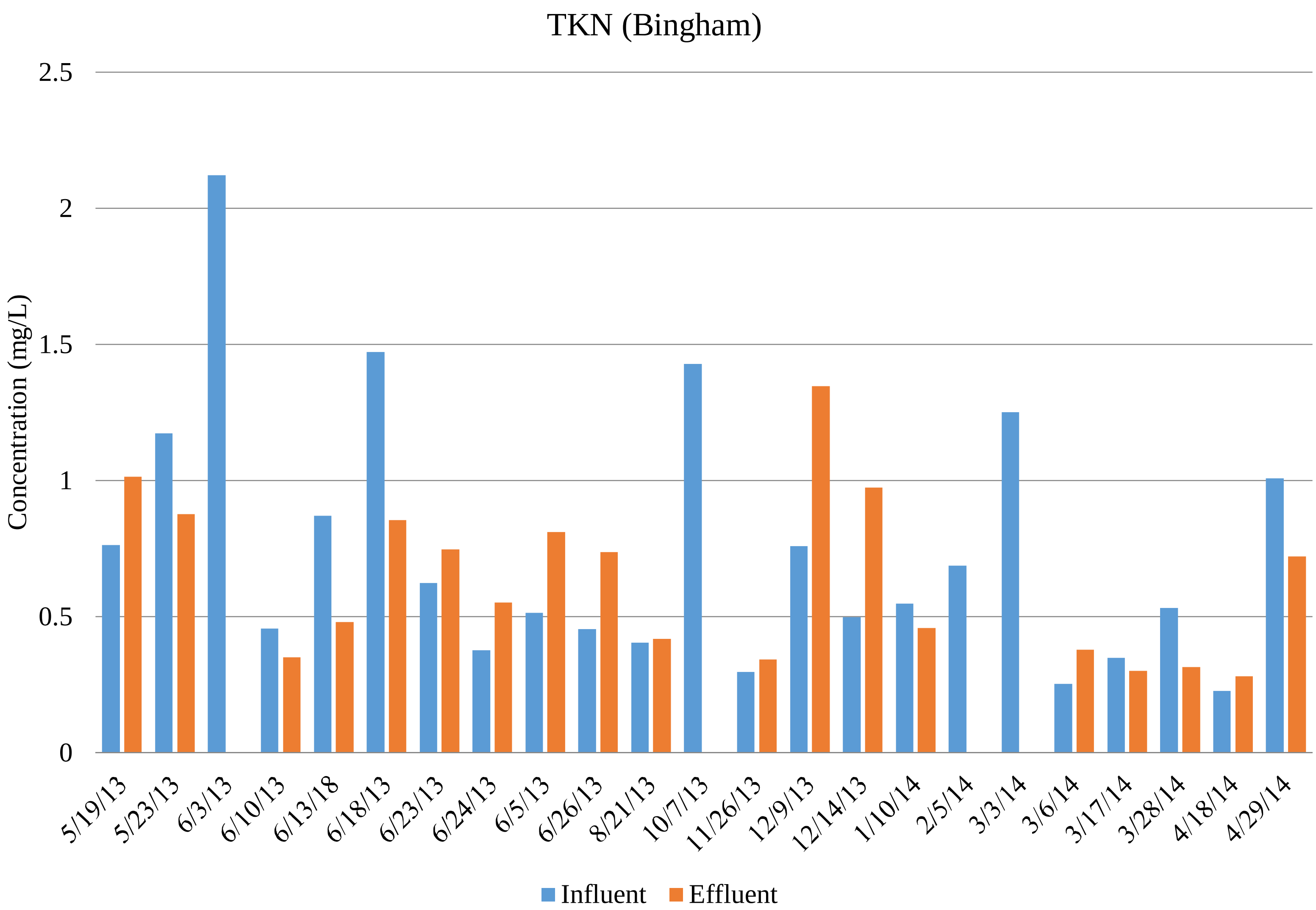


Figure D.1: Bingham TKN EMCs

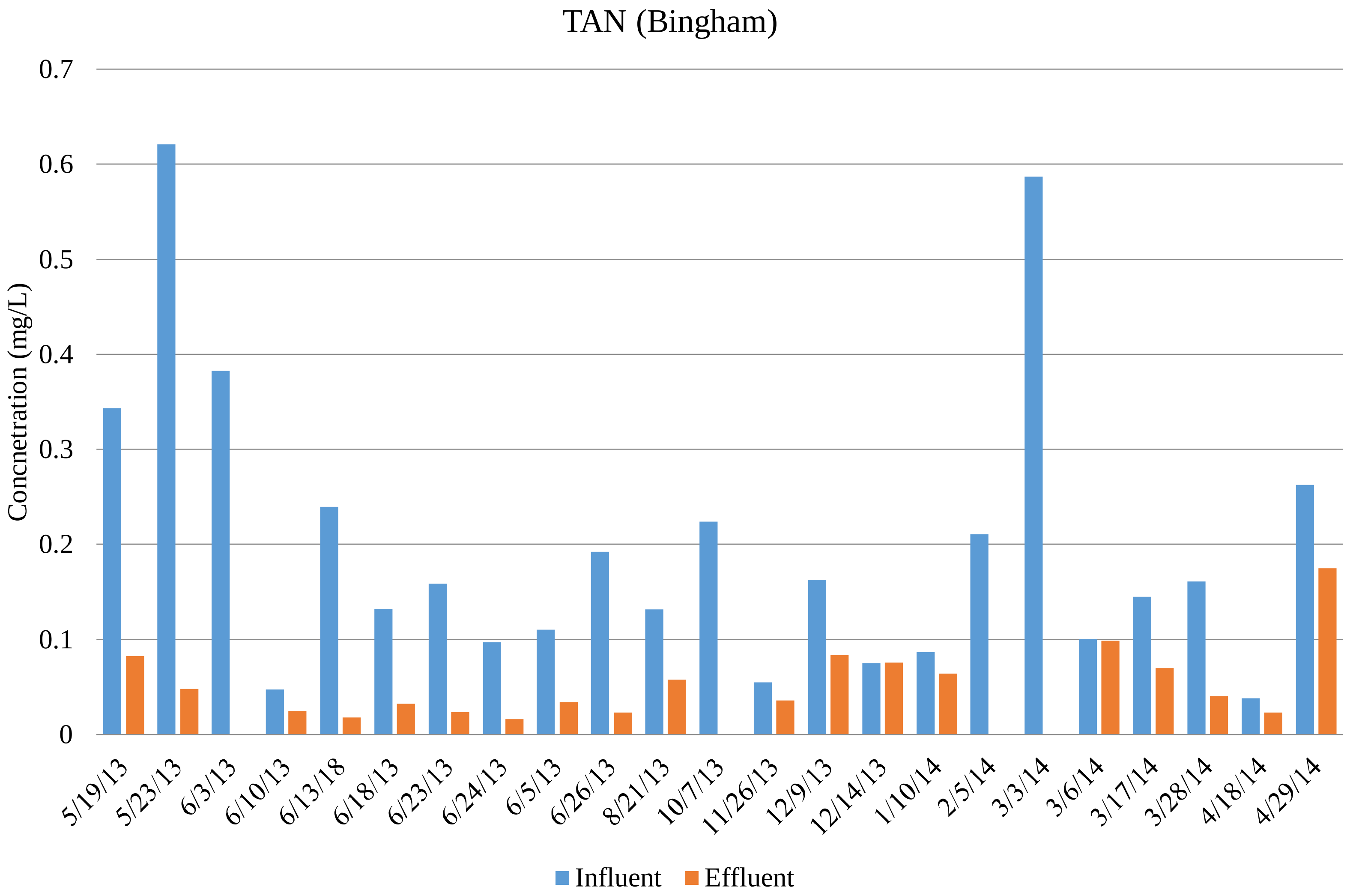


Figure D.2: Bingham TAN EMCs

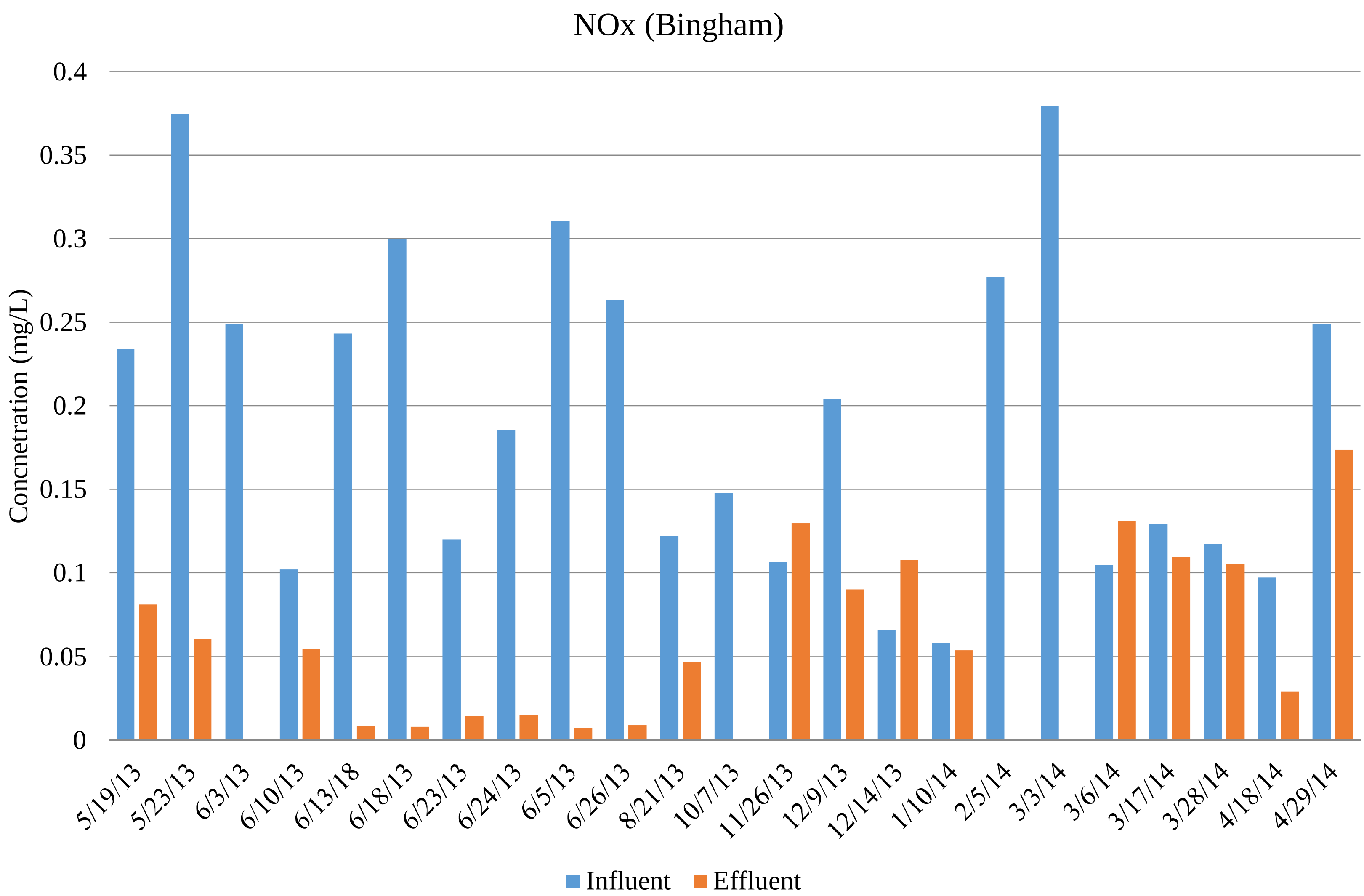


Figure D.3: Bingham NOx EMCs

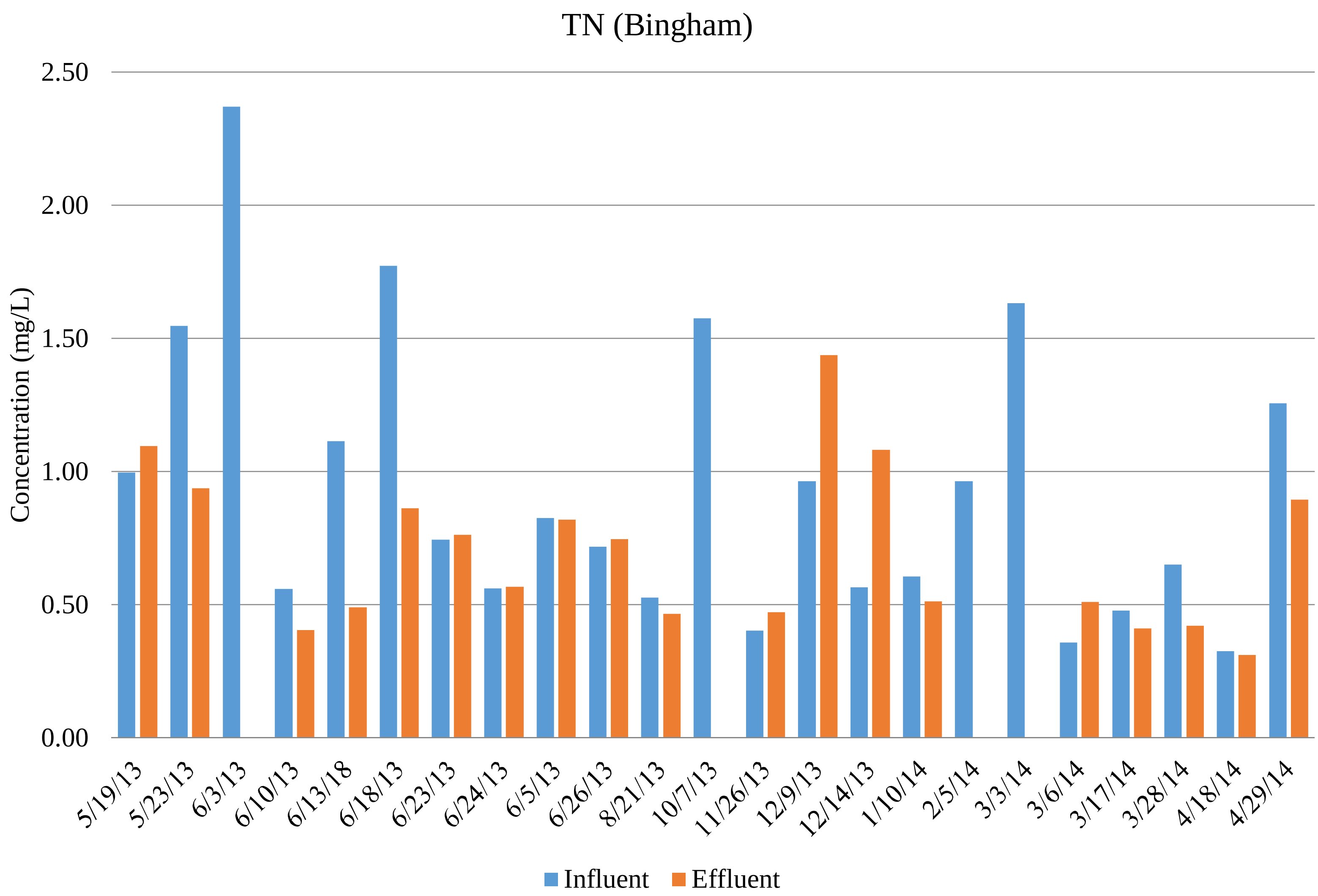


Figure D.4: Bingham TN EMCs

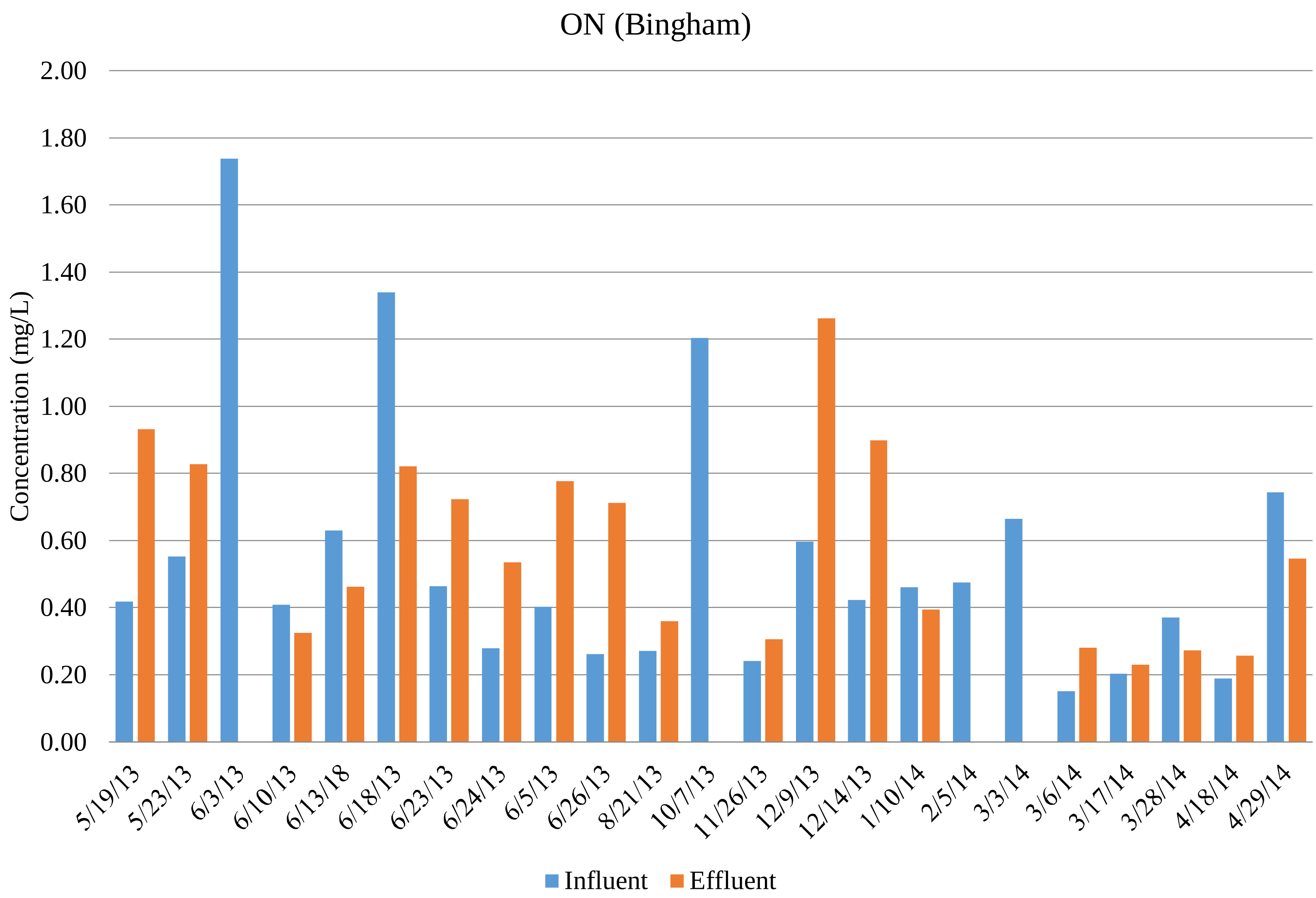


Figure D.5: Bingham ON EMCs

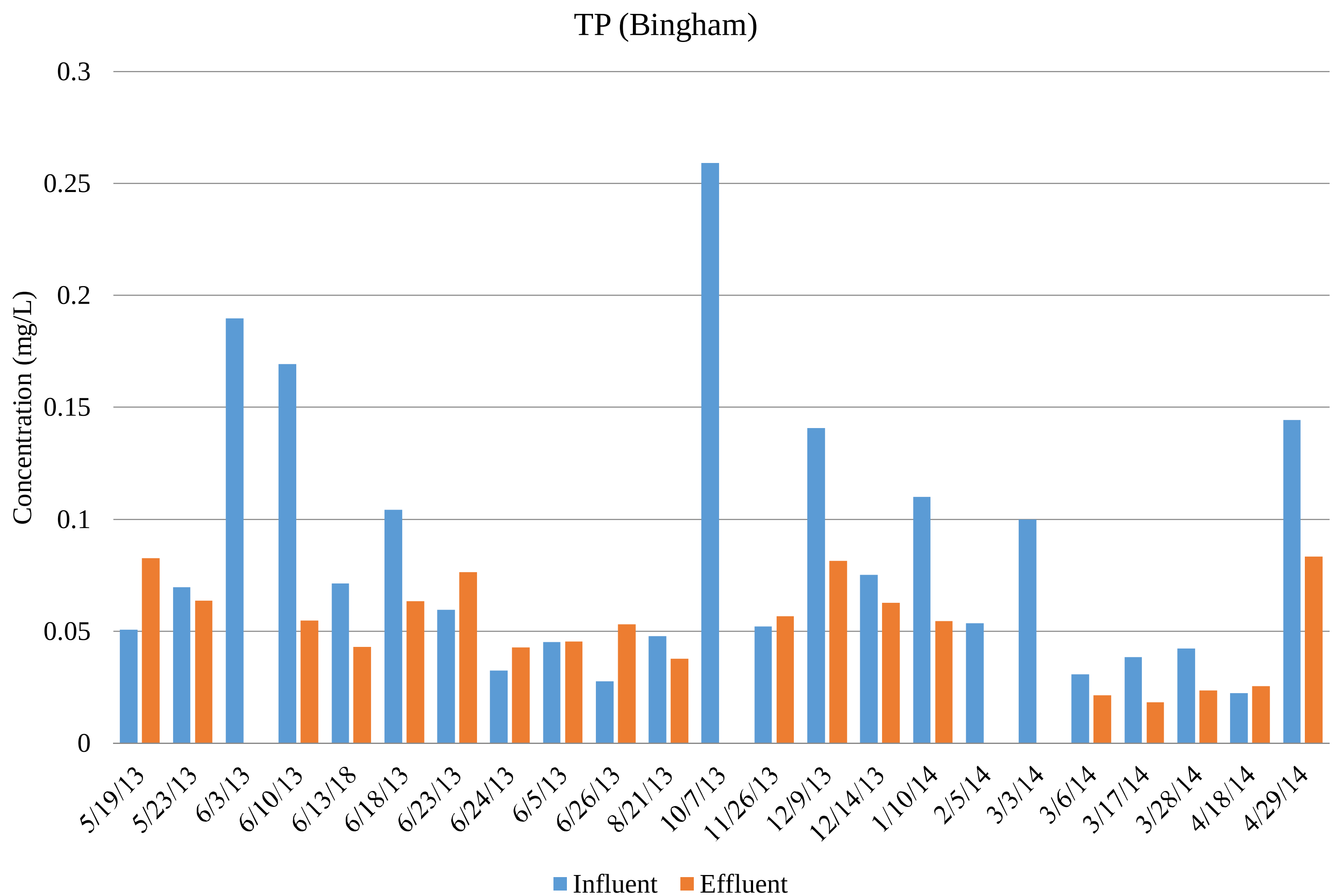


Figure D.6: Bingham TP EMCs

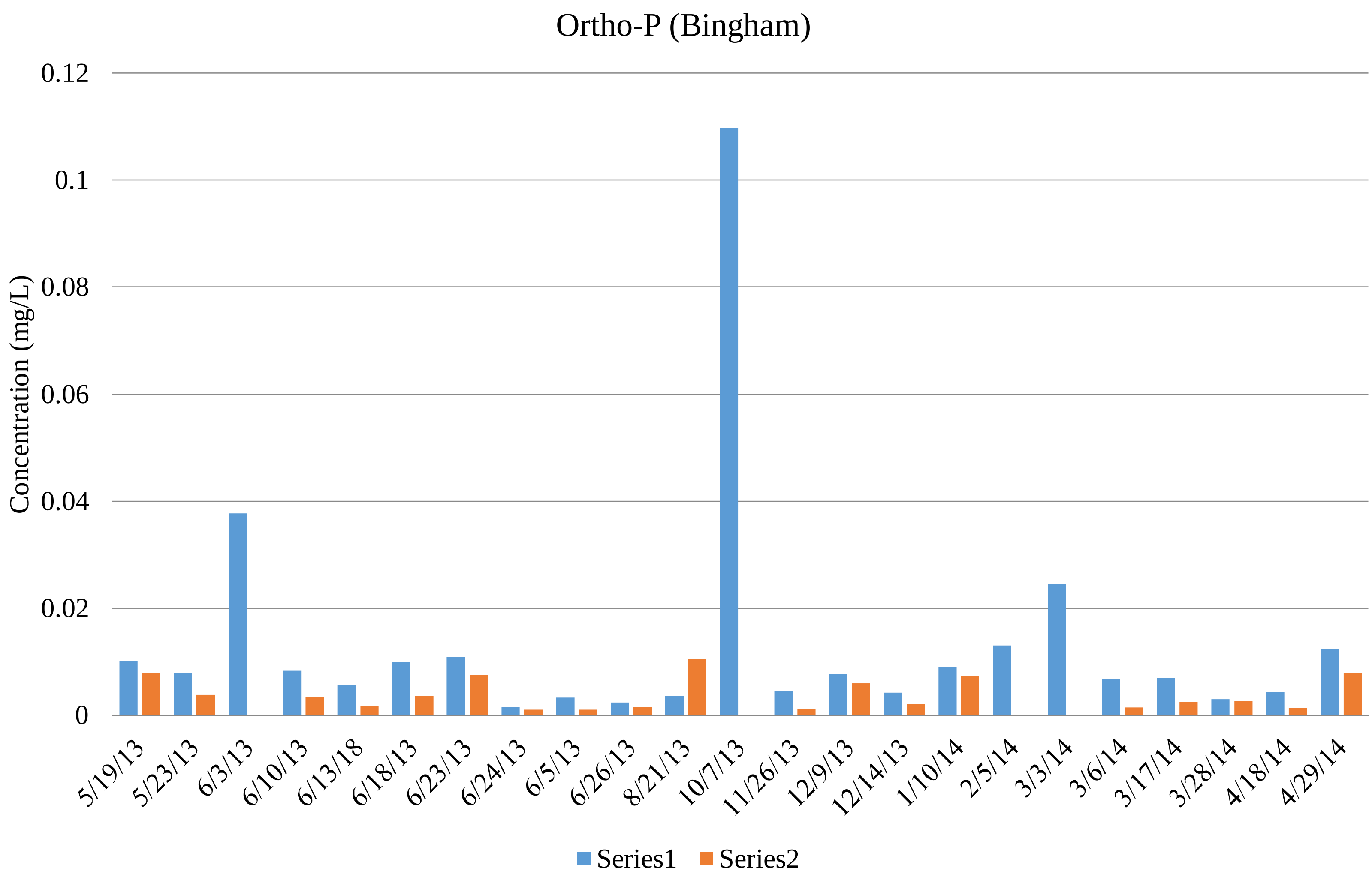


Figure D.7: Bingham Ortho-P EMCs

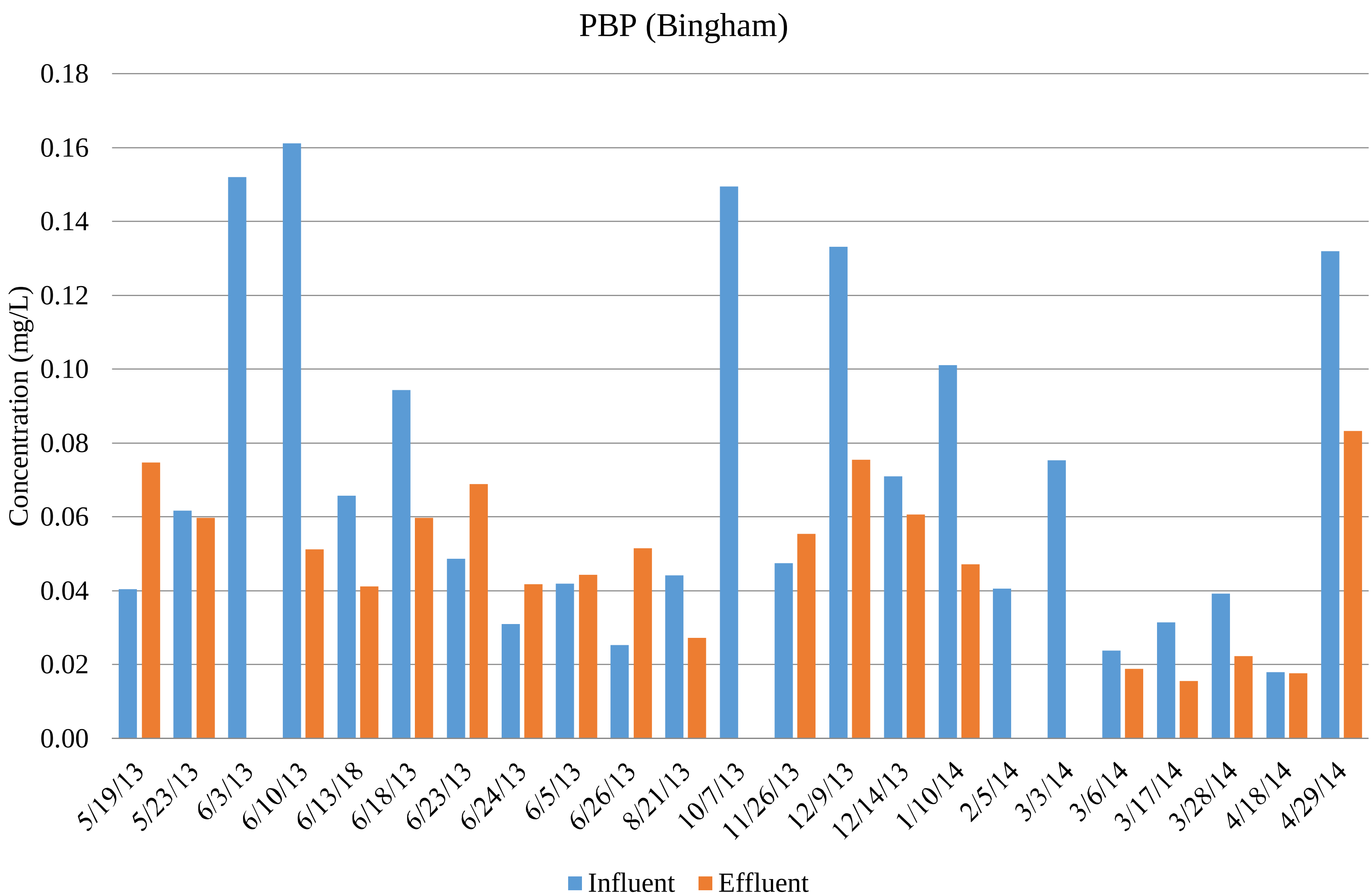


Figure D.8: Bingham PBP EMCs

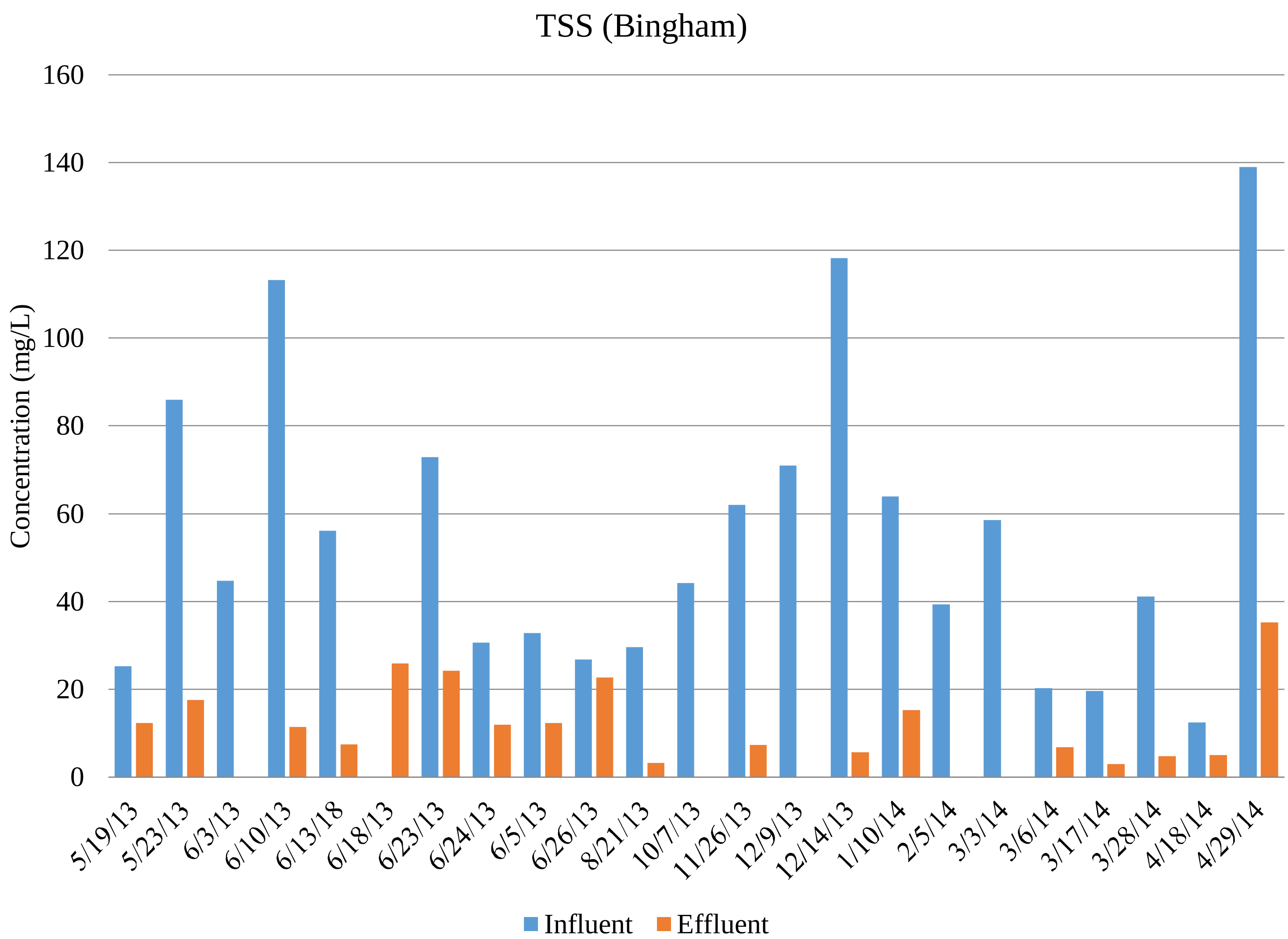


Figure D.9: Bingham TSS EMCs

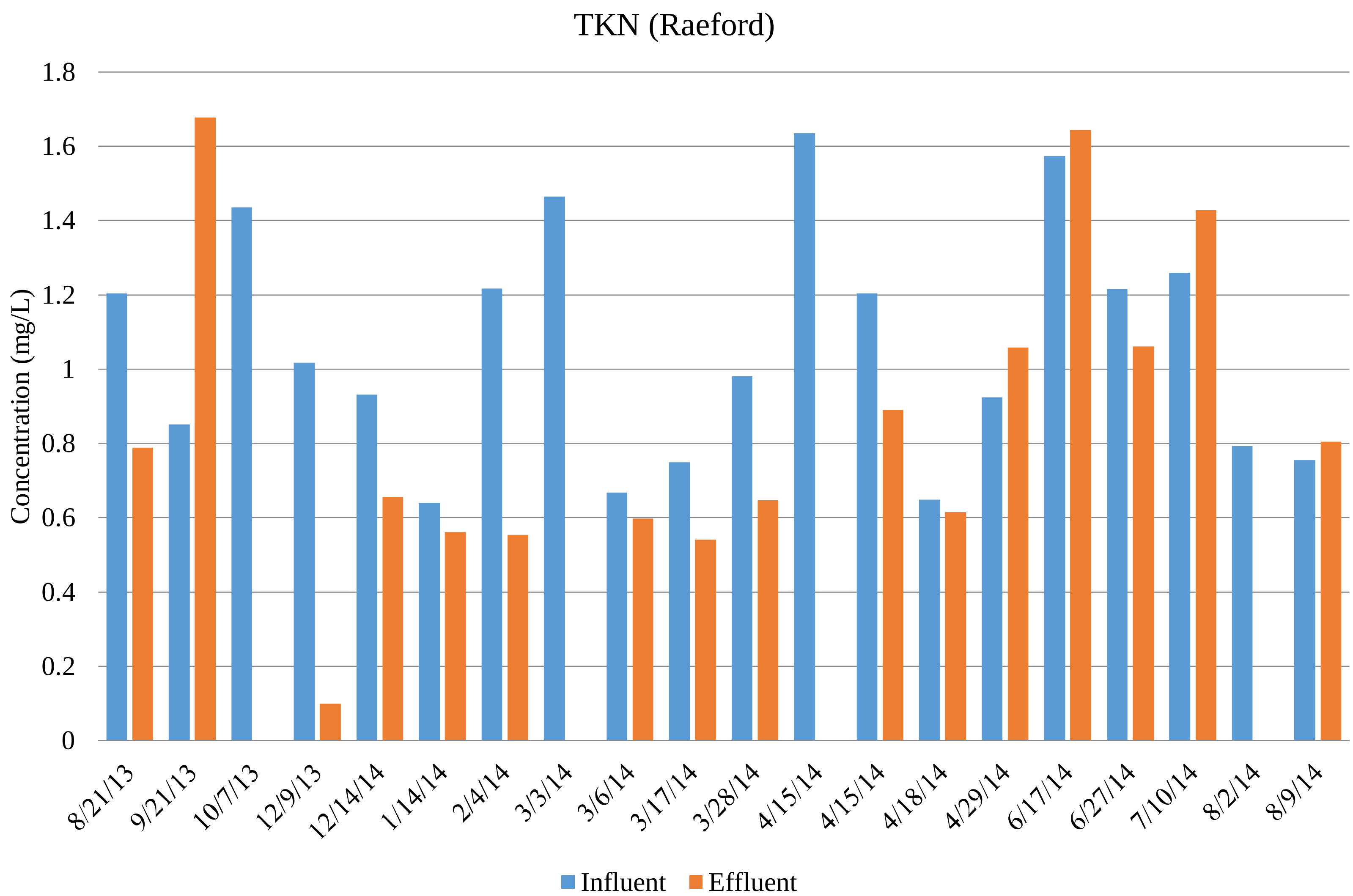


Figure D.10: Raeford TKN EMCs

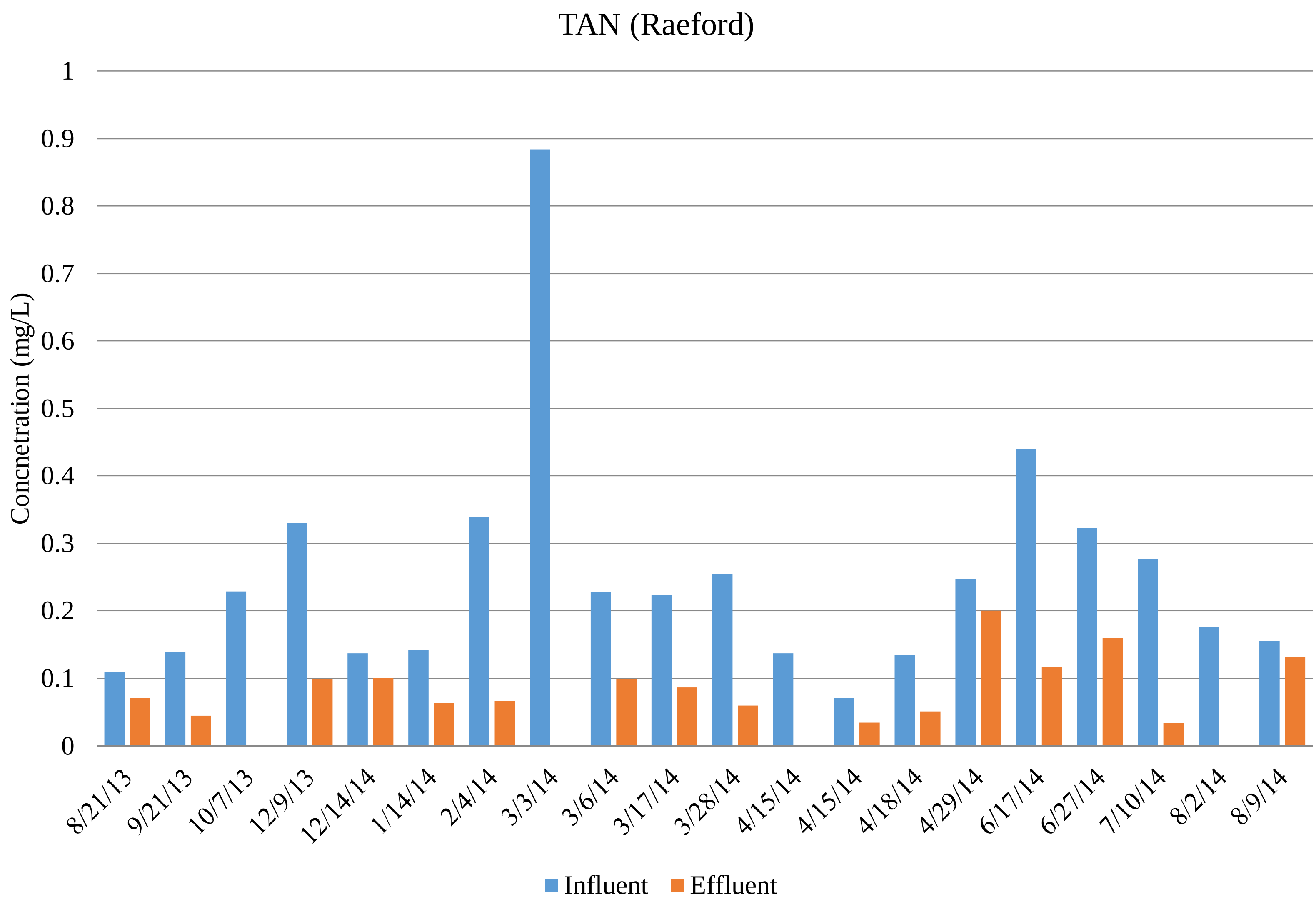


Figure D.11: Raeford TAN EMCs

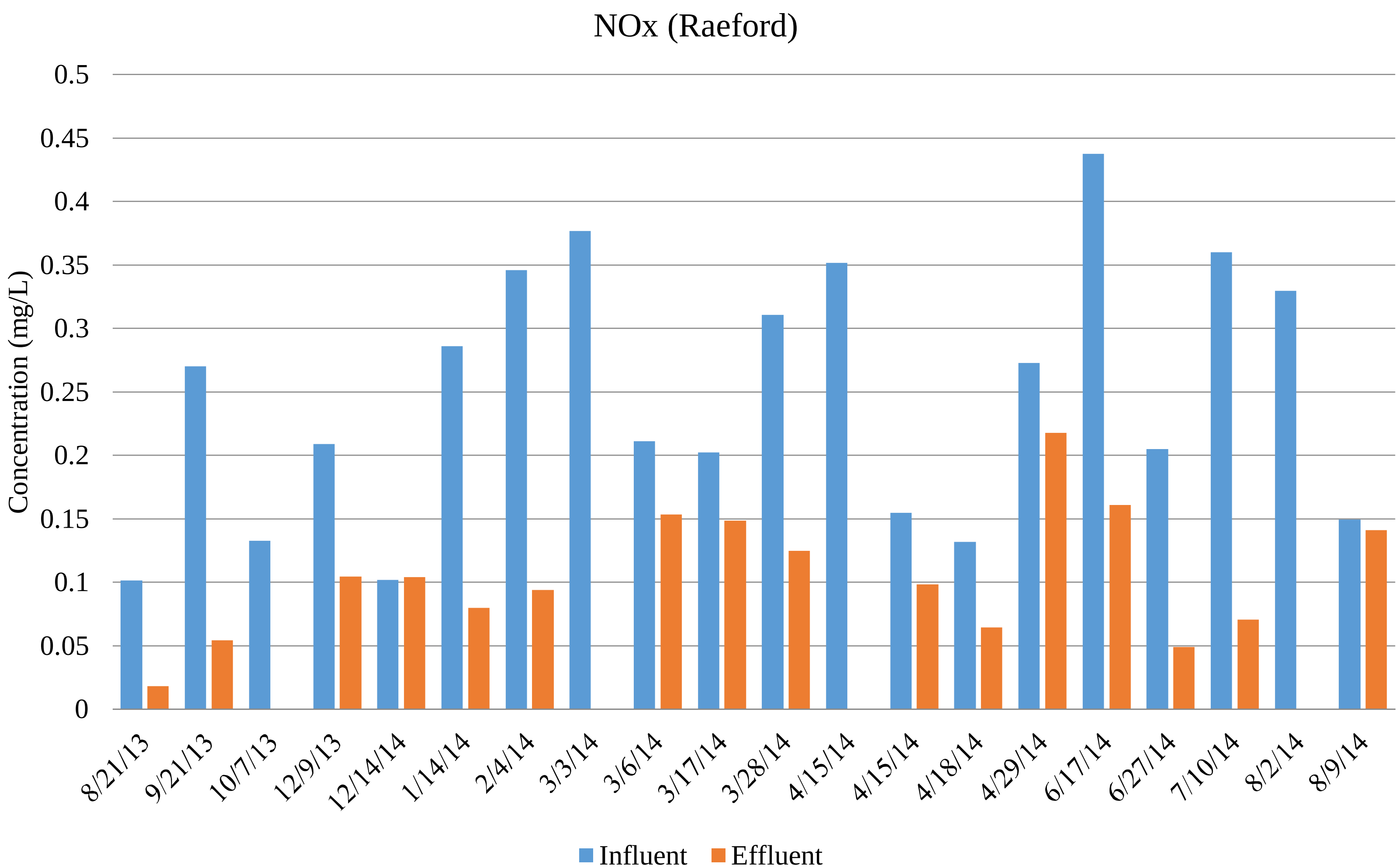


Figure D.12: Raeford NOx EMCs

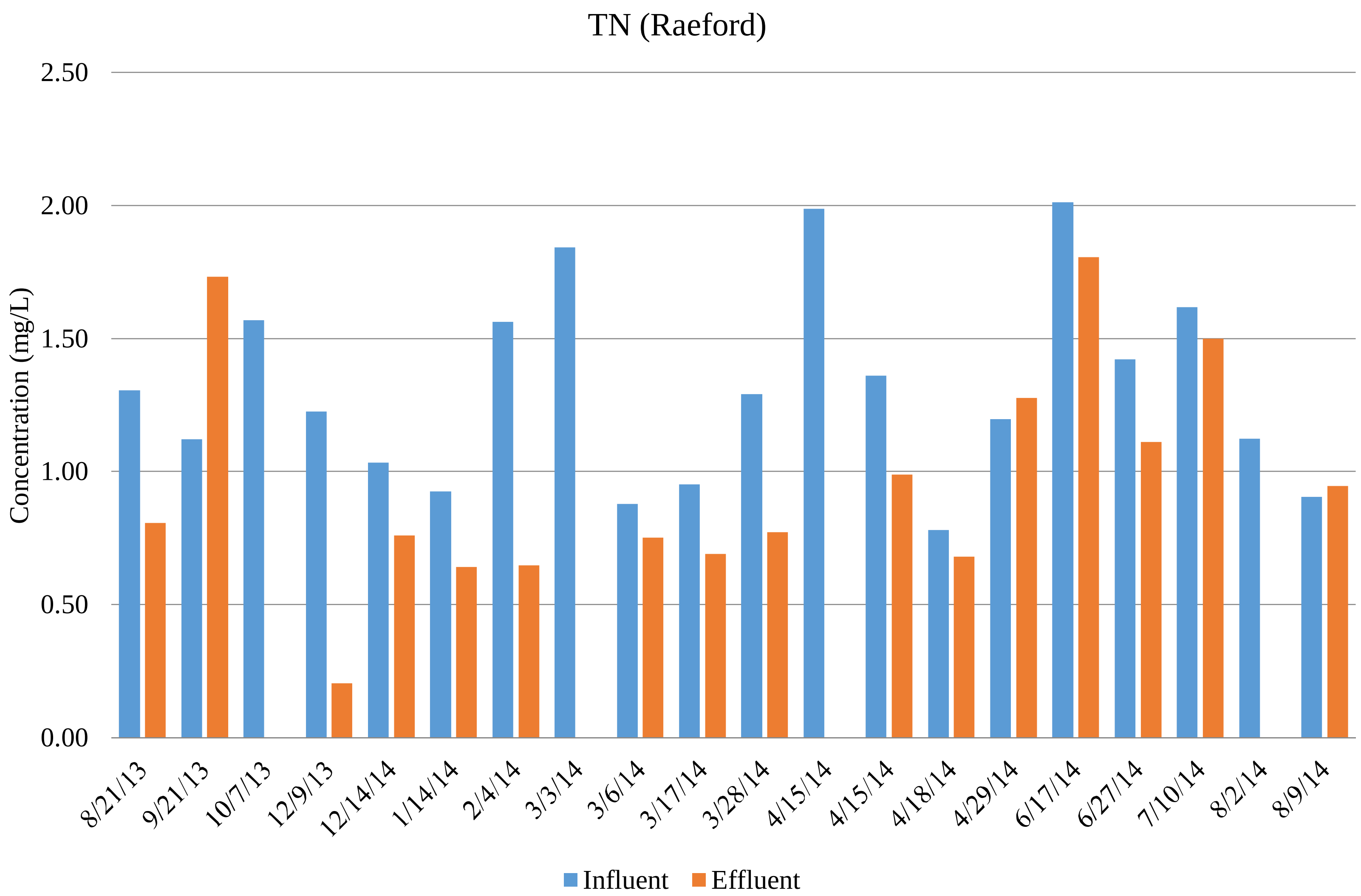


Figure D.13: Raeford TN EMCs

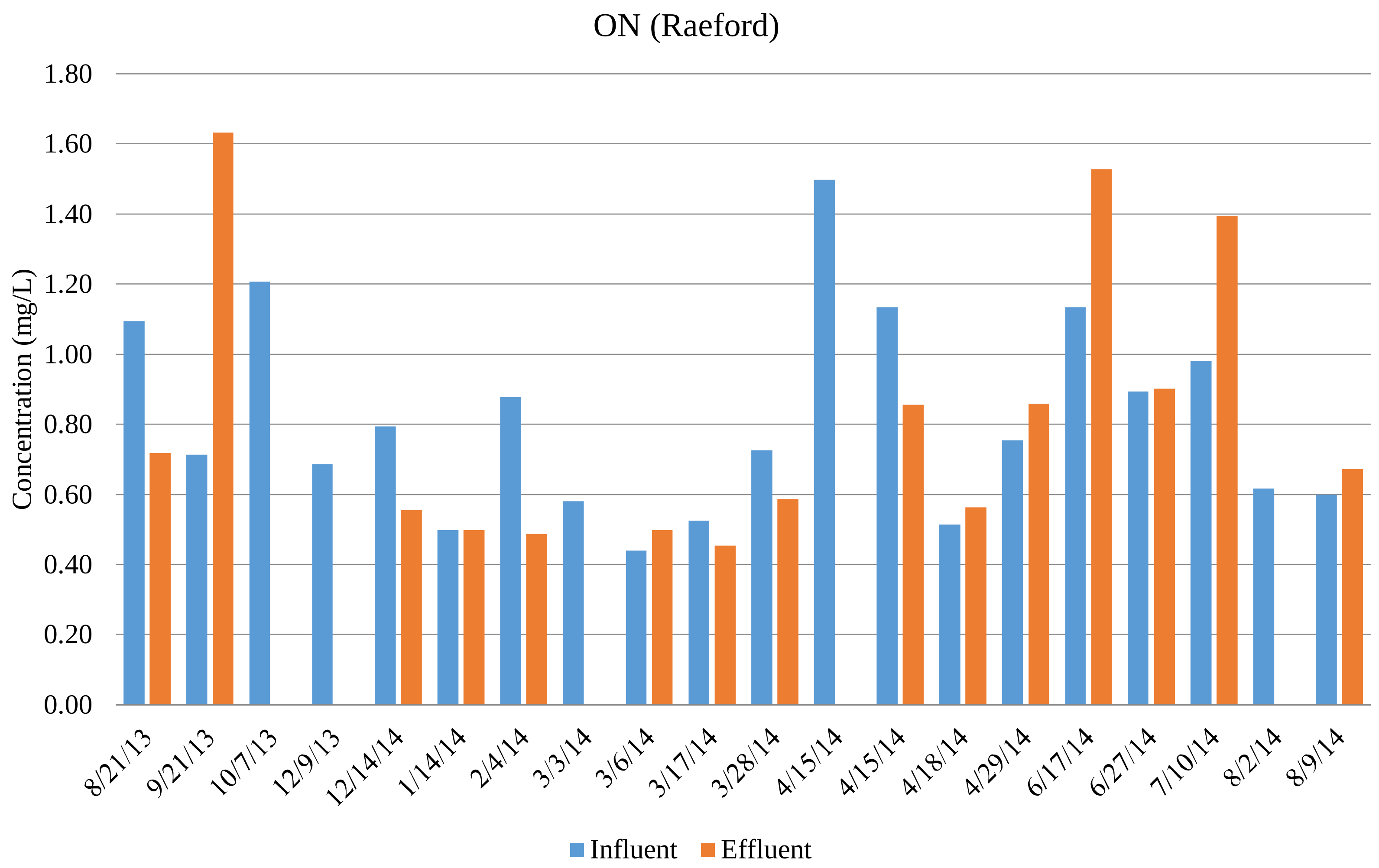


Figure D.14: Raeford ON EMCs

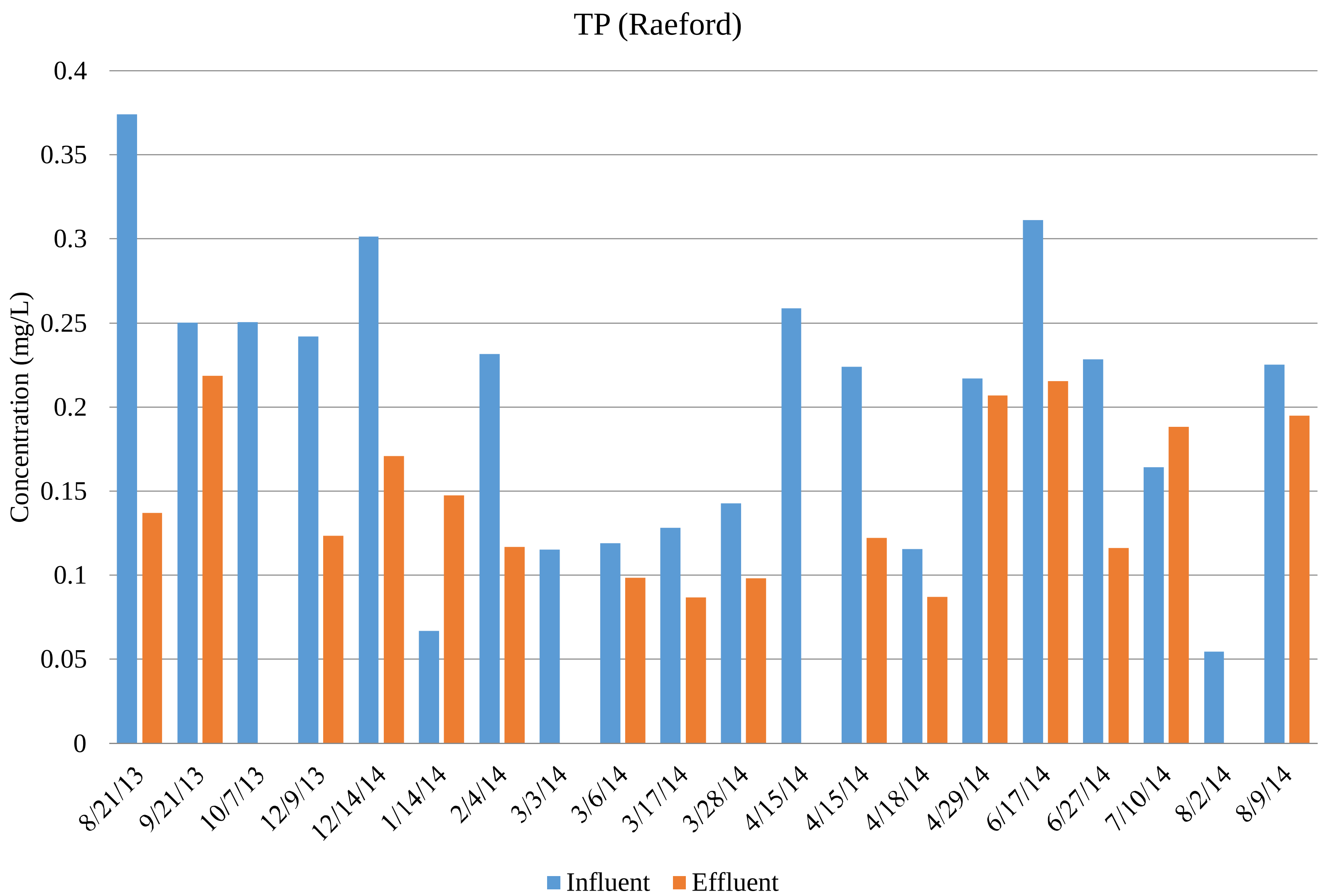


Figure D.15: Raeford TP EMCs

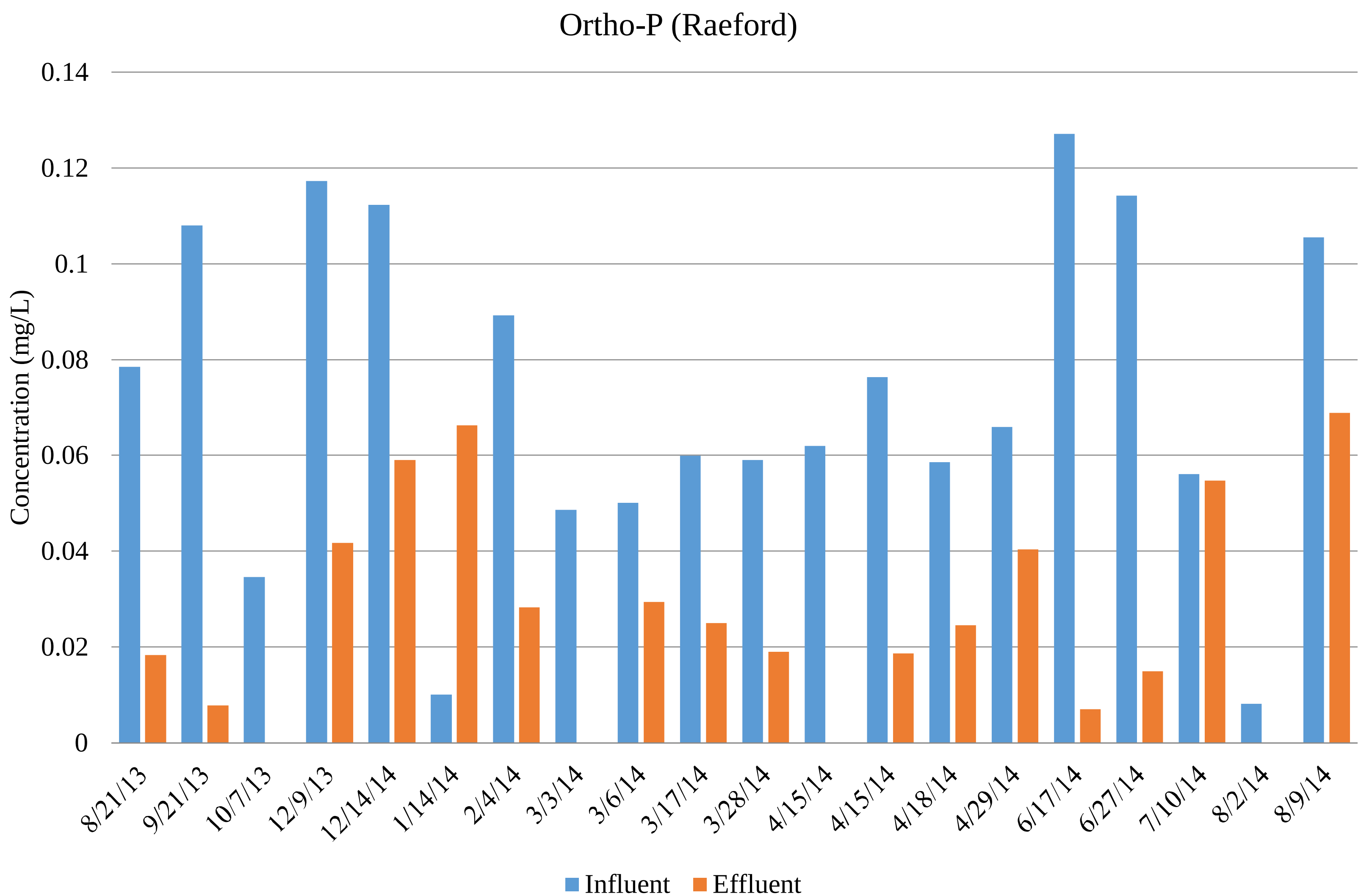


Figure D.16: Raeford Ortho-P EMCs

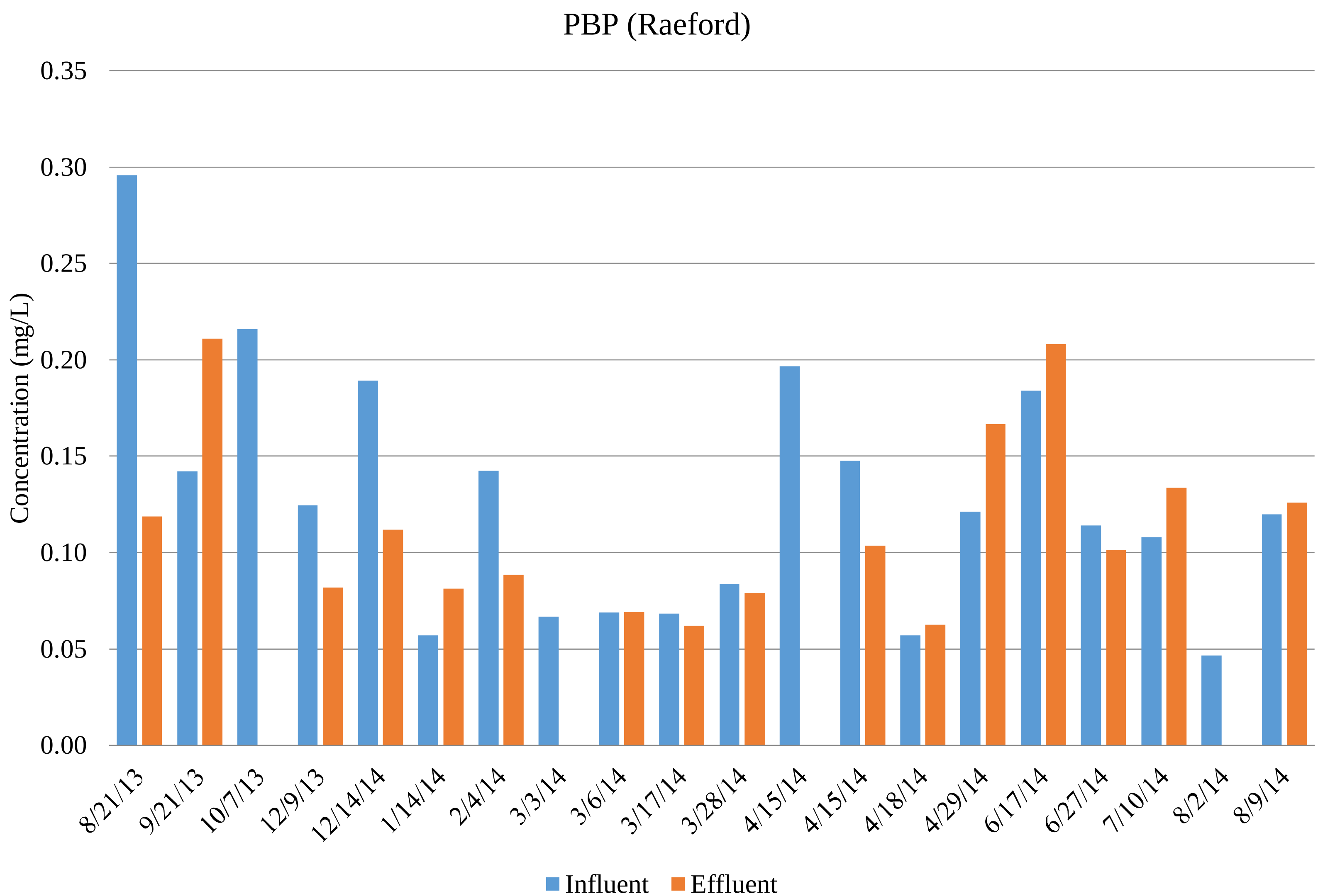


Figure D.17: Raeford PBP EMCs

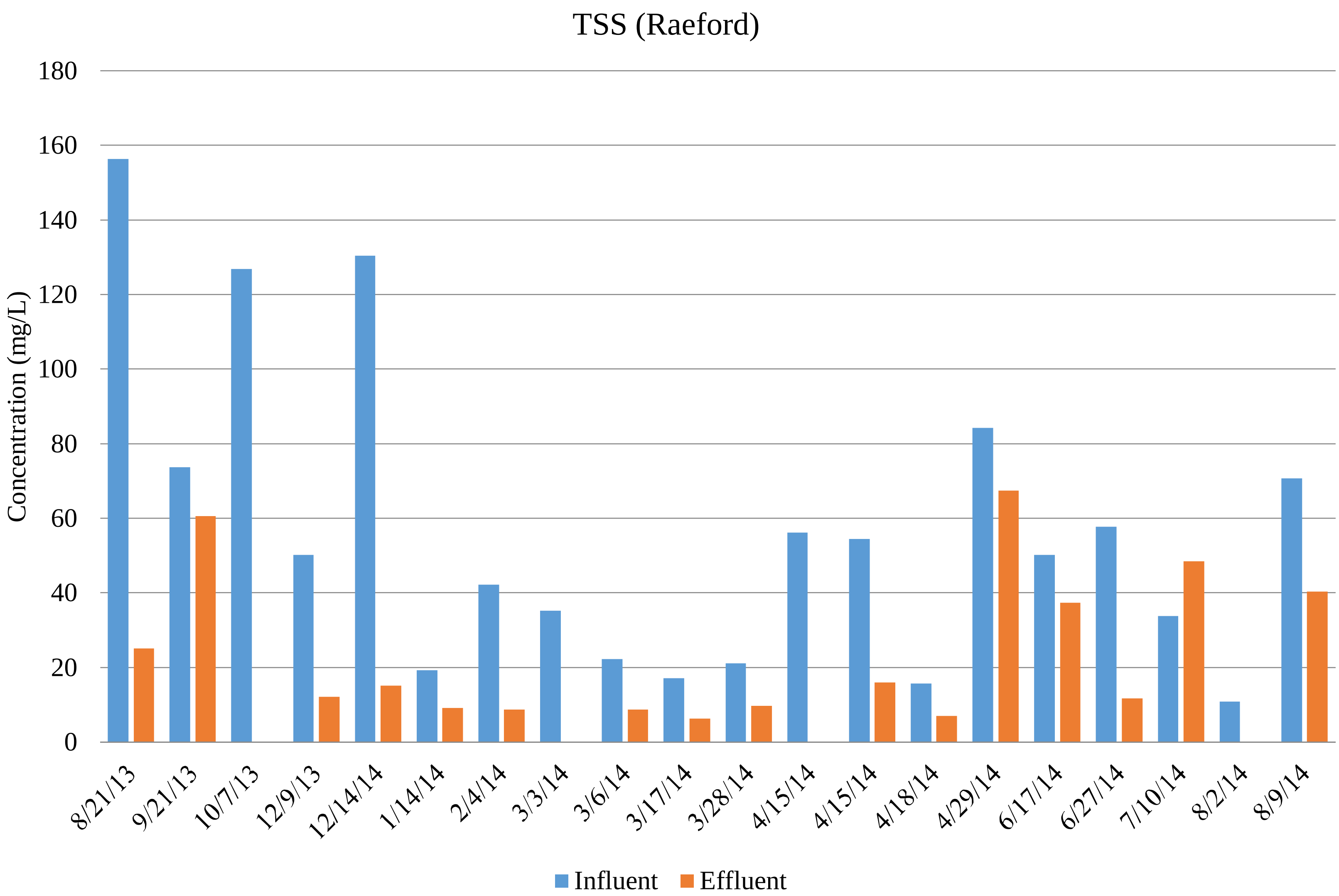


Figure D.10: Raeford TSS EMCs

Appendix E: Pollutant Load Calculations

Step 1: For each storm event, calculate the total mass of each pollutant that was exported from the EMC (mg/L) and outflow volume (m^3). Convert mass to kg.

$$Mass = V * EMC$$

Step 2: Sum pollutant masses for all water quality events (only those events with influent and effluent samples, storms with only influent samples were not included)

Step 3: Sum the influent volume and effluent volume that was sampled over the monitoring period. Determine the total influent volume and total effluent volume over the monitoring period of one year.

$$Loading\ \left(\frac{kg}{yr}\right) = \sum mass * \frac{total\ yearly\ volume}{volume\ sampled}$$

Step 4: Normalize each pollutant loading by the catchment area.

$$Loading\ \left(\frac{kg}{ha * yr}\right) = \frac{Loading\ (\frac{kg}{yr})}{Catchment\ area\ (ha)}$$

Loading Data can be found in Table E.1 and Table E.2.

Table E.1: Summary of Bingham Loading

		TKN (g)		NH3-N (g)		$NO_{2,3}$-N (g)		TN (g)		TP (g)		Ortho-P (g)		TSS (g)	
Storm	Rainfall (mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
5/19/13	18	211	60	95	5	65	5	275	65	14	5	3	0	6966	732
5/23/13	6	134	25	71	1	43	2	177	27	8	2	1	0	9823	504
6/10/13	29	169	87	18	6	38	14	206	100	63	14	3	1	41956	2836
6/13/13	13	123	34	34	1	34	1	157	34	10	3	1	0	7933	521
6/18/13	8	177	21	16	1	36	0	213	21	13	2	1	0		639
6/23/13	25	179	175	46	6	35	3	213	178	17	18	3	2	20944	5673
6/24/13	12	50	43	13	1	25	1	74	44	4	3	0	0	4050	926
6/25/13	14	89	113	19	5	54	1	143	114	8	6	1	0	5674	1712
6/26/13	16	80	62	34	2	46	1	126	63	5	4	0	0	4721	1910
8/21/13	18	88	39	29	5	27	4	115	43	10	4	1	1	6491	298
11/26/13	42	148	29	28	3	53	11	201	40	26	5	2	0	31023	610
12/9/13	16	144	37	31	2	39	2	182	39	27	2	1	0	13422	
12/14/13	39	179	194	27	15	24	21	202	216	27	12	2	0	42441	1125
1/10/14	70	557	397	88	56	59	47	616	444	112	47	9	6	65151	13185
3/6/14	39	211	124	84	32	88	43	299	167	26	7	6	0	16949	2208
3/17/14	15	97	24	40	6	36	9	132	33	11	1	2	0	5419	239
3/28/14	37	366	84	111	11	81	28	447	113	29	6	2	1	28305	1256
4/18/14	25	142	72	24	6	61	7	202	79	14	7	3	0	7741	1285
4/29/14	76	956	620	250	151	236	149	1192	769	137	72	12	7	132026	30273

Table E.2: Summary of Raeford Loading

		TKN (g)		NH_3-N (g)		$NO_{2,3}$-N (g)		TN (g)		TP (g)		Ortho-P (g)		TSS (g)	
Storm	Rain (mm)	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff	Inf	Eff
8/21/13	20	416	23	38	2	35	1	451	24	129	4	27	1	53974	734
9/21/13	19	276	47	45	1	88	2	364	49	81	6	35	0	23932	1704
12/9/13	20	265	13	86	13	54	14	320	26	63	16	31	5	13098	1577
12/14/13	40	602	292	89	45	66	46	668	338	195	76	73	26	84284	6694
1/14/14	5	14	12	3	1	6	2	20	14	1	3	0	1	416	199
2/4/14	14	202	36	56	4	57	6	260	42	38	8	15	2	7012	558
3/6/14	46	411	242	140	40	130	62	541	304	73	40	31	12	13724	3507
3/17/14	22	244	130	73	21	66	36	310	166	42	21	20	6	5577	1498
3/28/14	34	431	222	112	21	137	43	568	265	63	34	26	7	9288	3337
4/15/14	21	430	144	25	6	55	16	485	160	80	20	27	3	19404	2575
4/18/14	31	190	138	39	12	39	14	229	152	34	20	17	5	4574	1571
4/29/14	81	1138	1299	304	246	336	267	1474	1565	151	254	81	49	103693	82714
6/17/14	28	724	117	202	8	201	11	926	129	143	15	58	1	23073	2665
6/27/14	24	458	217	121	33	77	10	535	227	86	24	43	3	21712	2402
7/10/14	21	306	60	68	1	88	3	394	63	40	8	14	2	8230	2042
8/9/14	102	1190	1056	245	173	236	185	1426	1241	355	256	167	90	111504	52904

Appendix F: Discussion of Draw-down Times

The optimal draw-down time of a wet pond (infiltrating or non-infiltrating) should be based upon how often a rain event occurs in that particular area. Designing a wet pond with a draw down time similar to that of the average rainfall occurrence allows the wet pond to detain water for the longest amount of time while still being able to capture the following storm event. Longer detention times allow for more water to infiltrate, evaporate and for more particulates to settle out. In North Carolina, a rain event typically occurs on average every 3.3 days, however that frequently changes from the coastal plains to the mountains. During the monitoring period, the average antecedent dry period was determined to be 4.14 days at the Bingham pond and 5.14 days at the Raeford pond. To calculate draw-down, the water had to reach the top of the outlet structure (overflow) ensuring the pond was at full capacity. Second, the water level had to return to the normal pool prior to the next event occurring. At the Bingham pond, this occurred on two occasions, while at the Raeford pond it only occurred once. The draw down time for the storm events at the Bingham pond were 2.22 days and 2.38 days, an average draw down time of 2.30 days. At the Raeford pond, the draw down time was determined to be 4.81 days. Figure F:1 shows the draw down curves for one of the storms at the Bingham and Raeford sites. The draw down time for both wet ponds were within the required 2-5 days set by NC DENR, however they are on opposite sides of the spectrum. It was surprising to see the Raeford pond having a large draw down time despite the infiltration that was occurring. The draw down time was strictly a function of the drawdown orifice size and depth of storage volume above the orifice. Based on the calculated average antecedent dry period at the Raeford pond, the orifice size at the Raeford pond was designed well for an infiltrating pond. The detention time of 4.81 days takes full advantage of the average time between storms and allows infiltration, evaporation and particulates to settle out while sill emptying before the next storm event. The orifice at the Bingham pond could have been designed smaller for even better performance of the wet pond. The pond was releasing the captured volume of water in a sufficient amount of time prior to the average next storm event. A smaller orifice would detain the captured volume longer and intuitively increase infiltration, evaporation and water quality performance.

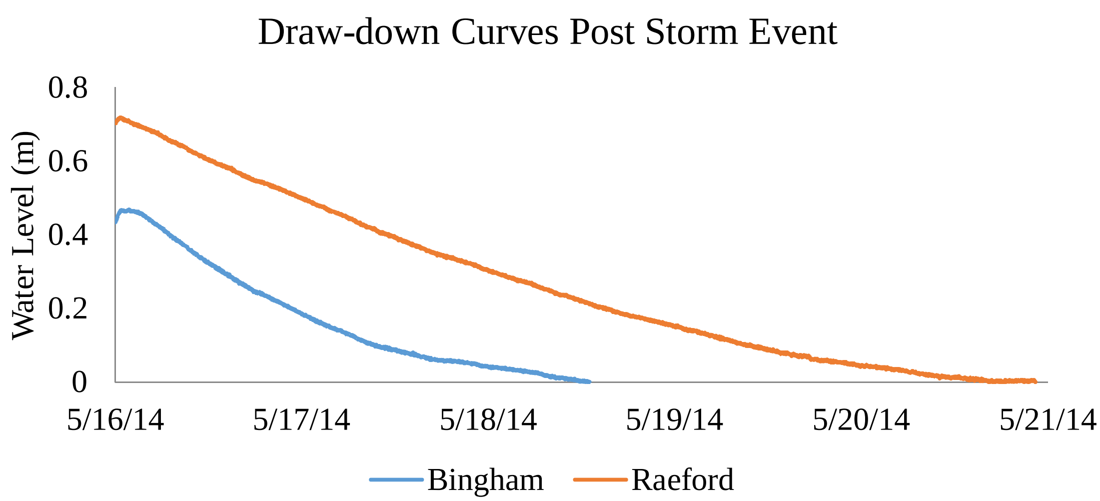


Figure F:1: Draw-down curves post storm event at both Bingham and Raeford locations (the storm event filled the ponds to capacity)

Appendix G: Example R code

```
#load Packages
library("reshape")
library("ggplot2")
library("plyr")
library("nortest")

#Set Working Directory
setwd("C://Users//Joshua//Documents//JBB//fville//r")

#read in csv file
bingwq1.df <- read.csv("bing_wq1.csv")
View(bingwq1.df)

tkn.df <- bingwq1.df[1:19,1:2]
tknm.df <- melt(tkn.df)
colnames (tknm.df) <-c("Location", "Conc")
View(tkn.df)

nox.df <- bingwq1.df[1:19,3:4]
noxm.df <- melt(nox.df)
colnames (noxm.df) <-c("Location", "Conc")
View(nox.df)

tn.df <- bingwq1.df[1:19,5:6]
tnm.df <- melt(tn.df)
colnames (tnm.df) <-c("Location", "Conc")
View(tn.df)

tan.df <- bingwq1.df[1:19,7:8]
tanm.df <- melt(tan.df)
colnames (tanm.df) <-c("Location", "Conc")
View(tan.df)

on.df <- bingwq1.df[1:19,9:10]
onm.df <- melt(on.df)
colnames (onm.df) <-c("Location", "Conc")
View(on.df)

op.df <- bingwq1.df[1:19,11:12]
opm.df <- melt(op.df)
colnames (opm.df) <-c("Location", "Conc")
```

```
View(op.df)

pbp.df <- bingwq1.df[1:19,13:14]
pbpm.df <- melt(pbp.df)
colnames (pbpm.df) <-c("Location", "Conc")
View(pbp.df)

tp.df <- bingwq1.df[1:19,15:16]
tpm.df <- melt(tp.df)
colnames (tpm.df) <-c("Location", "Conc")
View(tp.df)

tss.df <- bingwq1.df[1:17,17:18]
tssm.df <- melt(tss.df)
colnames (tssm.df) <-c("Location", "Conc")
View(tss.df)

#To check Normality
qqplot <- function(x){
  qqnorm(x)
  qqline(x, col="red")
}

#TKN###########
qqplot(tknm.df$Conc[tknm.df$Location=="TKNIn"])
qqplot(tknm.df$Conc[tknm.df$Location=="TKNout"])

nt.tkn <- ddply(tknm.df, .(Location), summarise,
                Shap.Wilk = shapiro.test(Conc)[2],
                Ad.test = ad.test(Conc)[2],
                Lillifors = lillie.test(Conc)[2])
View(nt.tkn)

#log transform Bing PF data
tknml.df <- tknm.df
tknml.df$Conc <-log(tknml.df$Conc)

View(tknml.df)

#Normality of Log Trans Data
qqplot(tknml.df$Conc[tknml.df$Location=="TKNIn"])
qqplot(tknml.df$Conc[tknml.df$Location=="TKNout"])
```

```
nt.tknl <- ddply(tknml.df, .(Location), summarise,
                 Shap.Wilk = shapiro.test(Conc)[2],
                 Ad.test = ad.test(Conc)[2],
                 Lillifors = lillie.test(Conc)[2])
View(nt.tknl)

#Box Plots

ggplot(tknm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(tknml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(tknml.df$Conc[tknml.df$Location=="TKNIn"],
tknml.df$Conc[tknml.df$Location=="TKNout"], paired=TRUE)

wilcox.test(tknm.df$Conc[tknm.df$Location=="TKNIn"],
tknm.df$Conc[tknm.df$Location=="TKNout"], paired=TRUE)

#NOx##########
qqplot(noxm.df$Conc[noxm.df$Location=="NOxIn"])
qqplot(noxm.df$Conc[noxm.df$Location=="NOxOut"])

nt.nox <- ddply(noxm.df, .(Location), summarise,
               Shap.Wilk = shapiro.test(Conc)[2],
               Ad.test = ad.test(Conc)[2],
               Lillifors = lillie.test(Conc)[2])
View(nt.nox)

#log transform Bing PF data
noxml.df <- noxm.df
noxml.df$Conc <-log(noxml.df$Conc)

View(noxml.df)

#Normality of Log Trans Data
qqplot(noxml.df$Conc[noxml.df$Location=="NOxIn"])
```

```
qqplot(noxml.df$Conc[noxml.df$Location=="NOxOut"])

nt.noxl <- ddply(noxml.df, .(Location), summarise,
              Shap.Wilk = shapiro.test(Conc)[2],
              Ad.test = ad.test(Conc)[2],
              Lillifors = lillie.test(Conc)[2])
View(nt.noxl)

#Box Plots

ggplot(noxm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(noxml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(noxm.df$Conc[noxm.df$Location=="NOxIn"],
noxm.df$Conc[noxm.df$Location=="NOxOut"], paired=TRUE)

#TN###########
qqplot(tnm.df$Conc[tnm.df$Location=="TNIn"])
qqplot(tnm.df$Conc[tnm.df$Location=="TNOut"])

nt.tn <- ddply(tnm.df, .(Location), summarise,
             Shap.Wilk = shapiro.test(Conc)[2],
             Ad.test = ad.test(Conc)[2],
             Lillifors = lillie.test(Conc)[2])
View(nt.tn)

#log transform Bing PF data
tnml.df <- tnm.df
tnml.df$Conc <-log(tnml.df$Conc)

View(tnml.df)

#Normality of Log Trans Data
qqplot(tnml.df$Conc[tnml.df$Location=="TNIn"])
qqplot(tnml.df$Conc[tnml.df$Location=="TNOut"])
```

```
nt.tnl <- ddply(tnml.df, .(Location), summarise,
                Shap.Wilk = shapiro.test(Conc)[2],
                Ad.test = ad.test(Conc)[2],
                Lillifors = lillie.test(Conc)[2])
View(nt.tnl)

#Box Plots

ggplot(tnm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(tnml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(tnml.df$Conc[tnml.df$Location=="TNIn"],
tnml.df$Conc[tnml.df$Location=="TNOut"], paired=TRUE)

wilcox.test(tnm.df$Conc[tnm.df$Location=="TNIn"],
tnm.df$Conc[tnm.df$Location=="TNOut"], paired=TRUE)

#TAN###########
qqplot(tanm.df$Conc[tanm.df$Location=="TANIn"])
qqplot(tanm.df$Conc[tanm.df$Location=="TANOut"])

nt.tan <- ddply(tanm.df, .(Location), summarise,
              Shap.Wilk = shapiro.test(Conc)[2],
              Ad.test = ad.test(Conc)[2],
              Lillifors = lillie.test(Conc)[2])
View(nt.tan)

#log transform Bing PF data
tanml.df <- tanm.df
tanml.df$Conc <-log(tanml.df$Conc)

View(tanml.df)

#Normality of Log Trans Data
```

```
qqplot(tanml.df$Conc[tanml.df$Location=="TANIn"])
qqplot(tanml.df$Conc[tanml.df$Location=="TANOut"])

nt.tanl <- ddply(tanml.df, .(Location), summarise,
            Shap.Wilk = shapiro.test(Conc)[2],
            Ad.test = ad.test(Conc)[2],
            Lillifors = lillie.test(Conc)[2])
View(nt.tanl)

#Box Plots

ggplot(tanm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(tanml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(tanml.df$Conc[tanml.df$Location=="TANIn"],
tanml.df$Conc[tanml.df$Location=="TANOut"], paired=TRUE)

#ON###########
qqplot(onm.df$Conc[onm.df$Location=="ONIn"])
qqplot(onm.df$Conc[onm.df$Location=="ONOut"])

nt.on <- ddply(onm.df, .(Location), summarise,
            Shap.Wilk = shapiro.test(Conc)[2],
            Ad.test = ad.test(Conc)[2],
            Lillifors = lillie.test(Conc)[2])
View(nt.on)

#log transform Bing PF data
onml.df <- onm.df
onml.df$Conc <-log(onml.df$Conc)

View(onml.df)

#Normality of Log Trans Data
qqplot(onml.df$Conc[onml.df$Location=="ONIn"])
```

```
qqplot(onml.df$Conc[onml.df$Location=="ONOut"])

nt.onl <- ddply(onml.df, .(Location), summarise,
                Shap.Wilk = shapiro.test(Conc)[2],
                Ad.test = ad.test(Conc)[2],
                Lillifors = lillie.test(Conc)[2])
View(nt.onl)

#Box Plots

ggplot(onm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(onml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(onml.df$Conc[onml.df$Location=="ONIn"],
onml.df$Conc[onml.df$Location=="ONOut"], paired=TRUE)

#OP###########
qqplot(opm.df$Conc[opm.df$Location=="OPIn"])
qqplot(opm.df$Conc[opm.df$Location=="OPOut"])

nt.op <- ddply(opm.df, .(Location), summarise,
              Shap.Wilk = shapiro.test(Conc)[2],
              Ad.test = ad.test(Conc)[2],
              Lillifors = lillie.test(Conc)[2])
View(nt.op)

#log transform Bing PF data
opml.df <- opm.df
opml.df$Conc <-log(opml.df$Conc)

View(opml.df)

#Normality of Log Trans Data
qqplot(opml.df$Conc[opml.df$Location=="OPIn"])
qqplot(opml.df$Conc[opml.df$Location=="OPOut"])
```

```
nt.opl <- ddply(opml.df, .(Location), summarise,
               Shap.Wilk = shapiro.test(Conc)[2],
               Ad.test = ad.test(Conc)[2],
               Lillifors = lillie.test(Conc)[2])
View(nt.opl)

#Box Plots

ggplot(opm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(opml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(opml.df$Conc[opml.df$Location=="OPIn"],
opml.df$Conc[opml.df$Location=="OPOut"], paired=TRUE)

#PBP###########
qqplot(pbpm.df$Conc[pbpm.df$Location=="PBPIn"])
qqplot(pbpm.df$Conc[pbpm.df$Location=="PBPOut"])

nt.pbp <- ddply(pbpm.df, .(Location), summarise,
              Shap.Wilk = shapiro.test(Conc)[2],
              Ad.test = ad.test(Conc)[2],
              Lillifors = lillie.test(Conc)[2])
View(nt.pbp)

#log transform Bing PF data
pbpml.df <- pbpm.df
pbpml.df$Conc <-log(pbpml.df$Conc)

View(pbpml.df)

#Normality of Log Trans Data
qqplot(pbpml.df$Conc[pbpml.df$Location=="PBPIn"])
qqplot(pbpml.df$Conc[pbpml.df$Location=="PBPOut"])
```

```
nt.pbpl <- ddply(pbpml.df, .(Location), summarise,
               Shap.Wilk = shapiro.test(Conc)[2],
               Ad.test = ad.test(Conc)[2],
               Lillifors = lillie.test(Conc)[2])
View(nt.pbpl)

#Box Plots

ggplot(pbpm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(pbpml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(pbpml.df$Conc[pbpml.df$Location=="PBPIn"],
pbpml.df$Conc[pbpml.df$Location=="PBPOut"], paired=TRUE)

wilcox.test(pbpm.df$Conc[pbpm.df$Location=="PBPIn"],
pbpm.df$Conc[pbpm.df$Location=="PBPOut"], paired=TRUE)

#TP###########
qqplot(tpm.df$Conc[tpm.df$Location=="TPIn"])
qqplot(tpm.df$Conc[tpm.df$Location=="TPOut"])

nt.tp <- ddply(tpm.df, .(Location), summarise,
              Shap.Wilk = shapiro.test(Conc)[2],
              Ad.test = ad.test(Conc)[2],
              Lillifors = lillie.test(Conc)[2])
View(nt.tp)

#log transform Bing PF data
tpml.df <- tpm.df
tpml.df$Conc <-log(tpml.df$Conc)

View(tpml.df)

#Normality of Log Trans Data
qqplot(tpml.df$Conc[tpml.df$Location=="TPIn"])
```

```
qqplot(tpml.df$Conc[tpml.df$Location=="TPOut"])

nt.tpl <- ddply(tpml.df, .(Location), summarise,
                Shap.Wilk = shapiro.test(Conc)[2],
                Ad.test = ad.test(Conc)[2],
                Lillifors = lillie.test(Conc)[2])
View(nt.tpl)

#Box Plots

ggplot(tpm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(tpml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(tpml.df$Conc[tpml.df$Location=="TPIn"],
tpml.df$Conc[tpml.df$Location=="TPOut"], paired=TRUE)

#TSS###########
qqplot(tssm.df$Conc[tssm.df$Location=="TSSIn"])
qqplot(tssm.df$Conc[tssm.df$Location=="TSSOut"])

nt.tss <- ddply(tssm.df, .(Location), summarise,
               Shap.Wilk = shapiro.test(Conc)[2],
               Ad.test = ad.test(Conc)[2],
               Lillifors = lillie.test(Conc)[2])
View(nt.tss)

#log transform Bing PF data
tssml.df <- tssm.df
tssml.df$Conc <-log(tssml.df$Conc)

View(tssml.df)

#Normality of Log Trans Data
qqplot(tssml.df$Conc[tssml.df$Location=="TSSIn"])
qqplot(tssml.df$Conc[tssml.df$Location=="TSSOut"])
```

```
nt.tssl <- ddply(tssml.df, .(Location), summarise,
             Shap.Wilk = shapiro.test(Conc)[2],
             Ad.test = ad.test(Conc)[2],
             Lillifors = lillie.test(Conc)[2])
View(nt.tssl)

#Box Plots

ggplot(tssm.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

ggplot(tssml.df)+
  geom_boxplot(aes(x=Location, y=Conc), notch=TRUE)+
  theme_bw()+
  labs(x="Location", y="Conc")

#T Test
t.test(tssml.df$Conc[tssml.df$Location=="TSSIn"],
tssml.df$Conc[tssml.df$Location=="TSSOut"], paired=TRUE)
```