ABSTRACT

Thesis Title: TREATMENT OF AGRICULTURAL STORMWATER RUNOFF BY A CASCADING SYSTEM OF FLOODWAY STORMWATER CONTAINMENT BASINS

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A series of four cascading basins were installed at Hambleton Creek Farm in Chestertown, Maryland to treat agricultural stormwater from a 45.4 ha watershed. The basins drain into Hambleton Creek, a tributary of the Chesapeake Bay. The basin system was monitored for 22 months from July 2013 to April 2015 for concentrations and mass loads of suspended sediments, phosphorous and nitrogen. Over the duration of the study, 27 storm events were successfully sampled and tested. During this time, the basin system provided statistically significant reductions of sediments, total phosphorus and total nitrogen mass loads. The total volume reduction exhibited by the system was 56%; volume reduction appears to be the main mechanism of removal for suspended sediments, phosphorus, and nitrogen. Total mass reductions based on an input/output approach for suspended solids, total phosphorus and total nitrogen were 65%, 59%, and 64%, respectively.

TREATMENT OF AGRICULTURAL STORMWATER RUNOFF BY A CASCADING SYSTEM OF FLOODWAY STORMWATER CONTANMENT BASINS

by

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Thesis submitted to the Faculty of the Graduate School of the
University of Maryland, College Park in partial fulfillment
of the requirements for the degree of
Master of Science
2015

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Acknowledgements

This research was supported by High Impact Environmental (HIE) of Chestertown MD, Maryland Industrial Partnerships (MIPS), and the Maryland Department of Natural Resources.

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1.1. Introduction

The quality of the freshwater sources of the United States has become a topic of concern as anthropogenic sources have led to increased levels of pollutants entering surface waters through stormwater runoff (Howarth et. al., 1995). Efforts have been made to reduce the quantity of runoff entering streams while ameliorating the quality by implementing different methods of treatment, minimization, and storage. Stormwater Control Measures (SCMs) are widely used in urban settings for both prevention and treatment of polluted runoff (USDOT, 2002). Such SCMs include bioretention, detention ponds, filter strips, swales and porous pavements (USDOT, 2002). In the agricultural realm however, the majority of SCMs currently being used focus mainly on preventing the pollution of runoff and not the storage or treatment of polluted runoff. Agricultural SCMs consist of filter strips, no-till conditions, winter cover crops, and fertilizer management (Chesapeake Bay Program, 2012). These BMPs are targeted at

Table 1-1. U.S. EPA Breakdown of Nutrient Pollution Sources to Rivers, Streams, Lakes, and Ponds (USEPA, 2002)

Rivers and Streams	% Impaired	Lakes and Ponds	% Impaired
Agriculture	36.7	Unknown/ Unspecified	39.5
Unknown/ Unspecified	29.6	Agriculture	30.1
Hydromodification	25.6	Atmospheric Deposition	26.3
Habitat Alterations	16.6	Land Application/ Waste Sites	22.2
Natural	13.5	Hydromodification	22.0

reducing the amount of soil and sediment mobilized either before or during a storm event and are not designed to store runoff or treat dissolved nutrients. According to the U.S. EPA in 2002, and as shown in Table 1-1, one of the largest sources of nutrient-polluted runoff is over agricultural land where only a small fraction of land area is impervious.

Although almost all agricultural land areas are pervious, large amounts of water still drain from these areas simply due to the large surface areas associated with farm lands. In addition, the quality of this runoff is frequently poor as a result of the large amounts of fertilizer and pesticides applied to the land (Jordan et. al., 2003). When it rains, the stormwater will wash these contaminants from the ground surface and carry them into the natural ecosystem. Suspended solids are an issue with agricultural runoff as tilling and plowing loosen the ground surface, allowing sediment to become easily suspended in the runoff. Sediments carried away from a site can cause excessive erosion which is not desired for agricultural land uses.

A wide range of impacts to natural ecosystems is associated with increased concentrations of nutrients, pesticides, and suspended solids. Excess amounts of nutrients will lead to eutrophication and algae blooms in nearby ponds or streams. Algae, because it floats on the water's surface, blocks sunlight to plants living in the bed of the water body, inhibiting their survival (Smith, 2009). Dissolved oxygen levels also decrease as a result of eutrophication as the algae decompose and deplete the oxygen supply in the water, which natural organisms also need (Smith, 2009). Pesticides pose a problem to natural environments in that they often affect species of organisms outside of the target pest. Runoff containing high concentrations of pesticides that enters a stream or lake habitat can kill off many different species of insects or animals that are essential to the ecosystem (Dellamatrice, 2014). Finally, suspended solids that get carried into stream systems pose a threat in their deposition. When sediments eventually leave suspension, they are deposited on stream or lake beds and therefore cover up existing bed habitats (Walker et. al., 2006.) These solids therefore can block sunlight from plants, or fill in fish habitats in existing rock formations (Walker et. al., 2006.) Over time, deposited sediments can also raise the elevation of stream and lake beds causing issues with flooding (Walker et. al., 2006.)

Frequently employed agricultural SCMs consist of no-till conditions, winter cover crops, vegetated filter strips, contour buffer strips and riparian buffers (US EPA, 2010). According to a United States EPA report published in 2010, no-till conditions can reduce sediment loads by 16.28% to 99%, with the majority of reported values in the 80-90th percentile.   Harmel (2006) also noted a reduction in annual exports of total nutrients under no-till conditions compared to till conditions. However, Harmel (2006) also noted that under no-till conditions more dissolved species of nutrients were exported when compared to till conditions. Winter cover crops have been cited to reduce nitrogen concentrations in the sediment, which could lead to a reduction in nitrogen export (US EPA, 2010). Vegetated filter strips have been cited to reduce suspended solids exports by 64.3 – 92.4% according to a study conducted in the state of Maryland (Magette, 1989). Contour buffer strips and riparian buffers have exhibited suspended solid removals of 19% and 68-95%, respectively. Overall, the SCMs frequently used in the agricultural realm have a wide range of efficiencies and most reported values focus solely on removal of suspended solids. There is clearly room for improvement among agricultural SCMs.

In this study, a system of cascading stormwater basins was tested for its efficiency in the removal of sediment, nitrogen, and phosphorus from contaminated runoff off agricultural land. Four basins, set up in sequence within an existing dry channel, were designed to slow the flow of runoff while allowing for some storage of the runoff as well. Some vegetation was planted within the basins in an effort to further slow the runoff while also introducing an opportunity for plant uptake of nutrients. An input/output approach was implemented to determine the overall efficiency of this system based on removals of total suspended solids, phosphorus species, and nitrogen species.

The cascading system, different from those above, is designed to handle concentrated flow from agricultural sources. The system provides room for storage of runoff and therefore the opportunity for prolonged treatment of captured stormwater, whereas the majority of current SCMs are not designed to store runoff. In addition, the stored runoff may be treated for dissolved nutrients as well as suspended solids; current SCMs provide little opportunity for removal of dissolved nutrients.

1.2 Objectives of Research

This research project has several objectives and goals. The primary goal is quantifying the effectiveness at storing and treating the agricultural runoff entering the basin system. Nitrogen, phosphorus and suspended solids were monitored to determine the treatment efficiency of the system. Through this assessment, a second goal of the research is also explored. Current methods employed for treatment of agricultural runoff focus on the reduction of sediment, which has not been proven to also reduce nutrient concentrations. Therefore this research will also serve to investigate possible new SCMs for not only sediment reduction, but also the treatment of nutrients. Further, understanding the possible mechanisms of treatment that are employed within this system is a goal of the research project. A final goal of this research is to provide recommendations to improve the efficiency of this design. These recommendations could include adjusting the sizes of one or more of the basins, adjusting the designed volume of runoff that the basins can store, and/or adding baffles to the basins to help slow the flow of runoff. Having an understanding of how this system works can provide insight for future designs.

List of objectives:

1. Analyze the efficiency of the cascading basin system for removal of suspended solids, nitrogen and phosphorus.
2. Investigate the cascading basin system as a possible new SCM design.
3. Understand the mechanisms of treatment that are utilized within the cascading basin system.
4. Provide recommendations for improving the efficiency of the cascading basin design.

1.3 Site Description

The site is located on a privately owned agricultural farm known as Hambleton Creek Farm, headwaters of Hambleton Creek, near the city of Chestertown, Maryland as shown in Figure 1-1. The farm mainly grows wheat, switchgrass, and soy beans. A tributary to the Chesapeake Bay, known as Hambleton Creek, exists on the site and the runoff from the site ultimately ends up in this creek. The drainage area contributing runoff to the system is approximately 45 hectares (112 acres) in size. Four basins in line make up the cascading basin system, as shown in Figure 1-2. Runoff fills the basins sequentially, entering only through basin 1 and discharging to the second basin when capacity has been reached. This process is described further in the Methodology section.

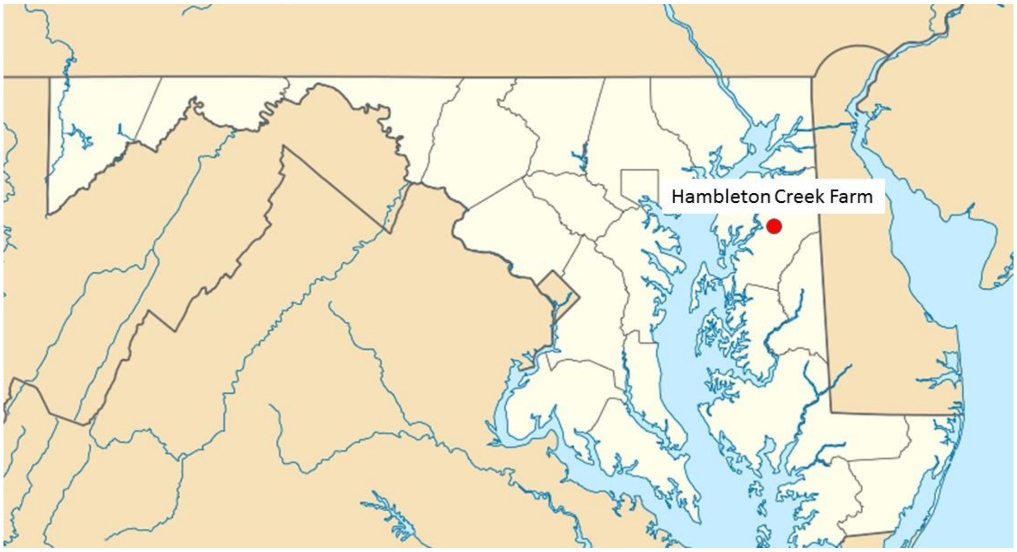


Figure 1-1. Map of the State of Maryland Showing the Location of the Research Site, Hambleton Creek Farm

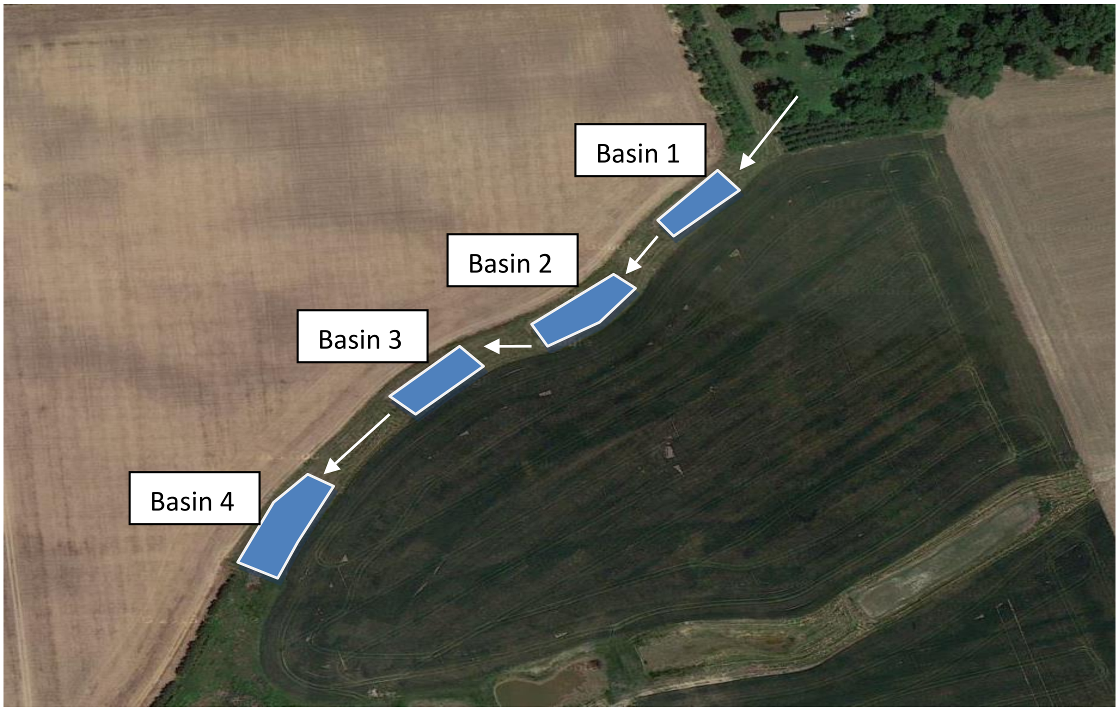


Figure 1-2. Aerial View of the Cascading Basin System Studied in Centreville, MD (39°11'11.7"N 75°59'50.8"W)

2 Methodology

2.1 Site Methodology

The cascading basin system consists of four sequential basins designed to fill consecutively. The majority of the watershed runoff enters the system through the first basin; when this basin reaches capacity it will discharge to the second basin and so on through the basins until the fourth basin is filled. If the fourth basin reaches capacity the system will discharge into a nearby creek. All four basins have varying dimensions as shown in Table 2-1.

As shown in Table 2-1, the total volume that can be stored in these basins is 1.65×10^6 L, or 58,400 ft^3. Based on the watershed area of 45 hectares, about 0.37 centimeters (0.14 inches) of rain over the entire watershed can be stored within the four basins. This value of 0.37 cm assumes that all rainfall that hits the watershed runs off, and there is no infiltration or evaporation. This value also assumes that the basins are empty at the start of the storm.

Table 2-1: Length, Width, Depth, and Volume of all Four Basins in the Cascading System

Basin Number	Length in meters (feet)	Width in meters (feet)	Depth in meters (feet)	Volume in L (ft^3)
1	39.6 (130)	11.3 (37)	0.6 (2)	272,250 (9,620)
2	45.7 (150)	13.7 (45)	0.7 (2.5)	477, 560 (16,875)
3	41.1 (135)	10.7 (35)	0.7 (2.5)	334,300 (11,813)
4	53.3 (175)	13.7 (45)	0.7 (2.5)	569,900 (20,138)
				Total Volume: 1,654,000 L 58445 ft^3

A survey of the drainage area was conducted in February 2015 by EarthData Incorporated of Centreville, Maryland to determine the contributing drainage area to the basins. More details about the contributing drainage area are contained within Figure 2-1. The survey was completed using LiDAR (Light Detection and Ranging), which is a remote sensing method that utilizes a pulsing laser to measure distances to the earth (NOAA, 2015). While the total drainage area contributing to the runoff entering the basin system is 45.4 hectares (112 acres), only 36.5 (90 acres) of those hectares contribute to the volume measured at the inlet of the system. Therefore, for total mass and volume calculations a ratio of 45.4/36.5 (112/90) was used to correct the measured runoff volumes and masses to reflect the total volume and mass expected to be actually entering the basin system.

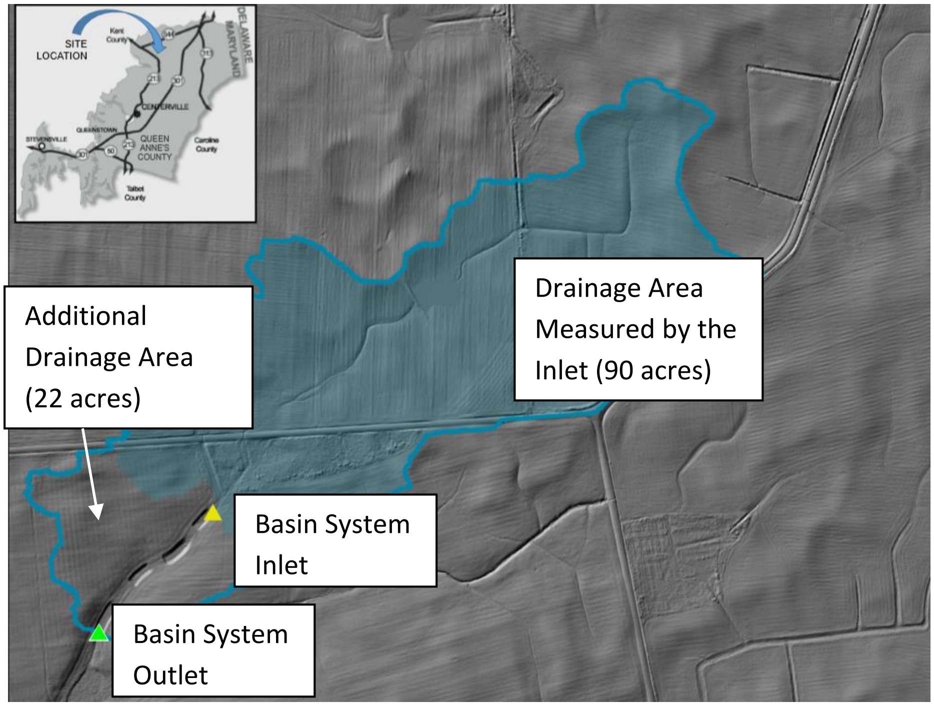


Figure 2-1. Drainage Area Analysis Conducted by EarthData Incorporated Showing the Drainage Area to the Inlet Sampling System and the Additional Drainage Area that Contributes Runoff to the Basins that is not Measured by the Inlet

In order to measure the volumes of water both entering and exiting the system, the inlet and outlet were modified. A two-foot Tracom cutthroat flume, pictured in Figure 2-2, was installed at the entrance to the first basin with an earthen berm surrounding it to funnel the water through the flume. On top of the berm close to the flume, a wooden palette was installed to support the sampling units. A 6712 ISCO sampler was secured to the palette along with an ISCO 674 rain gage; the rain gage has a sensitivity of 0.1mm (0.01 in) and recorded the amount of rainfall every 2 minutes. A bubbler line running from the flume to the sampler was used to track the height of the water passing through the flume at all times. Using this measurement and Equation 2-1, the runoff flowrate into the system was calculated:

$$Q = C*h^n \qquad \text{(Equation 2-1)}$$

Where Q is the flowrate in ft^3/s, C is the flume coefficient , h is the height of water measured in the flume in feet, and n is the flume exponent. As given by Tracom, the C coefficient for this flume is 7.11 and the n exponent is 1.56. These values were converted to L/s.

Water quality samples were drawn from an area in front of the flume. A geotextile was placed on the ground flush with the berm and to the side of the entrance to the flume, where the strainer was placed to draw samples.

A 120-degree V-notch weir, shown in Figure 2-3, was constructed at the outlet end of the system in order to measure the flow that was discharged during each storm event. To the side of the weir another wooden palette was secured; another 6712 ISCO sampler was mounted on top of this palette. A bubbler line was fastened to one edge of the V-notch weir and connected to the sampler in order to measure the height of water passing over the weir.

Figure 2-2. Tracom Cutthroat Flume Installed at the Influent End of the System

The flowrate discharged from the system was calculated using the following equation:

$Q = \frac{8}{15} C \tan\frac{\theta}{2} \sqrt[2]{2g}\, h^{5/2}$ (Equation 2-2, McCuen, 2004)

where Q is the flowrate in ft^3/s, C is the weir coefficient of 0.58, θ is the notch angle, g is the acceleration of gravity in ft/s^2, and h is the height of water flowing over the weir in feet.

Samples at the effluent end of the system were drawn in front of the weir. The strainer was set on the ground at the entrance to the weir to draw samples. Both the influent and effluent samplers were set to enable at a level reading 0.19 centimeters within the flume and the weir. Once enabled, the samplers follow the same program for drawing samples. Two types of sampling programs were used during sampling of storm events. The first was a composite program where samples were taken based on the volume of

Figure 2-3. 120-Degree V-Notch Weir Installed at System Outlet, Surrounded by a Berm

flow passing through the system. A ratio of sample volume to runoff volume was set within the program; this ratio was altered based on the size of the storm that was expected. This ratio typically fell within the range of one sample per every 100,000 to 300,000 liters measured through the flume.

The second type of program that was utilized during sampling was a discrete program; for this type, samples were taken at pre-set times and pumped into separate bottles. A maximum of twelve samples could be collected for one event. Three sequential programs were used with varying durations consisting of a 12 hour program, 24 hour program, and 36 hour program. The program selected for each event would vary based on the size of the storm expected. Typically a longer duration program would be set for the effluent sampler than the influent sampler for a given storm event. The times between each sample for each of the three programs is shown in Table 2-2.

In addition to stormwater runoff water quality samples, grab samples were also taken periodically from each of the basins and tested for the same water quality parameters. Samples were taken once a week as long as the basins were not empty. Additionally, if rain was forecasted, samples would be taken prior to the event and within two days following an event.

forecasted, samples would be taken prior to the event and within two days following an event.

Grab samples were all taken from the west bank of the basins. While samples from the

Table 2-2. Times (in minutes) Between Water Quality Sample Collection for a 12, 24, and 36 Hour Programs Used for Both the Input and Output of the Cascading Basin System

Sample Number	12 Hour Program	24 Hour Program	36 Hour Program
1	At Start	At Start	At Start
2	30	40	40
3	30	40	60
4	40	40	80
5	40	60	120
6	40	90	120
7	60	90	240
8	90	120	240
9	90	120	240
10	90	240	300
11	90	240	360
12	120	240	360

center of the basins would be more representative, wading into the basins would cause fine sediments that had settled out of the stored water to resuspend into the samples. The level of the water inside each basin was also monitored. A three-foot staff gage was placed in each basin, and a reading was taken each time a grab sample was taken.

Both glass and polyethylene 9.5 liter (2.5 gallon) bottles were used for composite sampling. 500 mL (0.13 gallon) cylindrical glass bottles were used for discrete sampling. Grab samples were taken in 1 L (0.26 gallon) polyethylene bottles. All bottles were washed thoroughly with phosphate-free soap, rinsed with deionized water, and allowed to sit in a 0.5 N HCl acid bath for 24 hours before used for sampling.

2.2 Analytical Methodology

All storm samples and basin samples were subjected to the following water quality tests: total suspended solids (TSS), total phosphorus (TP), total dissolved phosphorus (TDP), dissolved reactive phosphorus (DRP), total Kjeldahl nitrogen (TKN), nitrate and ammonium. In some cases, nitrite was measured as well. All concentrations were measured using procedures specified by the *Standard Methods* (APHA *et. al.* 1995) as listed in Table 2-3.

TSS was measured via a gravimetric process according to Standard Method 2540 D using at least 100 mL of sample. In cases where TSS was very high (greater than 2000 mg/L), less of the sample was used to ensure that the filter did not clog prior to all of the sample passing through the filter. All phosphorus species were measured according to Standard Method 4500 P using persulfate digestion and the ascorbic acid method. TDP samples were passed through a 0.2 *μm* membrane filter prior to digestion. DRP samples were also passed through a 0.2 *um* membrane, but did not require digestion. TKN measurements were taken using Standard

Method 4500 N_{org}; a sample volume of 200 mL was used for all samples. Nitrate measurements were made using an ICS-1100 Dionex ion chromatography system with a Dionex IonPac AS22 anion column. The eluent used for nitrate measurements was 4.5 mM Na_2CO_3 and 1.4 mM $NaHCO_3$. Ammonium and nitrite were tested according to Standard Method 4500 NH_3 and 4500 NO_2^-, respectively. All samples for nitrate, ammonium and nitrite analysis were filtered through a 0.2 μm membrane filter prior to testing.

Table 2-3: Pollutant Concentration Determination Analytical Methods

Pollutant	Standard Method (APHA *et.al.* 1995)	Analytical Detection Limit (mg/L)
Total Suspended Solids (TSS)	2540 D	2.5
Total Phosphorus (TP), Total Dissolved Phosphorus (TDP) and Dissolved Reactive Phosphorus (DRP)	4500 P	0.010
Total Kjeldahl Nitrogen	4500 N_{org}	0.14 as N
Nitrate	ICS 1100 ion chromatograph	0.10 as N
Ammonium	4500 NH_3	0.14 as N
Nitrite	4500 NO_2^-	0.010 as N

A Shimadzu UV 160-VIS spectrophotometer was utilized to take absorption measurements for phosphorus species, ammonium and nitrite. Dissolved organic phosphorus (DOP) and organic nitrogen (ON) were calculated by subtracting measured terms, as shown in the following equations:

$$DOP = TDP - DRP \qquad \text{(Equation 2-3)}$$

$$ON = TKN - NH_4\text{-}N \qquad \text{(Equation 2-4)}$$

Where TDP is the measured concentration of total dissolved phosphorus, DRP is the measured concentration of dissolved reactive phosphorus, ON is the concentration of organic nitrogen, TKN is the measured concentration of total Kjeldahl nitrogen, and $NH_4\text{-}N$ is the measured concentration of ammonium.

2.3 Quality Assurance and Quality Control and Variability of Analytical Methods

All sampling bottles and laboratory glassware were washed thoroughly, soaked in acid baths overnight, rinsed with deionized water and dried before used in the field or laboratory. Storm samples were removed from the sampler within 12 hours of the storm event and placed in a refrigerator on site until pick up and transport to the Environmental Engineering Laboratory at the University of Maryland. Standard calibration curves and blank samples were subjected to the same testing procedure as field samples. Standard calibration checks were conducted during analysis when appropriate to assure accurate readings. If the calibration checks failed, samples were re-tested using a new standard curve.

The variability of analytical methods was analyzed using results from two grab samples that were taken two days apart, April 2nd and April 4th, 2014. Similar results would be expected from these two samples as there was no input to the basin system between these samples. The largest discrepancy between concentrations measured for these two samples were for TSS and TKN. All other concentrations measured were very similar in magnitude. The difference in TSS for the data points was 5.7 mg/l (13.9 mg/L vis-à-vis 8.2 mg/L). These results are reasonable, as sedimentation should be occurring during this time period. TKN also includes portions of particulate nitrogen which could explain the discrepancy of 0.42 mg/L between the two data points (1.12 mg/L for April 2nd and 0.7 mg/L for April 4th).

Overall, the data between the two samples was very similar reflecting on the accuracy of the analytical methods. The limited discrepancies in the two data sets are reasonable given the context of the samples.

2.4 Soil Sample Methodology

On November 7, 2014 soil samples that where collected in October were analyzed by A&L Eastern Laboratories for nutrients and texture. A soil sample was taken from the top few centimeters of soil from multiple locations within each basin, as well as from the top layer of soil from multiple locations within the drainage area and stored within Zip-lock bags until tested. A&L Eastern Laboratories analyzed the texture of the soil samples.

2.5 Statistical Methodology

To compare the results of two data sets, statistical analyses were performed. Where appropriate, single or two-tailed t-tests were performed using a 5% level of significance. The null hypothesis stated that the parameter in question for the two data sets was equal, and therefore the level of significance represented the probability of rejecting the null hypothesis when the null hypothesis was actually true.

For sequential storm events, the event mean concentration (EMC) was calculated using Equation 2-5.

$$EMC = \frac{\sum_{i-1}^{N} C_i q_i \Delta t_i}{\sum_{i-1}^{N} q_i \Delta t_i} \qquad \text{(Equation 2-5, Franks 2012)}$$

Where C_i is the pollutant concentration of the sample, i, within an event, q_i is the flowrate for the sample, and Δt_i is the time between sampling events.

Chapter 3: Hydrologic Performance of the Cascading System

During the sampling period from July 3, 2013 to April 22, 2015, a total of 58 storm events were recorded at the site. A summary of the rainfall depths, inflow volumes, and outflow volumes are shown in Table 3-1. The largest depth of rainfall recorded at the site for a single event was 10.08 centimeters on October 13, 2013. The largest flows measured into and out of the basin system occurred during a 7.21 cm storm event on April 29th, 2014 and were 9.8×10^6 liters (with the additional drainage area taken into account) and 8.6×10^6 liters, respectively. For the winter period of late December 2013 to early February 2014, and for February 2015 no data were recorded due to snow precipitation and freezing conditions. Of the 58 storm events recorded, 27 were successfully sampled and tested for water quality.

Table 3-1: Summary of Recorded Rainfall Events With Corresponding Inflow and Outflow Volumes to the Cascading Basin System As Measured by the ISCO Autosampler. Inflow Volumes Were not Adjusted by 112/90 Ratio to Account for Land Not Draining Into Input Flume.

Date	Rainfall in cm. (in.)	Inflow volume in thousand liters (thousand gallons)	Outflow volume in thousand liters (thousand gallons)
*7/3/2013	0.69 (0.27)	456 (121)	0 (0)
*7/23/2013	2.51 (0.99)	2,008 (531)	375 (99)
8/1/2013	4.1 (1.61)	578 (153)	61 (16)
*10/13/2013	10.08 (3.97)	1,147 (303)	0 (0)
11/27/2013	0.28 (0.11)	0 (0)	0 (0)
12/7/2013	0.91 (0.36)	0 (0)	0 (0)
12/9/2013	1.09 (0.43)	0 (0)	0 (0)
*12/14/2013	1.57 (0.62)	1,594 (421)	0 (0)
12/22/2014	0.46 (0.18)	0 (0)	0 (0)
*12/29/2014	0.23 (0.09)	767 (203)	0 (0)
2/3/2014	0.48 (0.19)	0 (0)	0 (0)
*3/30/2014	6.07 (2.39)	3,950 (1,050)	1,874 (495)
4/4/2014	0.56 (0.22)	0 (0)	0 (0)
*4/15/2014	2.032 (0.8)	150 (40)	0 (0)
4/22/2014	0.18 (0.07)	0 (0)	0 (0)
*4/29/2014	7.21 (2.84)	7,905 (2,088)	8,560 (2,260)
5/11/2014	0.28 (0.11)	0 (0)	0 (0)
*5/16/2014	3.35 (1.32)	1,092 (289)	181 (48)
5/22/2014	0.18 (0.07)	0 (0)	0 (0)
5/27/2014	1.37 (0.54)	20 (5)	0 (0)
5/29/2014	0.12 (0.05)	0 (0)	0 (0)
6/4/2014	1.55(0.61)	0 (0)	0 (0)
*6/13/2014	4.95 (1.95)	565 (149)	371 (98)
*6/19/2014	3.53 (1.39)	2,033 (536)	826 (218)
*6/26/2014	0.81 (0.32)	214 (57)	0 (0)
*7/3/2014	3.25 (1.28)	1,368 (361)	1,040 (275)
7/9/2014	0.91 (0.36)	0 (0)	0 (0)
7/15/2014	3.89 (1.53)	1,295 (342)	0 (0)
7/21/2014	0.99 (0.39)	134 (35)	0 (0)
7/26/2014	1.19 (0.47)	253 (67)	0 (0)
*7/28/2014	0.36 (0.14)	70 (18)	0 (0)
8/2/2014	1.24 (0.49)	0 (0)	0 (0)
*8/12/2014	8.89 (3.5)	Sampler Error	Sampler Error
8/22/2014	0.41 (0.16)	0 (0)	0 (0)
9/1/2014	1.42 (0.56)	0 (0)	0 (0)

*9/26/2014	0.81 (0.32)	307 (81)	0 (0)
10/11/2014	0.36 (0.14)	0 (0)	0 (0)
10/13/2014	0.51 (0.2)	0 (0)	0 (0)
*10/16/14	2.57 (1.01)	1,052 (273)	0 (0)
*11/7/14	1.01 (0.4)	244 (63)	0 (0)
11/13/2014	0.1 (0.04)	0 (0)	0 (0)
*11/17/14	2.64 (1.04)	1,344 (355)	0 (0)
11/24/2014	0.48 (0.19)	0 (0)	0 (0)
*11/28/14	3.05 (1.2)	1,960 (517)	470 (124)
12/2/2014	1.68 (0.66)	600 (158)	0 (0)
*12/8/14	1.52 (0.6)	1,850 (490)	953 (252)
*12/12/14	Sampler Error	1,040 (273)	593 (157)
1/1/2015	0.23 (0.09)	0 (0)	0 (0)
1/2/2015	0.15 (0.06)	0 (0)	0 (0)
*1/5/2015	0.53 (0.21)	670 (176)	0 (0)
*3/13/2015	1.19 (0.47)	1,750 (462)	1,264 (334)
*3/16/2015	1.98 (0.78)	1,710 (450)	1,430 (377)
*3/22/2015	1.24 (0.49)	308 (81)	0 (0)
3/27/2015	0.64 (0.25)	108	0 (0)
4/13/2015	1.01 (0.4)	0 (0)	0 (0)
4/15/2015	3.05 (1.2)	0 (0)	0 (0)
*4/21/2015	7.11 (2.8)	Sampler Error	Sampler Error

*Indicates storms with water quality data

3.1 Distribution of Rainfall Events

Table 3-2 shows the distribution of rainfall events sampled at the Hambleton Creek research site. Only events that were successfully sampled and tested for water quality are included within Table 3-2, a total of 22 storm events. The distribution of these events is compared to historical data for the state of Maryland as found by Kreeb (2003). The historical data are presented in Table 3-2 within the parentheses for each depth and duration shown.

As can be seen from the historical data, almost one-third of all storm events for the state of Maryland fall under the shortest duration time of 0-2 hours and the smallest rainfall depth of 0.0254-0.254 centimeters (Kreeb, 2003). Compared to the corresponding proportions of storms measured at the research site of 0.14 and 0.00 for duration 0-2 hours and depth 0.0254-0.254 centimeters respectively, the data collected at Hambleton Creek is biased towards larger, longer duration storms. Storms greater than 2.54 centimeters made up more than half of the events sampled at the Hambleton Creek site. Additionally, storms longer than 24 hours also made up a large proportion of the event sampled, at 0.45. Larger, longer duration storms most likely dominate the distribution because these storms are more likely to produce significant runoff and therefore are more likely to be successfully sampled. Smaller storms which did not produce any runoff were not included in this rainfall distribution because they could not be sampled and tested for water quality; however, taking these storms into consideration would alleviate some bias in the sampled storm rainfall distribution.

Table 3-2: Distribution of Rainfall Events Captured and Tested for Water Quality and With Complete Depth and Duration Information (26 Events) at the Hambleton Creek Research Site and Compared to the Historical Distribution for the State of Maryland (Historical Data Shown in Parentheses) (Kreeb, 2003)

	Rainfall Depth (cm)					
Event Duration (hours)	0.0254-0.254	0.255-0.635	0.636-1.27	1.28-2.54	>2.54	Sum
0-2	0.00 (0.2857)	0.00 (0.0214)	0.04 (0.0167)	0.04 (0.0043)	0.04 (0.0008)	0.12 (0.3289)
2-3	0.00 (0.0164)	0.00 (0.0257)	0.04 (0.0221)	0.00 (0.0089)	0.00 (0.0025)	0.04 (0.0756)
3-4	0.00 (0.0085)	0.00 (0.0223)	0.04 (0.0198)	0.00 (0.0083)	0.00 (0.0038)	0.04 (0.0627)
4-7	0.00 (0.0099)	0.00 (0.0351)	0.00 (0.0475)	0.00 (0.0221)	0.04 (0.0087)	0.04 (0.1233)
7-13	0.00 (0.0058)	0.00 (0.0337)	0.00 (0.0629)	0.12 (0.0528)	0.08 (0.0266)	0.19 (0.1818)
13-24	0.00 (0.0024)	0.00 (0.007)	0.08 (0.0397)	0.04 (0.0611)	0.08 (0.0515)	0.19 (0.1617)
>24	0.00 (0.00)	0.04 (0.0009)	0.08 (0.0043)	0.04 (0.0172)	0.23 (0.0435)	0.38 (0.0659)
Sum	0.00 (0.3287)	0.04 (0.1461)	0.27 (0.213)	0.23 (0.1747)	0.46 (0.1374)	1.00 (1.00)

Shaded boxes represent those sampling proportions found to be statistically different when compared to the historical data by a single proportion test with an α=0.05 (McCuen, 2005.)

Given that this watershed was largely made up of permeable area, the depth of rainfall that would produce runoff was highly variable. The initial abstraction of the watershed was a function of both the amount of rainfall and the extent of the dry period since the last rainfall event. The smallest rainfall depth recorded at the site that produced a runoff was 0.23 cm, while the largest rainfall depth recorded at the site that did not produce a runoff was 1.09 cm. Due to this variability, a set rainfall depth that would assuredly produce runoff could not be determined. Further, the smallest rainfall depth to produce a discharge from the system was 1.19 cm; the largest rainfall depth recorded that did not produce a discharge was 10.08 cm.

3.2 Hydrographs

An example hydrograph from the storm event on March 30, 2014 is shown in Figure 3-1. The line at the top of the graph represents the rainfall for this event, which totaled 6.1 centimeters or 2.39 inches. Three distinct rainfall peaks can be seen in these data; these peaks resonate through the surface runoff as peak flows measured by the influent sampler. The peaks also resonate through the effluent end of the system, although the peak flows have been softened as shown by the Flow Out line. The difference between the Flow In and Flow Out data is indicative of both storage of the incoming stormwater as well as a slowing of the velocity of this water.

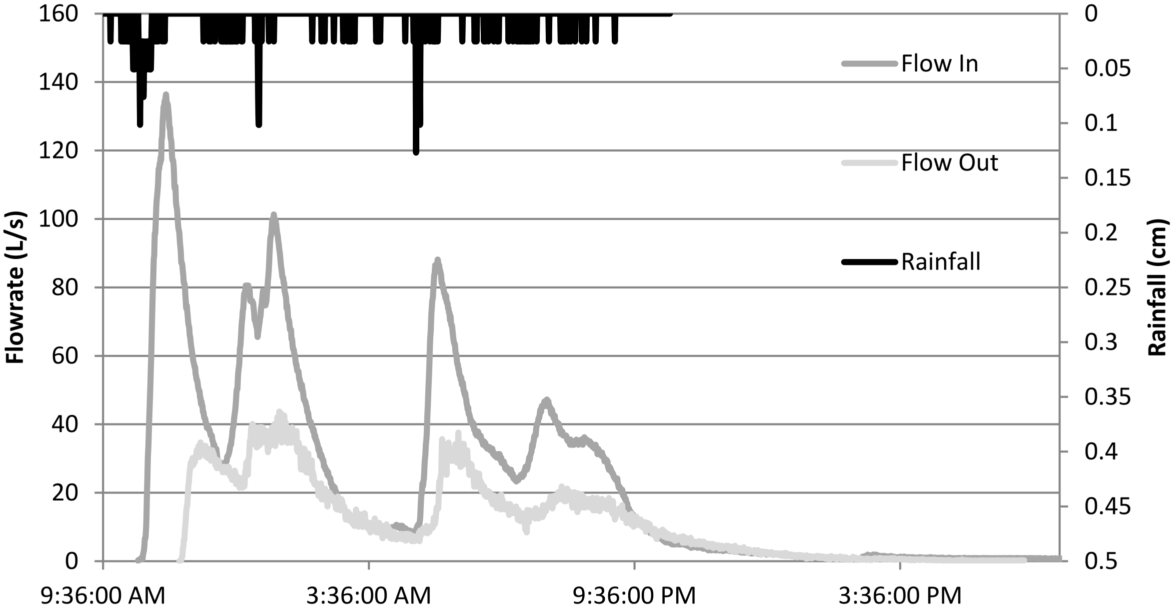


Figure 3-1: Example Hydrograph of March 30, 2014 Storm Event (6.1 cm Rainfall)

For this specific event, the basins at the beginning of the event were approximately half empty. This would allow for a significant amount of runoff to be stored, supporting the softening of the peaks between inflow and outflow.

3.3 Volume Reduction of Runoff

3.3.1 Relationship Between the Rainfall Depth and Runoff Volume

Of the 27 storm events that were successfully monitored, only 13 caused the system to produce an outflow. This is due to the amount of empty volume available in the basins, as well as the potential for significant infiltration in the watershed. Figure 3-2 shows the relationship between the depth of rainfall and the amount of runoff monitored by the influent sampler. Here, the runoff has been converted to a value of depth over the watershed to better understand the amount of rainfall that is able to infiltrate into the watershed. A drainage area of 36 hectares (90 acres) was used for this relationship as this is the drainage area believed to be contributing to the runoff measured by the influent sampler. An R^2 value of 0.34 was observed for this relationship, which is significant though not strong. A significant amount of scatter should be expected within this relationship. The amount of runoff from a storm event should be a function of the amount of rainfall as well as the dry period prior to the storm event. That is, if two storm events occur within a few days of each other, a higher proportion of rainfall can be expected to runoff from the second rainfall event due to potential saturation of the watershed from the preceding event.

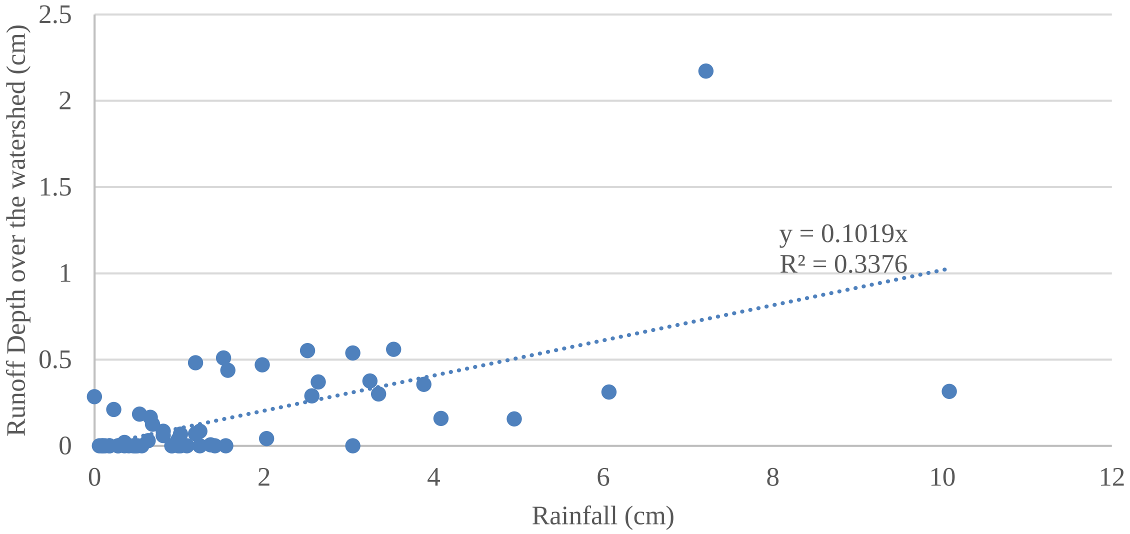


Figure 3-2: Relationship Between the Depth of Rainfall and the Volume of Runoff Measured at the Inlet for 20 Storm Events With Recorded Volume Data from the Hambleton Creek Study Site

The y-intercept for this correlation was forced through the origin to better reflect a realistic relationship between the two variables

The line of best fit for this figure has particular significance. The slope of 0.1019 is indicative of the runoff coefficient in the rational method for this watershed and can be used as a predictor for the amount of rainfall that may runoff of the watershed. According to McCuen (2004), the range of rational coefficients for cultivated land and hydrologic soil group B, which covers the majority of the watershed, for varying slopes is 0.11-0.21. The experimental value of

0.1019 falls very close to this range and correlates well for drainage areas of slopes within the range of 0-2%.

3.3.2 Volume Reduction in Basins

Evapotranspiration and infiltration were assumed to be responsible for the emptying of the basins over time. The Blaney-Criddle equation, shown below, was used to approximate the amount of evapotranspiration occurring in the basins (Allen, 1986.) The Blaney-Criddle equation is largely used when analyzing evapotranspiration from a reference crop (i.e., grass) and when the only meteorological data available is air temperature (Allen, 1986.) Therefore, the Blaney-Criddle equation is appropriate for estimating the evapotranspiration from the basins in this study. However, due to the limited inputs needed for the equation, the Blaney-Criddle equation should only be relied upon to provide an "order of magnitude" estimate for evaporation (Brouwer, 1986.) Further, in extreme weather events such as "windy, dry, sunny" conditions, the equation is known to underestimate evaporation by up to 60%, or in "calm, humid, cloudy" conditions, the equation may overestimate evaporation by up to 40% (Brouwer, 1986.) The amount of evapotranspiration should be constant for each basin as they are all exposed to the same temperature and amount of sunlight.

$$ET(mm/day) = p(0.46T+8) \qquad \text{(Equation 3-1)}$$

Where ET represents the evapotranspiration in mm/day, p represents the percentage of daylight hours, and T is the average daily temperature in degrees Celsius.

An evaporation rate was calculated using measured temperatures and hours of daylight for each day using data collected from local weather and astronomy websites (www.timebie.com, www.wunderground.com). These calculated values were then compared with observed data for the emptying of each basin. The emptying rates of the basins were calculated by the following equation:

$$R = \frac{\widehat{H_2} - \widehat{H_1}}{t} \qquad \text{(Equation 3-2)}$$

Where R is the emptying rate of the basin, H_2 and H_1 are water depths in the basin. The time elapsed between the two depth measurements is given by t (days.) Both H_2 and H_1 are in millimeters.

A plot of the Blaney Criddle approximation compared to the observed emptying data is shown in Figure 3-3. As shown in Figure 3-3, all four basins appear to empty more quickly in colder temperatures. As shown by the Blaney Criddle ET line, evaporation is about 3 mm/day throughout the month of January 2014. Therefore given the actual emptying rates of the basins during January 2014 (60, 45, 120, and 90 mm/day for basins 1, 2, 3 and 4 respectively) it can be assumed that during the winter the emptying rate of the basins is dominated by infiltration as opposed to evaporation. During warmer months the data points more closely correspond to the Blaney Criddle estimate, indicating that evaporation more closely matches infiltration during the summer months. In June 2014, Blaney-Criddle estimates evaporation around 12 mm/day. All four basins exhibited emptying rates around 25 mm/day for June 2014. Therefore it is possible that there is some clogging during the summer affecting the infiltration rates of the basins; during the winter this clogging may be overshadowed by potential cracking of the ground due to freezing temperatures. The basins, because they are all exposed to the same weather conditions, should all undergo very similar rates of evaporation. However, as can be seen in Figure 3-3, the emptying rates of the basins are very different from week to week. Therefore it can be assumed that significant infiltration is occurring within the basins and that this infiltration rate is different for each basin. Even if the Blaney-Criddle approximation has an error of 40-60% as given by Brouwer (1986), the conclusions made regarding infiltration in the basins are not affected.

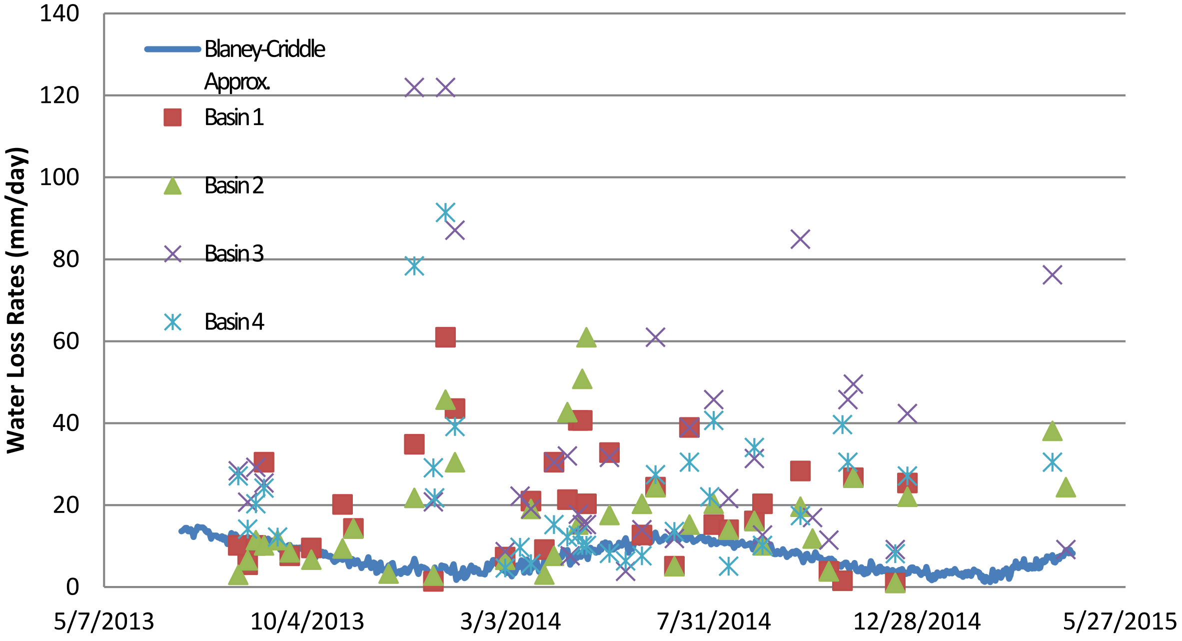


Figure 3-3: Plot of the Blaney Criddle Approximation for Evaporation Rate Compared With the Measured Emptying Rates of all Four Basins

The average emptying rates for the four basins throughout the study period are summarized in Table 3-3. Basins 3 and 4 on average empty more quickly than basins 1 and 2; this could be due to clogging of basins 1 and 2 as these basins may capture the majority of the sediment load as runoff enters the system. Table 3-3 also shows the yearly average for 2014 for all basins, as well as for the Blaney-Criddle Approximation. In 2014, basin 3 alone appeared to drain more quickly than the other three basins, which all had similar emptying rates of 21-23 mm/day. Compared with the average ET from Blaney-Criddle for 2014, the basins on average emptied much more quickly than what would be expected from evaporation alone. Therefore throughout the year, there is evidence to support substantial (15-26 mm/day) infiltration within the basins.

Table 3-3. Summary of the Average Emptying Rates of the Basins and Average ET From Blaney-Criddle for the Sampling Period and For the Year 2014

	Blaney-Criddle ET Approximation	Basin 1	Basin 2	Basin 3	Basin 4
Average Emptying Rate/ET During Sampling Period (mm/day)	7.33 +/- 3.66	20.2	17.5	34.5	22.8
Average Emptying Rate/ET for the Year of 2014 (mm/day)	7.8 +/- 3.9	23.3	21.2	33.0	21.0

3.3.3 Relationship Between the Volume of Runoff entering the System and the Volume of Runoff Discharged From the System

Figure 3-4 shows the relationship between the volume of runoff entering the basin system and the volume of runoff that is discharged from the system. Of the 32 events included in Figure 3-4, only 13 recorded a discharge from the system. The input volumes included in Figure 3-4 have been adjusted to account for the additional drainage area not measured by the flume. This relationship should be largely determined by the amount of storage in the basins. The total basin volume is 1.76×10^6 L and is shown on the graph as the vertical line.

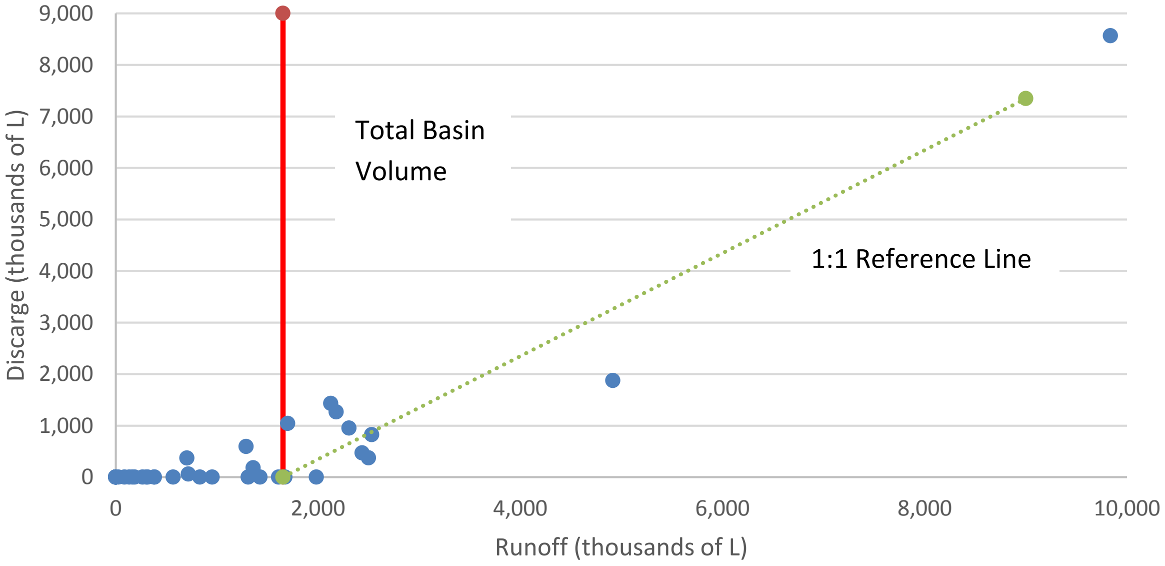


Figure 3-4: Relationship Between the Volume of Runoff Entering and Exiting the Basin System

*Input Volumes Have Been Adjusted Using the Additional Drainage Area Ratio

If a recorded influent runoff volume is less than the total volume of the basins, the expected discharged volume is zero. This statement largely holds true for the data shown; however some scatter is seen in the data left of the storage line, which can be attributed to the basins not being completely empty at the start of a storm event. Data to the right of the storage line represent larger storms with volumes large enough to fill the basins and cause a discharge. For these data, a 1:1 relationship of volume in to volume out can be expected beyond the storage line. That is, once the basins have reached capacity, all of the additional volume entering the system should be discharged with no further storage. Comparing the data to the right of the basin storage line to the 1:1 reference line shown in Figure 3-4, it appears that the larger storms do follow a 1:1 relationship once the capacity of the basins has been reached. Slight deviations of the data points beyond the storage capacity line in relation to the 1:1 reference line are noted. Some variation is expected as the basins do not have the same storage capacity at the start of every event, therefore some storage can occur within the larger events. The maximum depth of rainfall that can be fully captured by the basin system is 0.37 cm (0.14 in).

3.3.4 Probability Plot of Influent and Effluent Stormwater Volumes

A probability plot of the recorded storm events at the Hambleton Creek study site is shown in Figure 3-5. It is clear that all effluent volumes are less than influent volumes. The hollow data points represent a storm event that did not produce any discharge; therefore, the hollow data points indicate 100% capture of the storm event. The median value for the effluent volume is 0. Overall a volume reduction of 68% was exhibited by the system based on total flows measured into and out of the basin system during the sampling period as shown in Table 4-2. This value includes 33 storm events for which complete volume data was recorded.

Most conventional agricultural SCMs do not rely on volume reduction as a mechanism of treatment. Vegetated filter strips (VFSs), riparian buffers, and most wetland detention basins are usually designed to let all flow that enters also exit, although most do slow the pace of the runoff as it passes through the SCM. Some are engineered for significant capture and storage of stormwater, and therefore a wide range of volume reduction for these varying SCMs can be expected. For example, in a study conducted using a settling basin combined with VFSs for treatment of runoff from 300 livestock, a volume reduction of 85% was noted (Mankin, 2003). Another study utilizing a restored wetland as an SCM and with a ratio of wetland to drainage area of 0.09 recorded a volume reduction of only 14% (Jordan, 2003). For this reason, the reduction of 68% exhibited by this system is extremely significant, especially when taking into account the ratio of the drainage area taken up by the basins (0.005).

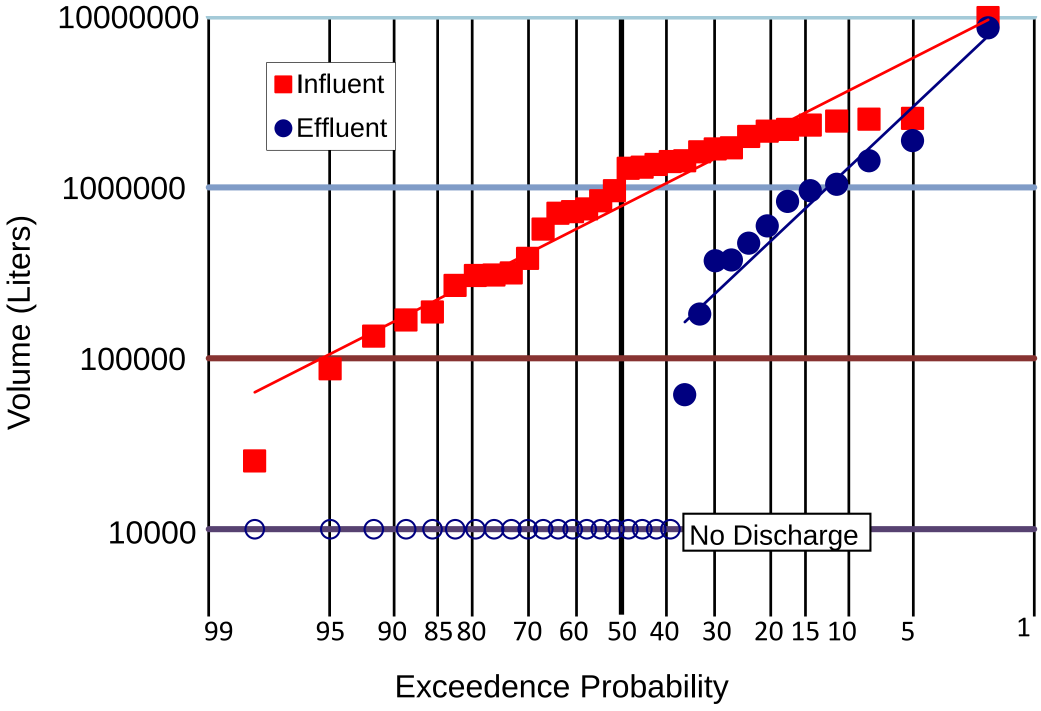


Figure 3-5: Probability Plot of the Influent and Effluent Volumes as Measured by the Autosampler at the Hambleton Creek Study Site

3.3.5 Conclusions

In conclusion, it is clear that the distribution of rainfall events examined at this site is biased towards larger, longer-duration storms when compared to historical data for the state of Maryland. The total volume measured over 25 events into and out of the system was 40,745,000 L and 17,944,000 L, respectively. The estimated rational coefficient as determined from the rainfall and runoff data collected at the research site of 0.1019 compares well with the range cited by McCuen (2004). Overall, in comparison to other frequently used agricultural SCMs, the volume reduction of this basin system of 68% is relatively good. Most other SCMs, such as VFSs and riparian buffers, are not designed to capture or store any volume of water. For detention basins, settling basins, and constructed wetlands which are designed to store some volume of water, the SCM area to drainage area ratio becomes very important. Typical values for this ratio range from 0.1 to 0.2, depending on the land use of the drainage area (Rocco, 2009.) Additionally, the U.S. EPA (1999) stated that ratios of less than 0.01 for wet detention ponds typically yield poor removal efficiencies. The ratio for this site is half of the value of 0.01 given by the EPA which makes the volume reduction of the system even more significant. Volume reduction of stormwater leads to less erosion of soils from the drainage area, as well as a lower pollutant load as the total mass discharged is a function of both the volume discharged as well as the concentration of the pollutant.

Chapter 4: Water Quality Results and Discussion

4.1 Total Suspended Solids (TSS)

4.1.1 Example Pollutograph

An example pollutograph from a storm event on the Hambleton Creek study site, occurring on June, 19th 2014, is shown in Figure 4-1. The rainfall depth of this particular storm was 3.53 cm, or 1.39 inches and the basins at the beginning of the event were about 60% full. The influent flow was significantly slowed by the basin system as seen by the Flow In and Flow Out lines in Figure 4-1. The total volume reduction for this event based on measured flows into the system (corrected by the area ratio) and measured flows out of the system was 67%. A TSS first flush was seen at both the inflow and outflow ends of the system. First flush refers to high concentrations of pollutants during the beginning of a storm; usually pollutants will build up on the ground surface in between rain events and then wash off during an event. The effluent first flush was significantly lower in concentration (approximately 7,000 mg/L for the influent compared to about 4,000 mg/L for the effluent) as well as delayed in terms of time by about 30 minutes.

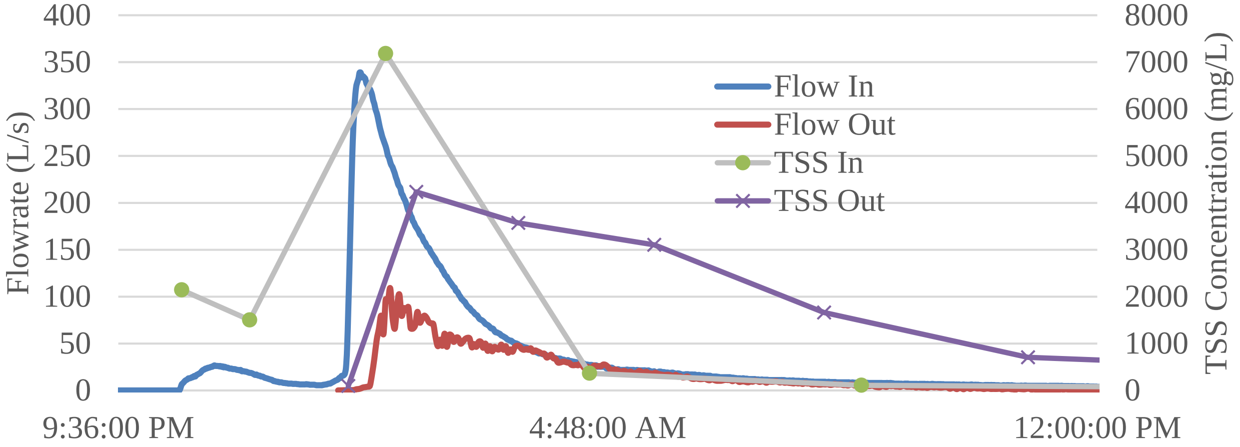


Figure 4-1. Example TSS Pollutagraph From a Storm Event Occurring on 6/19/2014 for the Cascading Basin System

The calculated TSS event mean concentration (EMC) entering the cascading basin system was 3,335 mg/L while the calculated TSS EMC exiting the system was 3,030 mg/L. Based on the total mass entering and exiting the system, a reduction of total suspended solids of 63% was observed during this storm. The total volume reduction for this storm (including the drainage area correction) was 67%.

4.1.2 Probability Plot of TSS Event Mean Concentrations (EMCs)

Shown in Figure 4-2 is a probability plot of the TSS EMCs for storm events monitored at the Hambleton Creek study site. It is clear that effluent EMCs are lower than influent EMCs. The hollow data points represent those storms that did not cause the basin system to discharge; therefore those data points represent 100% capture of suspended solids. The median influent and effluent value for TSS EMC is 172 mg/L and 0 mg/L due to no discharge, respectively. The average EMC into and out of the basin system respectively is 597 mg/L and 224 mg/L. The 90th and 10th percentiles for the influent were 3336 mg/L and 50 mg/L, while the effluent percentiles were 333 mg/L and 0 mg/L due to no discharge, respectively. A two-sample t-test was conducted for the influent and effluent data sets; the data sets were found to be statistically different at $\alpha=5\%$ with the no discharge data taken into account; without the no discharge data, the two data sets were not found to be statistically different. This may indicate that for larger storms which produce a discharge, there is minimal change in concentrations occurring within the basins. That is, the influent stormwater may be travelling through the basins unchanged during large storm events. Table 4-1 shows a summary of the influent and effluent EMC values for each storm.

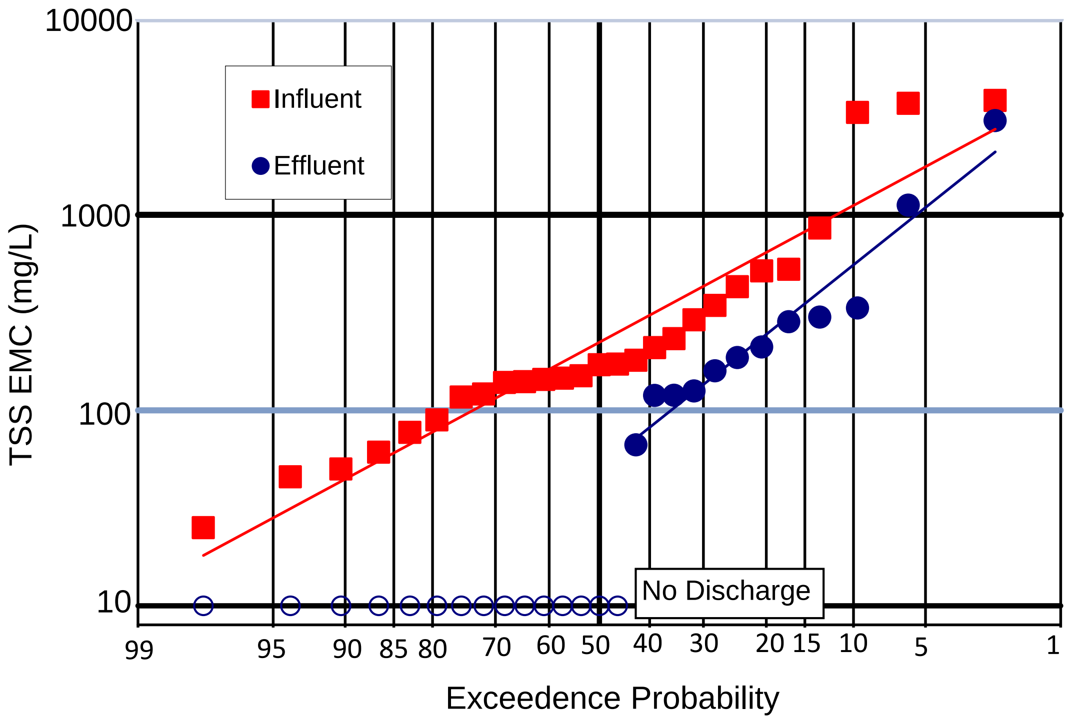


Figure 4-2. Probability Plot of the Influent and Effluent TSS EMC Values for the Cascading Basin System

Table 4-1. Summary of the Influent and Effluent TSS EMCs (mg/L) for Each Storm Event Measured at the Hambleton Creek Study Site

Date	Influent EMC (mg/L)	Effluent EMC (mg/L)
7/3/13	46	No Discharge
7/23/13	77	210
10/13/13	139	No Discharge
12/13/13	50	No Discharge
12/29/13	144	No Discharge
3/30/14	89	284
4/15/14	25	No Discharge
4/30/14	140	300
5/16/14	526	119
6/13/14	516	333
6/19/14*	3,336	3,029
6/26/14*	3,841	No Discharge
7/3/14*	3,710	1,119
7/28/14	855	No Discharge
8/12/14	171	No Discharge
9/26/14	343	No Discharge
10/16/14	232	No Discharge
11/7/14	117	No Discharge
11/17/14	180	No Discharge
11/28/14	146	125
12/8/14	121	119
12/12/14	290	67
1/5/15	150	No Discharge
3/13/15	209	186
3/16/15	172	159
3/22/15	61	No Discharge
4/22/15	428	No Discharge

*A tilling event within the drainage area was recorded on 6/15/14 which may be responsible for the high concentrations of TSS recorded on these dates

4.1.3 Suspended Solids Removal Mechanisms and Ultimate Fate

Suspended solids were reduced by two main removal mechanisms: volume reduction/storage and sedimentation. Volume reduction was the most effective removal mechanism during storm events. As shown in Table 4-2, the total runoff volume reduction for 26 events (with the drainage area taken into account) was 56%, while the total mass reduction for TSS was 65%. Based on these reductions, roughly 10% of the TSS entering the system was removed via sedimentation. Table 4-2 also shows the total masses and volumes into and out of the system. It is worth noting that only about 12% of the total mass of TSS and 25% of the total volume was observed in storm events that did not produce a discharge. Therefore while smaller storms are 100% captured by the system, they make up only a small proportion of the total mass and volume that the basin system receives. Greater attention should be given to the larger storms, most of which will cause a discharge, as these storm events make up the majority of the volume and pollutant mass over the course of a year.

Table 4-2. Summary of Volume and TSS Reduction Percentages and the Total Volumes and Masses of TSS Into and Out of the System for All Storm Events and Only Storm Events That Caused the System to Discharge

	Volume Reduction	TSS Reduction	Total Volume In (Out) in L	Total TSS Mass In (Out) in kg
Values Including All Storm Events	*56%	*65%	40.8×10^6 (17.9×10^6)	21,800 (7,700)
Values Including Only Storms That Produced an Outflow	*59%	*40%	30.4×10^6 (17.9×10^6)	19,400 (7,700)

*Values Calculated Using the Drainage Area Ratio of 112/90

Table 4-3. Typical TSS Mass Reduction Values for Frequently Used Agricultural BMPs

BMP	Source		
	U.S. EPA Report (2010) as cited by Merriman et al. (2009)	Ohio State University Agricultural BMPs Fact Sheet (2012)	Magette (1989)
Contour Buffer Strip	19%		
Riparian Forest Buffer	68-95%	Medium to High Effectiveness	
Vegetated Filter Strip	31-98%	Low to Medium Effectiveness	64.3-92.4%
No-Till	52.3-98%	Medium to High Effectiveness	

As shown in Table 4-2, the total removal shown by the cascading basin system for TSS was 65%. This value compares well with the reduction values compiled within Table 4-3. The value of 65% falls within the range of most of the values cited within the report published by the U.S. EPA in 2010 for various agricultural SCMs, although there is room for some improvement of the cascading basin system to achieve the upper reaches of the ranges shown in Table 4-3.

Figure 4-3 shows the TSS concentration within Basin 1 over time in relation to the depth of water contained in Basin 1, as well as the dates of recorded rainfall dates at the Hambleton Creek research site. When rainfall occurs, the depth of water observed in the basins rises, then over time the water level decreases. Similar conclusions can be drawn from Figure 4-3 and Table 4-4, which summarizes the changes in TSS concentration, TSS mass and volume over time in each of the basins; that is, during the periods of time between storm events both the concentration and mass of suspended solids decrease. The trend is less apparent in Figure 4-3, which relates concentration, but that is expected as the basins also undergo volume reduction during the dry periods. So while the total mass of TSS in the basins is decreasing, the concentration of TSS in the basins may not decrease as the volume of water contained in the basins also decreases.

The longer the dry period, the less turbid the captured stormwater becomes (as shown in Table 4-4 during a 3 week dry period), which should bode well for the quality of the stormwater discharged from the next storm event. However, scouring of the basin floors as evidenced by larger masses of TSS measured out of the system compared to masses of TSS measured into the system was apparently exhibited during two large storm events on March 30th, 2014 and April 30th, 2014 which had rainfall depths of 6.07 and 7.24 centimeters respectively. The total volumes measured into the basins for the March 30th and April 30th events, respectively, were $4.9\text{x}10^6$ L and $9.8\text{x}10^6$ L; the total volumes measured out of the basins were $1.9\text{x}10^6$ L and $6.8\text{x}10^6$ L, respectively. The total TSS mass measured into the system on the respective dates was 101 kg and 1,110 kg, while the masses out were 532 kg and 2,566 kg. During these storm events, significantly greater masses of suspended solids were observed exiting the basin system than observed entering the basins. The total mass reductions, taking the drainage area ratio of 112/90 into account, for the storms on March 30th and April 30th, 2014 were -323% and -86% respectively. Further, the peak flowrate into the system for March 30th, 2014 was 136 L/s while the peak flowrate out of the system was 44 L/s, showing a peak flow reduction of 68%. So while the flowrate was slowed, the total mass exported from the system was still more than the mass that entered the system.

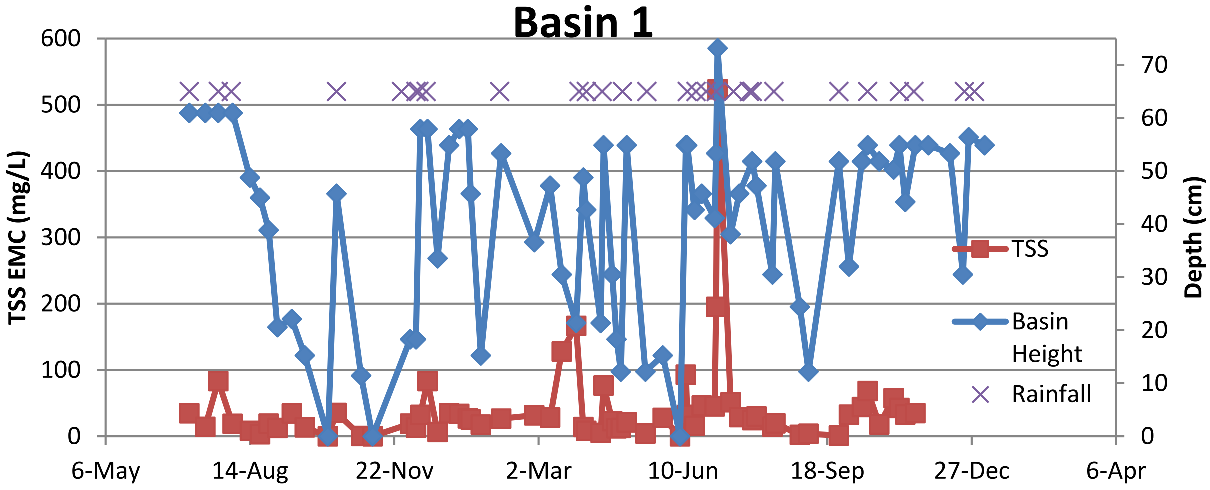


Figure 4-3. Depth and TSS Concentration Within Basin 1 Over Time With Dates of Recorded Rainfall Events

Sedimentation became the dominant removal mechanism in between storm events as the water was held within the basins. This storage period allowed smaller particles to slowly settle out of the runoff. The total mass suspended in the basins decreased as time passed between storm events, as shown in Table 4-4 for the dry period from August 13th, 2014 to September 5th, 2014, during which three sets of grab samples from the basins were taken. Concentrations within the basins generally followed the same trend, although some variation is shown; these variations were assumed to be due to slight resuspension of particles during sampling. Shallower depths within the basins made accurate sampling more difficult as it is easier to disturb the bottom of the basin during sampling. Since both volume and concentration decreased over time, the reduction in mass of suspended solids within the basins cannot be attributed to volume reduction alone, and significant sedimentation must also be occurring.

Table 4-4. Total TSS Mass Suspended Within All Four Basins For Three Separate Grab Sample Events During the Dry Period From August 13th, 2014 to September 5th, 2014

	Date											
	August 13th, 2014				August 30th, 2014				September 5th, 2014			
Basin #	1	2	3	4	1	2	3	4	1	2	3	4
TSS Conc. (mg/L)	20	34	30	26	2	18	16	3	4	7	3	0*
Depth (m)	0.52	0.82	0.82	0.64	0.24	0.55	0.29	0.06	.12	.49	0.21	0*
Volume (thousand L)	231	368	368	286	109	245	129	27	54	218	95	0*
TSS Mass, All 4 Basins (grams)	35,250				6,700				2,100			

*Basin Contained no Water

The ultimate fate of suspended solids that do not leave the basin system is removal via sedimentation, most likely between storm events. Sediments that were removed could accumulate for long periods in the system, but potentially be resuspended during a consequent storm event.

4.1.4 Relationship Between Basin TSS Concentrations and Input Concentrations

It is known that if Basin 1 receives a volume input, the majority of that volume comes from incoming stormwater. It is also known that if Basin 2 receives an input in volume, the majority of that volume is coming from the discharge of Basin 1. The same is true of Basins 3 and 4 which receive volume inputs mainly from Basins 2 and 3, respectively. Therefore, it can be expected that pollutant concentrations of adjacent basins are related. Shown in Figure 4-5 are the concentrations of TSS in the basins over time, along with the TSS concentrations of the volume-contributing storm or basin.

For Basins 2, 3, and 4, three types of inputs are shown, one labeled “plug-flow reactor” (“PFR”), one labeled “completely mixed flow reactor” (“CMFR”), and one labeled “Average

CMFR". Basin 1 only uses storm EMC values as inputs and therefore does not have a PFR/CMFR analysis. These terms are used to describe the mixing conditions in reactors. Plug-flow reactors allow for minimal mixing within the reactors, or basins. If the basins within the cascading system acted similar to plug-flow reactors, the cleaner water within the basins would have little opportunity to mix with the more-polluted water coming from the inputs. To simulate this possibility, the basin TSS concentration from the last sample before the date that an input was recorded was used as the input.

CMFRs allow flows to be thoroughly mixed before discharge. Within the cascading basin system, the incoming polluted water would mix thoroughly with the cleaner water that was stored in the basins before discharging to the subsequent basins. To simulate this condition the TSS basin concentration from the same date as the recorded inflow was used as the input.

The "Average CMFR" condition reflects the same principles as those stated for the CMFR data set, but takes into account the volume of water already contained in the basin that receives an input. Just like the CMFR condition, the TSS basin concentration from the same date as the recorded inflow is used as the input concentration, but in this case it was averaged with the concentration of the pollutant from the date prior to the input.

Figure 4-4 shows a diagram of the three input scenarios. In the diagram are two basins in series where the first basin in the series, pictured on the left, flows into the second basin in the series, shown on the right. The first basin shows two concentrations, $C_{1,1}$ and $C_{1,2}$. $C_{1,1}$ represents the concentration of pollutant in the first basin before an input in that basin has been received. $C_{1,2}$ represents the pollutant concentration in the first basin after an input into that basin has been received. Depending on which analysis (PFR or CMFR) is being used, either of these concentrations could flow from the first basin to the second basin, and therefore both are shown in the diagram. The second basin also has two concentrations, $C_{2,1}$ and $C_{2,2}$. Similar to the first basin, $C_{2,1}$ represents the pollutant concentration in the second basin before an input has been received, while $C_{2,2}$ represents the pollutant concentration after the second basin has received an input.

Using the designations for concentrations shown in Figure 4-4, the following relationships for the PFR, CMFR, and Average CMFR input concentrations into the second basin can be described:

PFR Input Concentration: $C_{1,1}$

CMFR Input Concentration: $C_{1,2}$

Average CMFR Input Concentration: $(C_{1,2} + C_{2,1})/2$

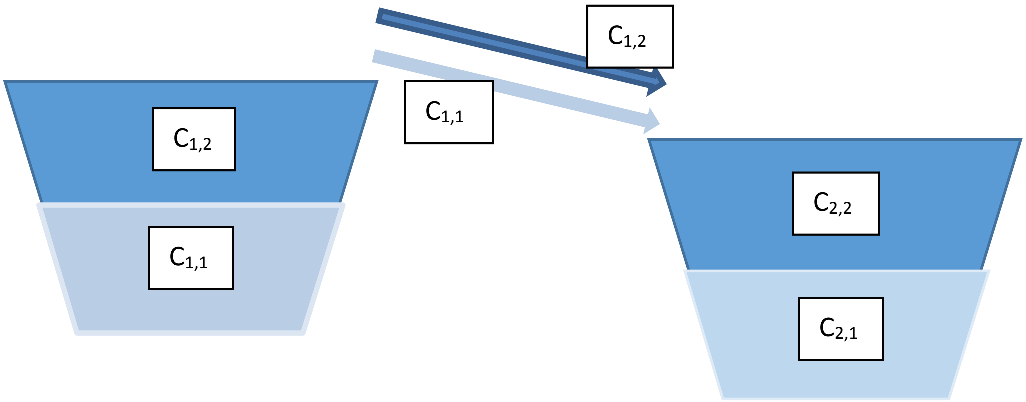


Figure 4-4. Diagram of the Three Input Conditions Analyzed in Order to Determine the Flow Conditions Within the Basin: PFR, CMFR, and Average CMFR

$C_{1,1}$ represents the concentration of pollutant in the preceding basin before that basin has received an input

$C_{1,2}$ represents the concentration of pollutant in the preceding basin after that basin has received an input

$C_{2,1}$ represents the concentration of pollutant in the subsequent basin before that basin has received an input

$C_{2,2}$ represents the concentration of pollutant in the subsequent basin after that basin has received an input

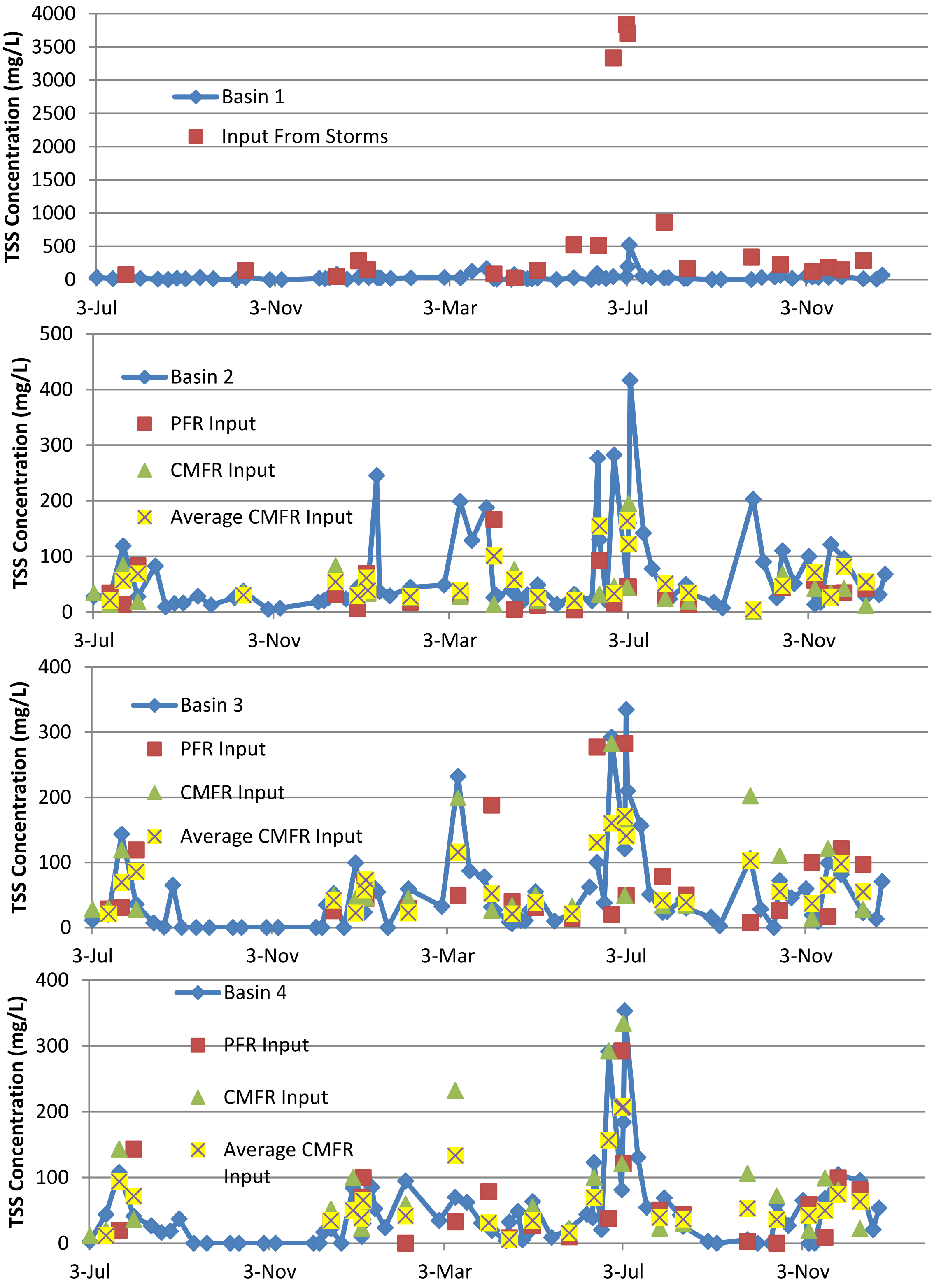


Figure 4-5. TSS Concentrations Within Each of the 4 Basins Overtime With the "PFR" and "CMFR" Input Concentrations From the Preceding Basin or Storm EMC

Figure 4-5 shows the concentrations of TSS in each of the four basins over time, as well as the different input concentrations under PFR, CMFR, and Average CMFR conditions. The figure for Basin 1 shows only the input concentrations from storm events, as this is the only possible input Basin 1 will receive. A two-sample paired T-test was conducted for each of the three flow conditions for Basins 2, 3, and 4. The results are summarized in Table 4-5; while the Average CMFR condition most closely matched the TSS concentration in Basin 2, Basins 3 and 4 correlated more closely with the CMFR condition and the PFR condition, respectively. The T-values for the PFR condition from Basin 2 to Basin 3 to Basin 4 decrease significantly from 2.48 to 0.12, indicating that the PFR input values from Basin 2 to subsequent basins becomes more closely correlated. A similar trend occurs within the Average CMFR T-values, but the range of T-values is smaller (1.37 to 0.41). Therefore, it is possible that the latter basins (Basins 3 and 4) operate more closely to PFR conditions, while the earlier basins (Basins 1 and 2) tend to operate under CMFR or Average CMFR conditions. This could be due to the flume at the influent end of the system, which concentrates the incoming flow through a smaller area therefore increasing the flowrate which may induce more mixing than if the flume were not present. Further implications of the basin flow conditions are discussed in Chapter 5.

Table 4-5. Summary of the Absolute-Value of the T-Statistic Values For PFR, CMFR and Average CMFR TSS Input Data Sets as Compared to the TSS Concentrations Measured in Basins 2, 3, and 4 (α=0.05, *n*=[24,27])

	Basin 2	Basin 3	Basin 4
PFR Flow Condition	2.48	0.53	0.12*
CMFR Flow Condition	2.58	0.43*	2.39
Average CMFR Flow Condition	1.37*	1.30	0.41

*Denotes the least different data set for each basin

4.1.5 Soil Test Results and Comparison to Settling Velocities .of Variously Sized Particles

The results of the texture analyses from A&L Eastern Laboratories are shown in Figure 4-6. If sedimentation were taking place, higher proportions of larger particles (sand) would be expected in Basin 1 as the runoff enters through this basin and the larger particles should settle out relatively quickly. The texture analysis shows a lower proportion of sand in each of the basins when compared to the soil sample from the drainage area, as well as higher proportions of sand in Basins 3 and 4 than Basins 1 and 2. Overall, there is little evidence from these data that significant sedimentation is taking place between the basins. This could be due to the potential scouring of the bottom of the basins carrying sediments through to the discharge. A significantly higher proportion of clay is found within the basins than in the soil sample from within the drainage area. Clay has the smallest diameter of the particles tested in the texture analysis, and therefore can be assumed to be the easiest to suspend within the runoff. Therefore it is expected that larger proportions of clay become suspended into runoff and enter the basins. The fact that the basins have larger proportions of clay support the idea that the basins provide a long enough retention time, most likely in between storm events, as clay takes a significant amount of time to settle (see Table 4-7).

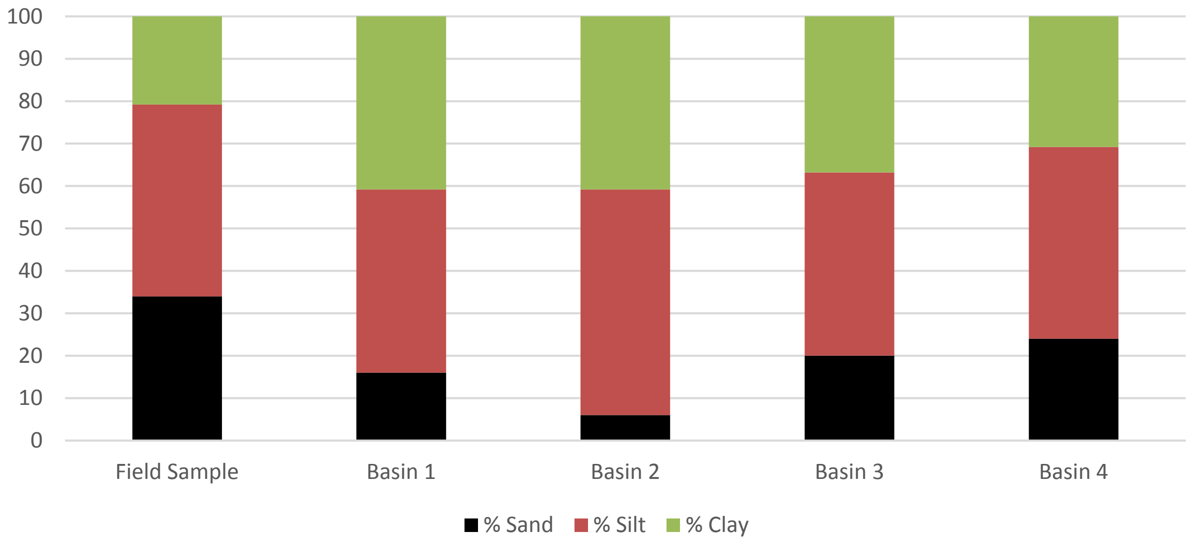


Figure 4-6. Texture Analysis Results for Soil Samples From Each of the Four Basins and One Soil Sample From Within the Drainage Area

Although it appears that little sedimentation is taking place between the basins during a storm event, the expected sedimentation rates of sand, silt and clay particles were estimated using Stokes' Law and the approximate retention times of the basins. Based on Stokes' Law (Equation 4-1), and the calculated retention times of each basin shown in Table 4-6, the basin system should collectively allow enough time for all silt and sand particles to be settled and removed prior to discharge.

$$V_t = \frac{2}{9}(\rho_p\text{-}\rho_f)\frac{g}{\mu}R^2 \qquad \text{(Equation 4-1)}$$

Where V_t represents the particle settling velocity, ρ_p represents the mass density of the particle (assumed as 2650 kg/m^3), ρ_f represents the mass density of the fluid (in this case water), g represents the acceleration due to gravity, μ represents the dynamic viscosity of the fluid and R represents the radius of the particle. Values of 1000 kg/m3 and 0.001 Pa-s were used for ρ_f and μ.

The retention times for each basin were calculated using the highest intensity (cm/hour) storm event recorded at the site, which occurred on June 19th, 2014. The maximum flowrate for this event was calculated (339 L/s) and used in conjunction with the individual basin volumes (270,000 L, 480,000 L, 330,000 L and 570,000 L for Basins 1, 2, 3, and 4 respectively) to determine the hydraulic retention times of each basin using Equation 4-2.

$$T_r = \frac{V}{Q} \qquad \text{(Equation 4-2)}$$

Where T_r represents the retention time, V represents the volume of each basin, and Q represents the average flowrate of the storm event. The results are shown in Table 4-6.

Table 4-6. Estimated Retention Times for Each Basin Within the Cascading Basin System Using an Average Flowrate From the Highest Intensity Storm Event Recorded

	Basin 1	Basin 2	Basin 3	Basin 4
Retention Time (hours)	0.22	0.39	0.27	0.47
			Total	1.36

Settling times for sand, silt, and clay were calculated and compiled in Table 4-7. Based on these values and the retention times calculated for the basins, it is clear that all sand should be removed by the basins; that is, the total retention time of the basins of 1.36 hours is longer than the settling time of the smallest (0.008 mm radius) sand particle, giving this particle enough time to settle during the storm event. Silt particles would be expected to be partially removed (60% for the largest radius and 10% for the smallest radius) during a storm event. Some of the larger clay particles (0.001 mm radius) may be removed by the basin (2.3%) as given by the ratio of the retention time over the settling time, but the majority of clay will not have adequate time to settle out during storm events. For dry periods on the order of ten days, more clay will be expected to settle. Note: this analysis assumes Plug-flow conditions which may not be true of the cascading basin system under storm conditions, as noted in Section 4.1.3.

Table 4-7. Settling Times of Variously Sized Particles Based on Stokes' Law and a Basin Depth of 0.75m

	Maximum and Minimum Radius (mm)	Time to Settle Based on Basin Depth of 0.75 m (hours)
Sand	1	~0
	0.008	0.9
Silt	0.005	2.4
	0.002	14.7
Clay	<0.001	>58.9

Comparing these data to the soil texture analysis, a lack of sedimentation during storm events seems more evident. The smallest (0.008 mm radius) sand particles should settle, according to Stokes' Law, in less than an hour. Therefore, 100% of sand particles entering the basin system should easily be removed during a storm event based on the basin retention time of 20.3 hours, yet this fact is not supported by the soil texture results from the basins. A higher proportion of sand is observed in the drainage area than in the basins, which is not expected if significant sedimentation were occurring.

Given the high proportions of clay within the basins as compared to the proportion measured in the drainage area soil sample, and the estimated settling time of clay particles of

58.9 hours, it appears that there is typically enough time between storm events to allow the majority of clay particles to settle out.

Figures 4-7 and 4-8 show the layer of sediment that has accumulated in Basins 1 and 3 respectively from January 2011 to May 22, 2015. The thickness of the sediment layer in Basin 1 was almost 2 inches, while the accumulation in Basin 3 was about 0.5 inches. Based on the total mass assumed to be captured by the basin system during the monitoring of this research, a 0.2-inch sediment layer expected to have accumulated from July 2013 to April 2014. This value assumes even accumulation in all four of the basins and suggests a reasonable balance on the sediment.

Figure 4-7. Image of the Approximately 2 Inch Sediment Layer that has Accumulated in Basin 1 From January 2011 to May 22, 2015

Figure 4-8. Image of the Approximately 0.5 Inch Sediment Layer that has Accumulated in Basin 3 from January 2011 to May 22, 2015

4.1.5 Conclusions

Overall, the cascading basin system exhibited a TSS mass removal efficiency of 65%. This value was slightly better than the volume reduction efficiency of 56%, showing that little sedimentation is occurring during storm events. This fact was supported by the soil texture analysis and Stokes' Law comparison, which showed less sand particles accumulating in the basins than would be expected based on theory. The total mass of suspended particles in the basins between storm events was shown to decrease with time; this fact was also supported by the soil texture results and Stokes' Law comparison. Higher proportions of clay particles were observed in the basins than in the drainage area soil sample, while only 30% of clay particles would be expected to settle out during a storm event. Therefore, the majority of clay particles must be settling out during dry periods between storm events.

The influent and effluent EMC values for storm events measured for TSS at the cascading basin system were found to be statistically different at *α=10%*. Additionally, the TSS removal efficiency of 65% compared well with removal efficiencies reported for other agricultural SCMs, although there is certainly room for improving the cascading basin system to better match some of the high removal rates compiled in Table 4-3. Methods for improving the cascading basin system for better TSS removal will be discussed further in Chapter 5.

4.2 Phosphorus

4.2.1 Example Pollutograph

Figure 4-9 shows the pollutograph for total phosphorus (TP) for the storm event occurring on June 19th, 2014; the rain depth for this event was 3.53 cm (1.39 in). The data points for TP In peak around the same time that the Flow In line peaks, exhibiting a first flush. The peak of TP Out is delayed from the peak shown for Flow Out by about 2 hours. In this case, the peaks for TP In and TP Out are the same concentration (9 mg/L), although the peak for TP Out occurs approximately two hours after the peak for TP In. Based on the peak flowrate of this storm (339 L/s) and the total volumes of each basin, the travel time through the cascading basin for this event should have been 1.4 hours, which is relatively close to the observed time of 2 hours

Not only were the peak concentrations the same for In and Out, but the speciation of both concentrations were almost identical (approximately 0.2 mg/L inorganic phosphorus, 8.8 mg/L particulate phosphorus, and 0.1 mg/L organic phosphorus for both In and Out concentrations).

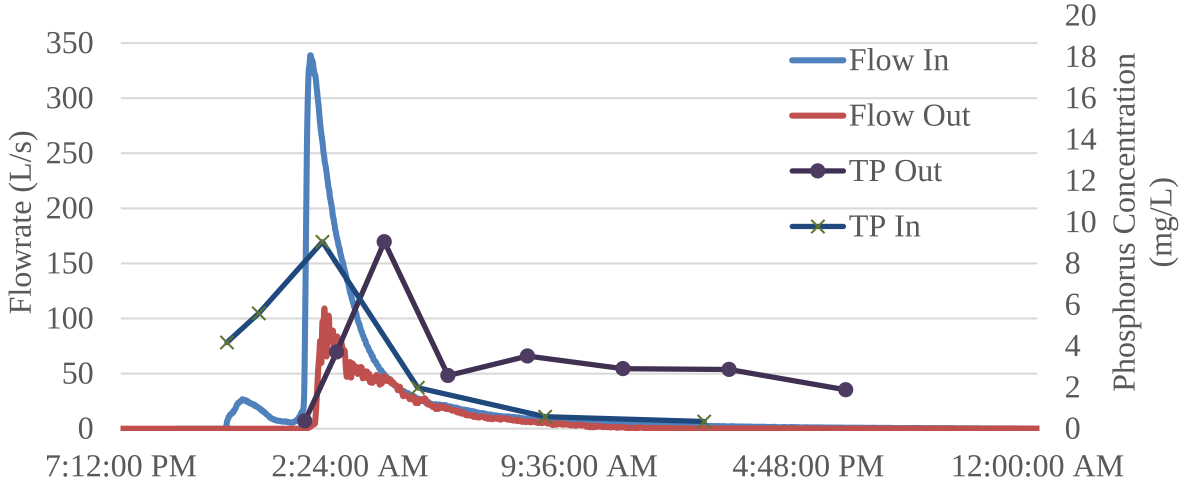


Figure 4-9. Pollutograph of Total Phosphorus (TP) Concentrations and Flowrates Into and Out of the Basin System for a Storm Event Occurring on June 19th, 2014

Therefore it would appear that the influent water passes through the system unchanged, with the exception of volume reduction shown by the Flow In and Flow Out lines in Figure 4-9.

4.2.2 Phosphorus Speciation, Removal Mechanisms, and Ultimate Fate

Total phosphorus can be broken down into the following types, or species: Particulate Phosphorus (PP), Dissolved Organic Phosphorus (DOP), and Dissolved Inorganic Phosphorus (DIP). DIP and DOP together may also be referred to as Total Dissolved Phosphorus (TDP). DIP is of particular significance as this species of phosphorus is the most bioavailable and therefore most connected to algal blooms and eutrophication (Hallegraeff, 1993).

The speciation of phosphorus in stormwater samples appeared most dependent upon fertilizing and tilling events. Fertilizing events occurred every year in May; two tilling events in the drainage area were recorded per year during the study period, occurring May and September. Input phosphorus concentrations following fertilizing in May 2013 were dominated by dissolved species; on average particulate phosphorus for events following fertilization (three in total) made up only 30% of the total phosphorus. In contrast, for events following a recorded tilling event in May 2014 (six events in total), particulate phosphorus concentrations made up about 80% of the total input phosphorus on average. Overall, particulate phosphorus averaged 63% of the total input phosphorus concentration for all events tested for water quality.

Since the majority of phosphorus entering the system is in particulate form, similar removals for TP can be expected as for TSS. The relationship between the concentrations of PP and TSS for storm events tested for water quality is shown in Figure 4-10; a strong correlation is noted with a correlation coefficient of 0.62. The trend line shown and corresponding correlation coefficient has been forced through the origin to better reflect a realistic relationship.

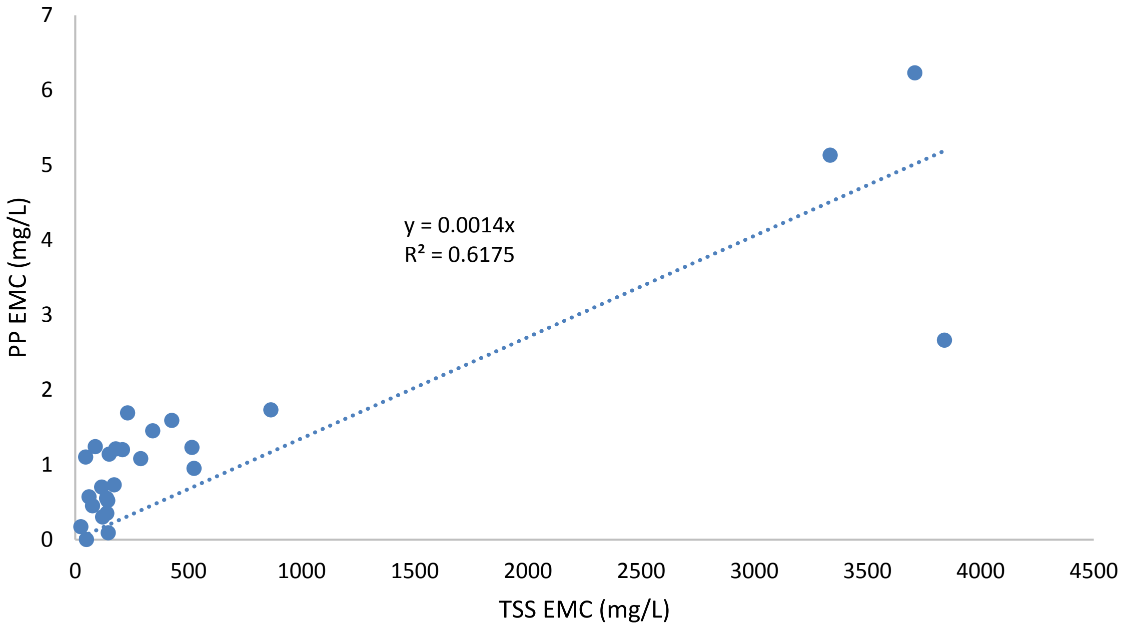


Figure 4-10. Correlation Between the Influent Concentration of Particulate Phosphorus (PP) and Total Suspended Solids (TSS) for Water Quality-Tested Storm Events at the Hambleton Creek Research Site

A similar correlation is noted for concentrations of TSS and PP in the effluent of the basin system and is shown in Figure 4-11. Here, a very strong correlation of 0.86 is shown. This trendline has also been forced through the origin to reflect a more realistic relationship between PP and TSS. Additionally, the slopes of each trend line are shown in Figures 4-10 and 4-11; for the influent and effluent correlation, the slopes are, respectively, 1.4 mg-PP/g-TSS and 1.6 mg-PP/g-TSS, and represent the amount of P affiliated with the particulate matter. These two slopes are very close in magnitude and may be indicative of similar proportions of PP and TSS both entering and exiting the system. Therefore, it appears that phosphorus is minimally adsorbing to the sediments while in the basins.

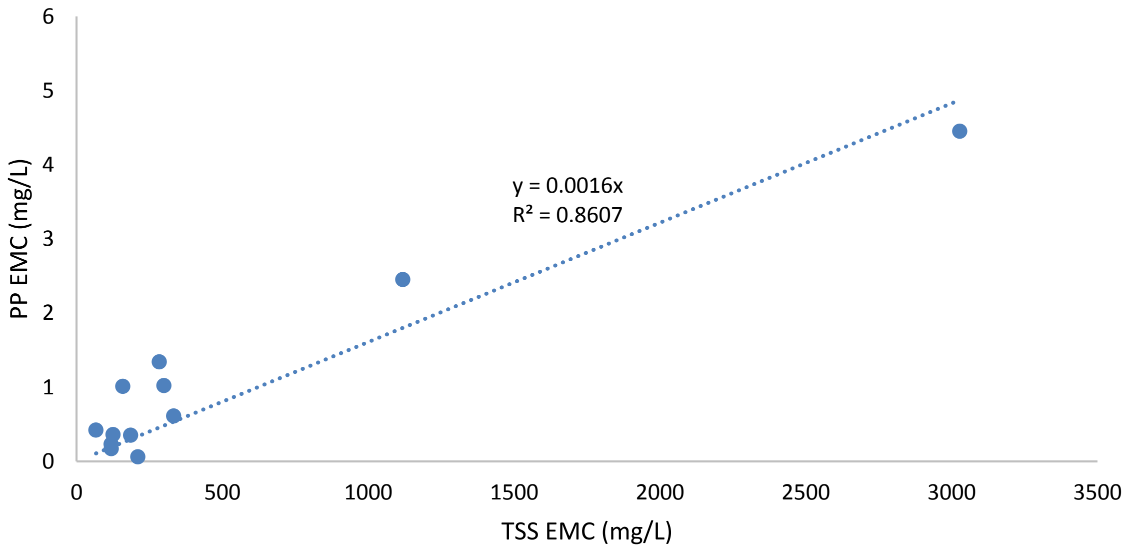


Figure 4-11. Correlation Between the Effluent Concentration of Particulate Phosphorus (PP) and Total Suspended Solids (TSS) for Water Quality-Tested Storm Events at the Hambleton Creek Research Site

Given the relationship between PP and TSS, similar removal mechanisms can be expected for this form of phosphorus and for TSS. That is, sedimentation and volume reduction should dominate the removal of particulate phosphorus.

The overall removals for TP, PP, DP, DIP and DOP for the entire study are shown in Table 4-8. The removal of TP is 4% higher than the value shown for volume reduction; therefore it may be assumed that some other mechanisms are taking place for phosphorus removal. The reduction of PP is less than that for TSS by 8%, and is very close to the reduction of volume, therefore it can be assumed that sedimentation has less of an effect for PP than TSS and that volume reduction is the main removal mechanism for PP. The reduction of DOP is close to the reduction shown for volume reduction, and therefore volume reduction can be assumed to be the primary removal mechanism for DOP as well.

DIP makes up the majority of DP (80%), and exhibits the highest removal of all the types of phosphorus. As previously stated, DIP represents the form of phosphorus that is most bioavailable, and therefore that which is most readily taken up by plants and microorganisms. This species of dissolved phosphorus could be taken up by the plant life existing in the basins between storm events. During some summer months, algae was noted growing within the basins. Algae growth would utilize significant portions of the inorganic phosphorus entering the basins and therefore would also lead to some removal of the dissolved phosphorus entering the basins (Norton, 2014). Other microorganisms such as bacteria and fungi can also take up dissolved phosphorus similar to algae and contribute to the removal (Norton, 2014). Dissolved phosphorus could also be removed through adsorption onto particles followed by sedimentation. Conclusions cannot be drawn at this point as to which mechanisms, in addition to volume reduction and sedimentation, are having the most effect on the reduction of phosphorus, although it is safe to assume some other processes are taking place given the difference between volume and TSS reduction and P reduction values.

Table 4-8. Reductions Based on Total Volume and Mass Measured Into and Out of the Basin System and Including the Drainage Area Ratio

	Volume (L)	TSS (kg)	TP (kg)	PP (kg)	DP (kg)	DIP (kg)	DOP (kg)
Total Volume/Mass in	40.7×10^6	21,800	64,800	43,100	17,300	14,200	3,500
Total Volume/Mass Out	17.9×10^6	7,700	25,900	18,300	6,300	4,800	1,600
Reduction	56%	65%	60%	57%	63%	66%	54%

Table 4-9 shows the removal efficiency for TP/Nutrients for frequently used agricultural SCMs. The removals reported by the EPA Report (2010) span a wide range for TP, from 2 to 97% for the various SCMs. The BMP Fact Sheet (2012) qualitatively assessed the efficiency of the various SCMs for both soluble and adsorbed nutrients. It is clear that riparian forest buffers, vegetated filter strips and no-till conditions all have minimal efficiency for removal of soluble nutrients according to the Fact Sheet (2012). These same SCMs have moderate to high removals for adsorbed nutrients. Finally, Magette (1989) reported a TP removal efficiency of 27% for vegetated filter strips. The removal efficiency for TP by the cascading basin system was 60%, which compares well with the values compiled in Table 4-9. Further, the removal efficiency for dissolved phosphorus for the cascading basin system was 63%; only the BMP Fact Sheet

Table 4-9. Typical Total Phosphorus/Nutrient Mass Reduction Values for Frequently Used Agricultural SCMs

SCM	Source			
	EPA Report (2010) as cited by Merriman et al. 2009 (Total Phosphorus)	Ohio State University Agricultural BMPs Fact Sheet (2012) (Soluble Nutrients)	Ohio State University Agricultural BMPs Fact Sheet (2012) (Adsorbed) Nutrients)	Magette (1989) (Total Phosphorus)
Contour Buffer Strip	8-58%			
Riparian Forest Buffer	56%	No Control to Low Effectiveness	Medium to High Effectiveness	
Vegetated Filter Strip	2-93%	No Control to Low Effectiveness	Low to Medium Effectiveness	27%
No-Till	5-97%	No Control to Low Effectiveness	Medium to High Effectiveness	

provided qualitative removals for particulate and dissolved forms of phosphorus separately. According to the Fact Sheet (2012), little removal of dissolved species of phosphorus would be expected from the frequently used SCMs included in Table 4-9, and therefore the removal of DP for the cascading basin system of 63% is particularly significant, although likely dominated by the volume reduction.

Figure 4-12 shows the concentration of phosphorus in Basin 1 over time. Data points for inorganic phosphorus, organic phosphorus, and particulate phosphorus are shown; these three types of phosphorus together add up to total phosphorus. Overall, there were only four storm events at which dissolved phosphorus dominated the speciation; particulate phosphorus most frequently governed the speciation of phosphorus within the basins, averaging 65% of TP over 22 events, although the concentration of dissolved phosphorus is also significant. Levels of total phosphorus peaked in June of both 2013 and 2014, following fertilizing events, reaching maximum concentrations of 6.2 and 7.6 mg/L, respectively for each year.

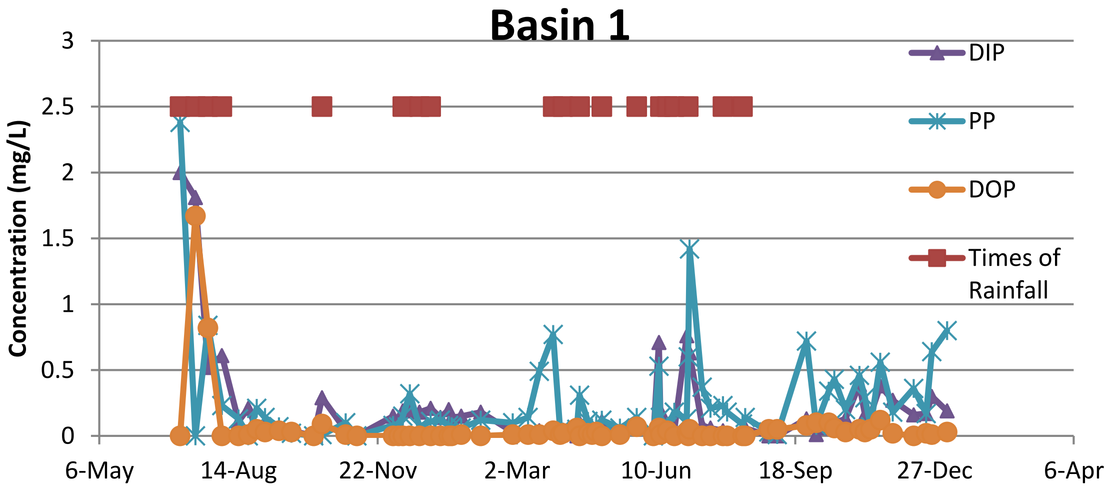


Figure 4-12. Concentrations of DIP, PP, and DOP in Basin 1 Over Time With the Times of Rainfall Events

The ultimate fate of phosphorus that entered the basin system was most likely dependent on the speciation. Particulate phosphorus would meet similar fates to those of TSS; particulate phosphorus would either be removed via sedimentation or possibly discharged with effluent stormwater. Dissolved portions of phosphorus may have adsorbed onto suspended particles and consequently settled out as one possible fate. They may have also been taken up by plant life in the basins and incorporated into biomass. Dissolved phosphorus can also infiltrate into the groundwater with infiltrating stormwater.

4.2.3 Probability Plot of Phosphorus EMCs

Shown in Figures 4-13 through 4-16 are the probability plots of the Total Phosphorus, Dissolved Phosphorus, Dissolved Inorganic Phosphorus, and Particulate Phosphorus EMCs measured at the Hambleton Creek research site. It is clear that the effluent concentrations from the basin system are lower than the influent concentrations. The hollow data points represent those storms that did not cause the basin system to discharge and therefore represent 100% capture of the event. Table 4-10 summarizes the medians and the 90th and 10th percentiles for each phosphorus species for the influent and effluent data sets. Each phosphorus species was also analyzed using a two-sample t-test with a significance level of 5%; these results are also summarized in Table 4-10.

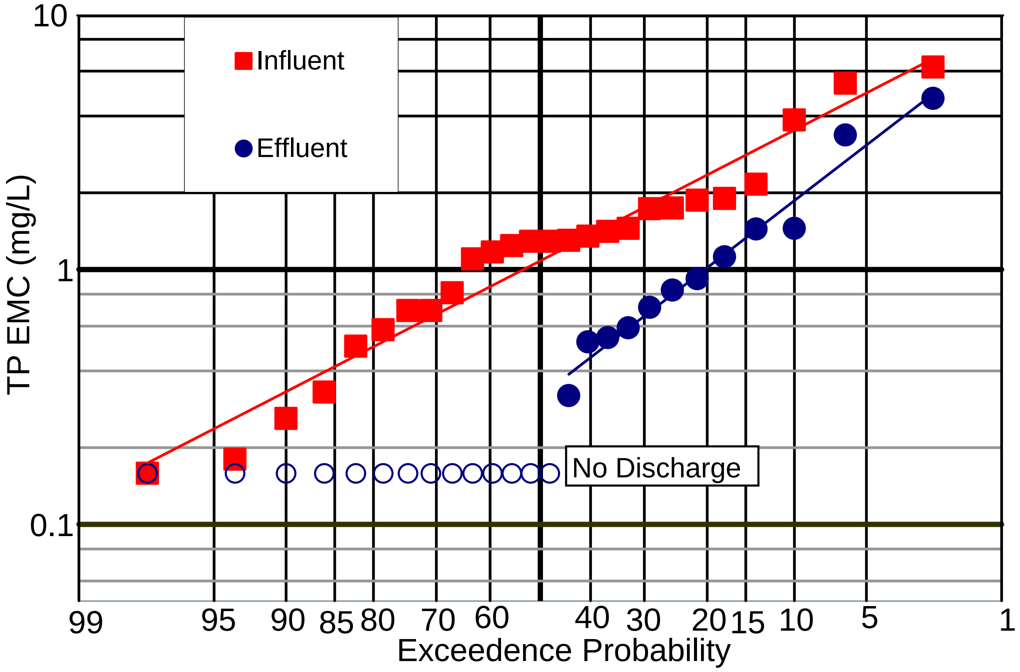


Figure 4-13. Probability Plot of the Influent and Effluent Total Phosphorus (TP) EMCs for Storm Events Captured at the Hambleton Creek Research Site

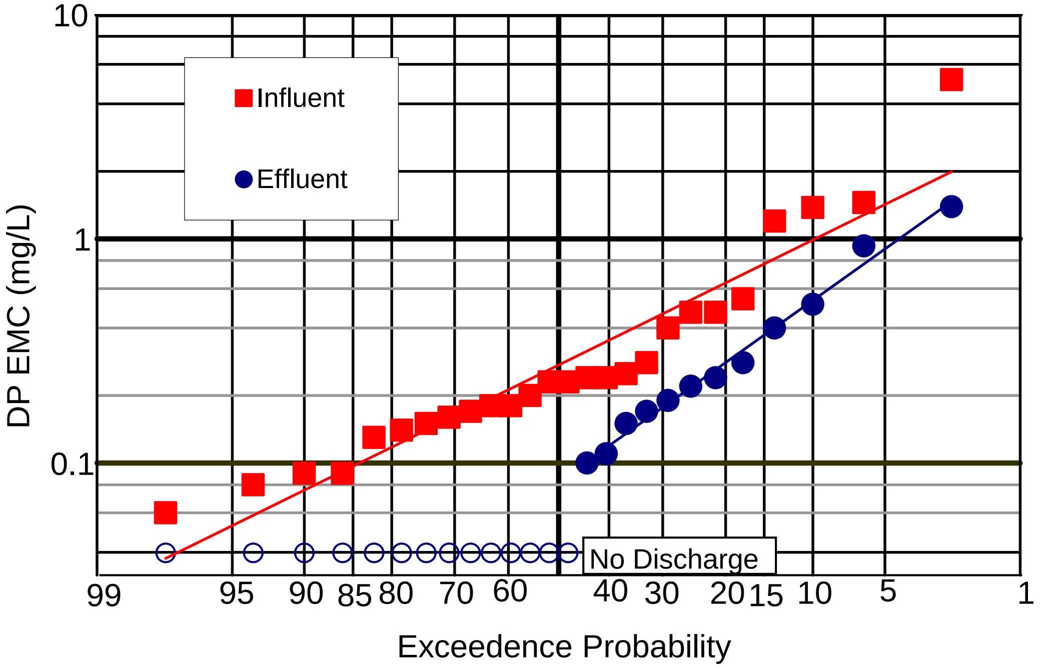


Figure 4-14. Probability Plot of the Influent and Effluent Dissolved Phosphorus (DP) EMCs for Storm Events Measured at the Hambleton Creek Study Site

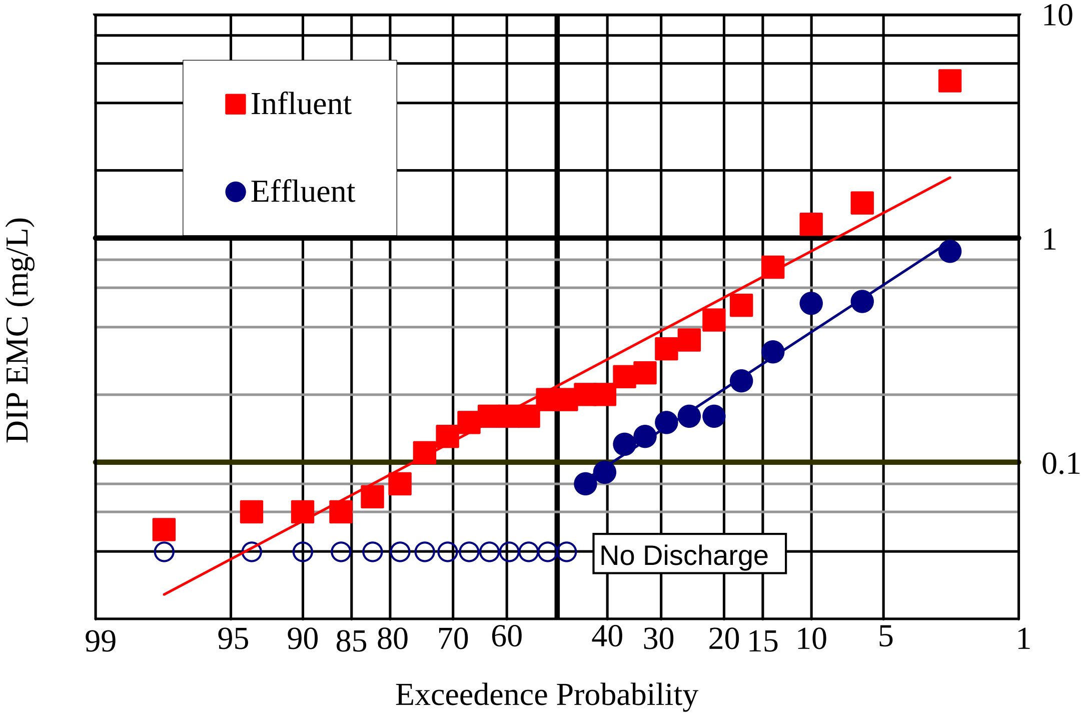


Figure 4-15. Probability Plot of the Influent and Effluent Dissolved Inorganic Phosphorus (DIP) EMCs for Storm Events Measured at the Hambleton Creek Study Site

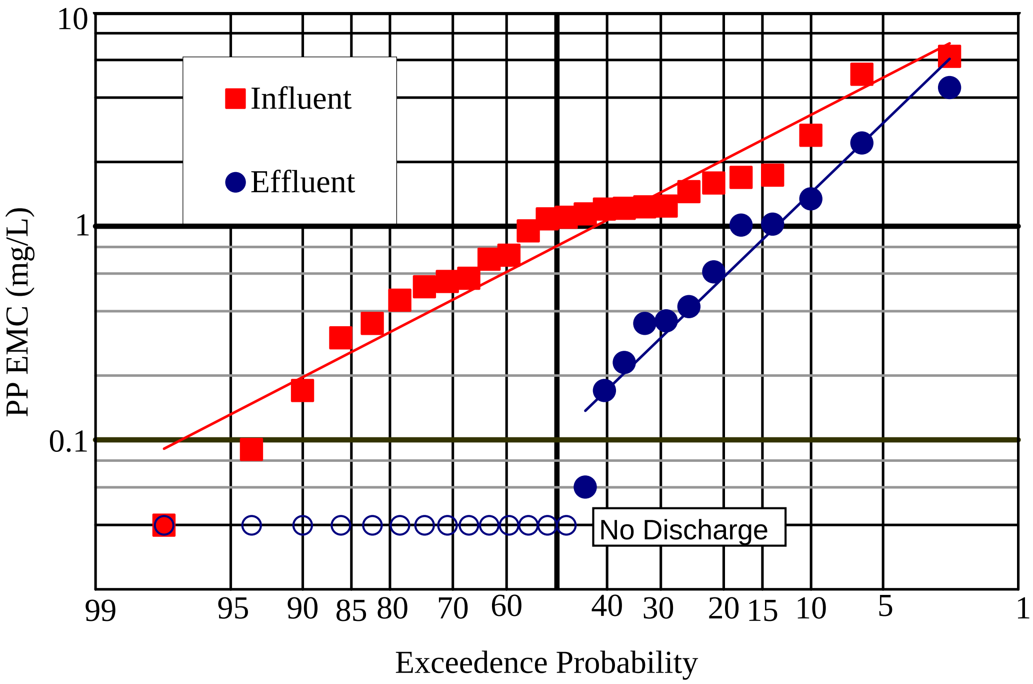


Figure 4-16. Probability Plot of the Influent and Effluent Particulate Phosphorus (PP) EMCs for Storm Events Measured at the Hambleton Creek Study Site.

Table 4-10. Summary of the 90th and 10th Percentiles, Median Values, and t-Test Results for Influent and Effluent Data Sets for TP, DP, DIP, and PP at the Hambleton Creek Study Site

		90th Percentile	Median	10th Percentile	Statistically Different two-sample t-test? (α=5%, including no flow data)	Statistically Different two-sample t-test? (α=5%, without no-flow data)
TP	Influent	5.38	1.3	0.33	Yes	No
	Effluent	1.45	0*	0*		
DP	Influent	1.38	0.23	0.09	Yes	No
	Effluent	0.51	0*	0*		
DIP	Influent	1.15	0.19	0.06	Yes	No
	Effluent	0.51	0*	0*		
PP	Influent	2.66	1.09	0.17	Yes	No
	Effluent	1.34	0*	0*		

Given the probability plots in Figures 4-11 to 4-14, as well as the results compiled in table 4-10, it is clear that the effluent data sets are indeed lower than the influent data sets. However, taking into account only those storms that produced a discharge, the data sets were not found to be statistically different. This may indicate that there is little change in concentration occurring in the basins in the influent and effluent data sets for storms that are large enough to produce a discharge.

4.2.4 Relationship Between Basin Phosphorus Concentrations and Input Concentrations

The CMFR/PFR analysis was conducted for phosphorus concentrations, yielding similar results to TSS. Figure 4-17 shows the TP concentrations in the basins over time as well as the various calculated input concentrations. Basin 1 shows only the storm EMCs as the input. A paired two-sample t-test was conducted for each set of input concentrations with the corresponding basin concentrations. Table 4-11 shows a summary of the absolute value of the t-values for each input into each basin.

Table 4-11. Summary of the Absolute-Value of the T-Statistic Values For PFR, CMFR and Average CMFR TP Input Data Sets as Compared to the TP Concentrations Measured in Basins 2, 3, and 4 (α=0.05, *n*=[24,27])

	Basin 2	Basin 3	Basin 4
PFR Input	0.92	0.45	0.48
CMFR Input	1.34	1.12	1.06
Average CMFR Input	0.31*	0.32*	0.47*

*Denotes the least different data set for each basin

For each basin, the Average CMFR Input values correlated best with the concentrations in the basins, indicating that there is adequate mixing of incoming stormwater with water stored in the basins during a storm event. The t-values for the Average CMFR Input, however, are only marginally different from the PFR values for basins 3 and 4, making the t-values for Average CMFR less significant for these basins. Additionally, the values for Average CMFR increase from Basin 2 to Basin 3 to Basin 4 showing that the data sets are becoming more different. Therefore, while the Average CMFR Input values correlated best with the concentrations in the three basins, the PFR input values become more significant for Basins 3 and 4.

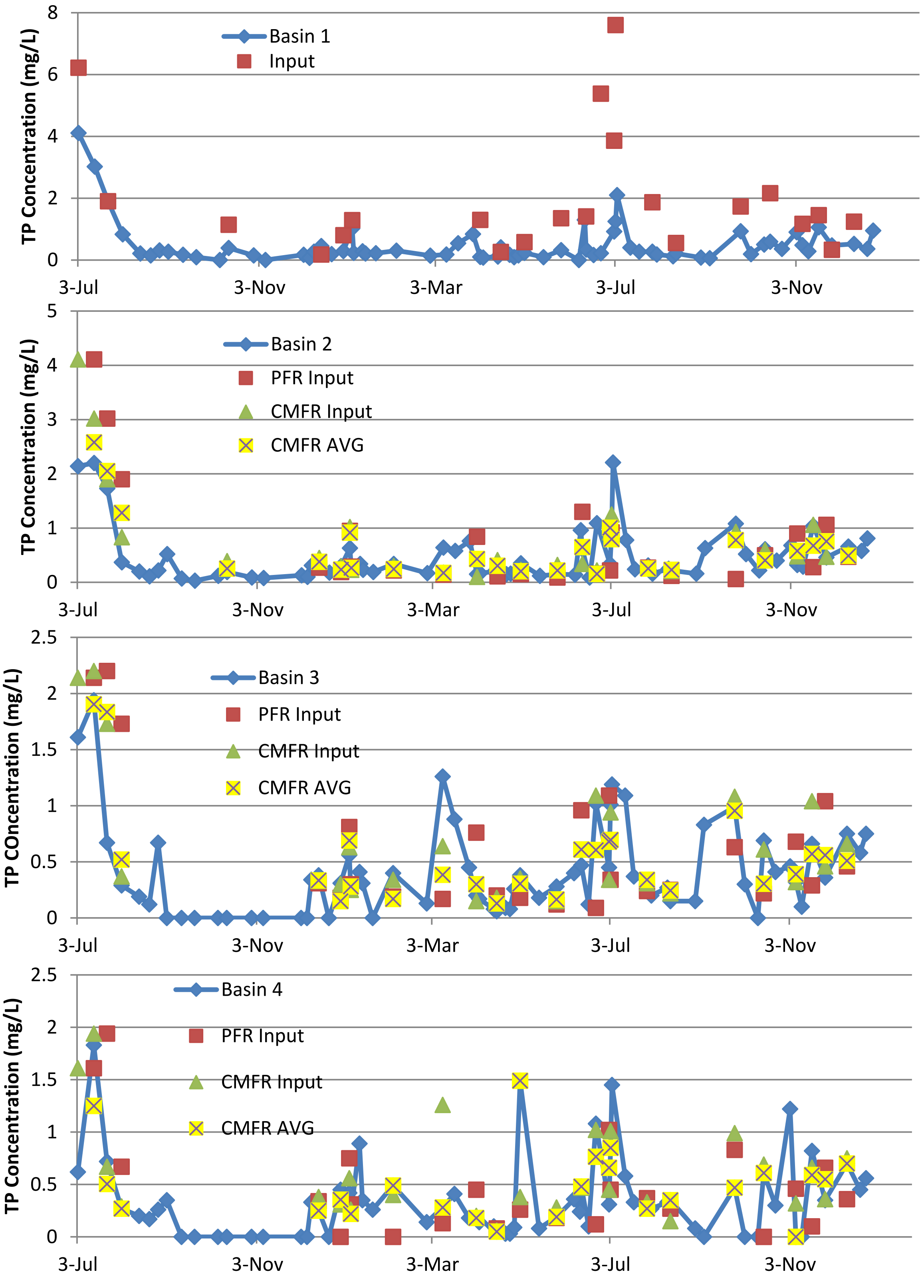


Figure 4-17. Concentration of Phosphorus Inside of All Four Basins Overtime With Storm Input Concentrations and PFR/CMFR Input Concentrations

The t-values calculated for TP agree fairly well with the values that were calculated for TSS. While the TSS Average CMFR values were not the best fit for all three basins, a similar trend was noted; both TSS and TP t-values concluded that Basin 2 concentrations were most similar to the Average CMFR, while latter basins (3 and 4) showed significant similarity to the PFR Input Values. The conclusions from this analysis will be discussed further in the recommendations for improving the design if the basin system.

4.2.5 Conclusions

Overall, volume reduction remains to be the primary mechanism causing removal of total phosphorus. Particulate phosphorus tends to dominate the speciation of phosphorus (~67% based on total incoming mass) within runoff, although the concentration of dissolved phosphorus is significant. Periods following fertilization and tilling events are of particular concern as these events cause annual peaks in runoff concentrations up to 7.6 mg/L. The PFR/CMFR input analysis supports that significant mixing occurs during a storm event, especially in Basins 1 and 2, allowing the cleaner water within the basins to thoroughly mix with incoming stormwater.

4.3 Nitrogen

4.3.1 Example Pollutograph

Shown in Figure 4-18 is an example pollutograph of the total nitrogen (TN) concentration during a storm event on June 19th, 2014. This particular event occurred shortly after a fertilizing event in May as reported by the site property owner, so the concentrations of nitrogen are relatively high for this event. The influent TN concentration follows the peaks in the influent flow, especially early on during the first flush. Similarly, the effluent TN data match up very well with the flowrate peaks from the discharge flow. The peak concentrations for TN In and Out are similar in magnitude (17.5 and 16.4 mg-N/L, respectively), although the speciation of the peaks was different; the nitrate concentration for the influent peak was 9.7 mg-N/L compared to the effluent nitrate concentration of 4.7 mg-N/L and the ammonium concentrations for the influent and effluent peaks, respectively, were 1.2 mg-N/L and 0.7 mg-N/L. Therefore, unlike phosphorus, the speciation of nitrogen as it passes through the basins does appear to change.

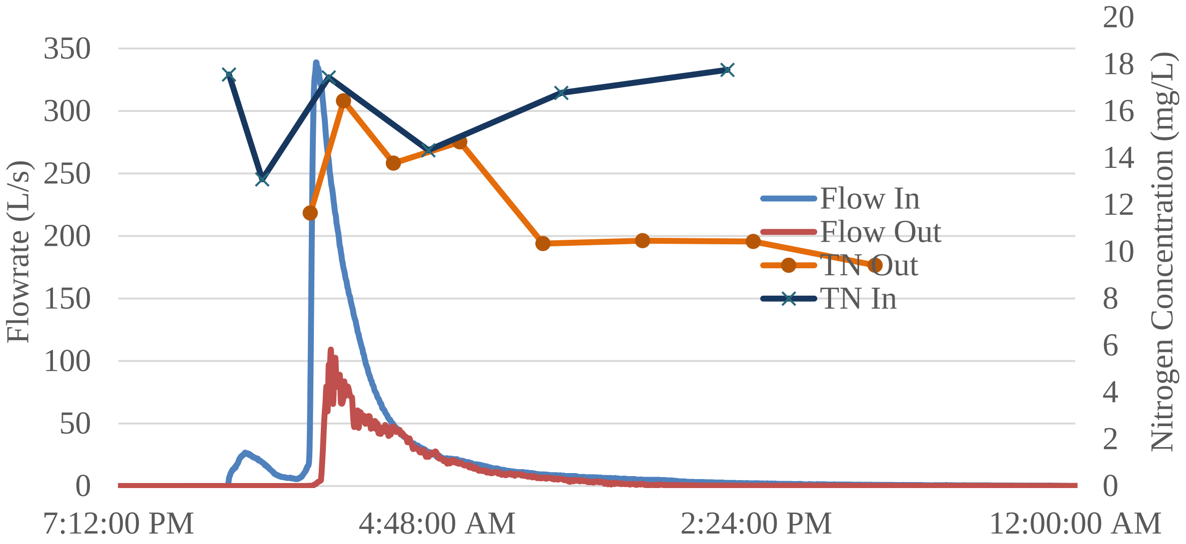


Figure 4-18. Pollutograph of the Total Nitrogen (TN) Concentration During a Storm Occurring on June 19th, 2014 at the Hambleton Creek Research Site

Based on the total masses into and out of the system (total mass in corrected using the drainage area ratio), the TN reduction for this storm was 64%. The nitrogen species with the highest mass removal was nitrate at 72%, while the species with the lowest removal was ammonium at 40%. These removals are very close to the total removals calculated for all of the storm events, which is discussed further in Section 4.3.3.

4.3.2 Probability Plots of Nitrogen EMCs

Figures 4-19 through 4-22 show the probability plots for Total Nitrogen (TN), Ammonium, Organic Nitrogen (ON), and Nitrate. In each plot, the effluent concentrations are below influent concentrations. The median value for effluent TN and ON is 0 mg/L due to no discharge. Median effluent values for ammonium and nitrate were 0.07 and 0.18 mg-N/L respectively, while the influent median values were 0.33 and 1.32 mg-N/L.

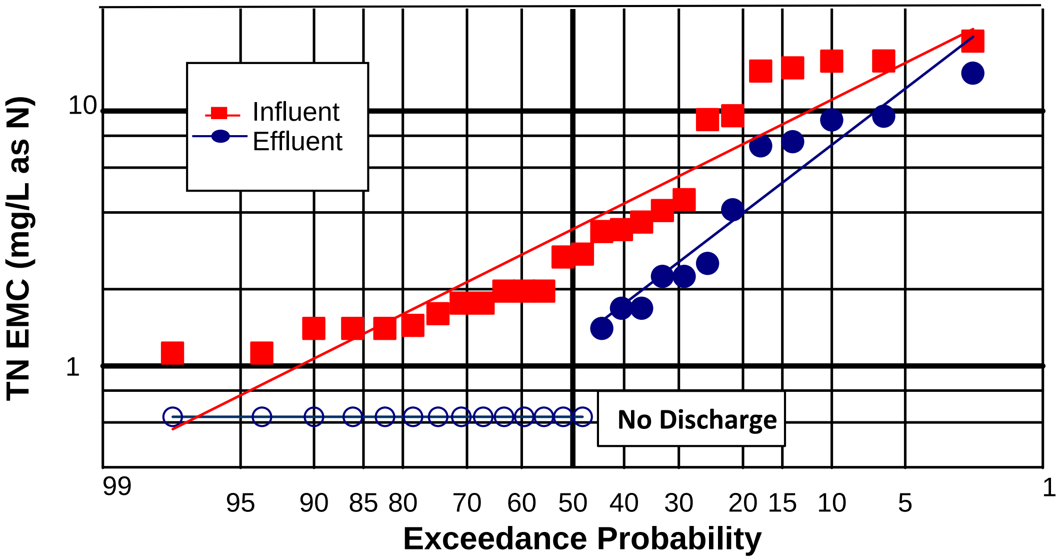


Figure 4-19. Probability Plot for Influent and Effluent Total Nitrogen EMCs (27 Events) at the Hambleton Creek Study Site

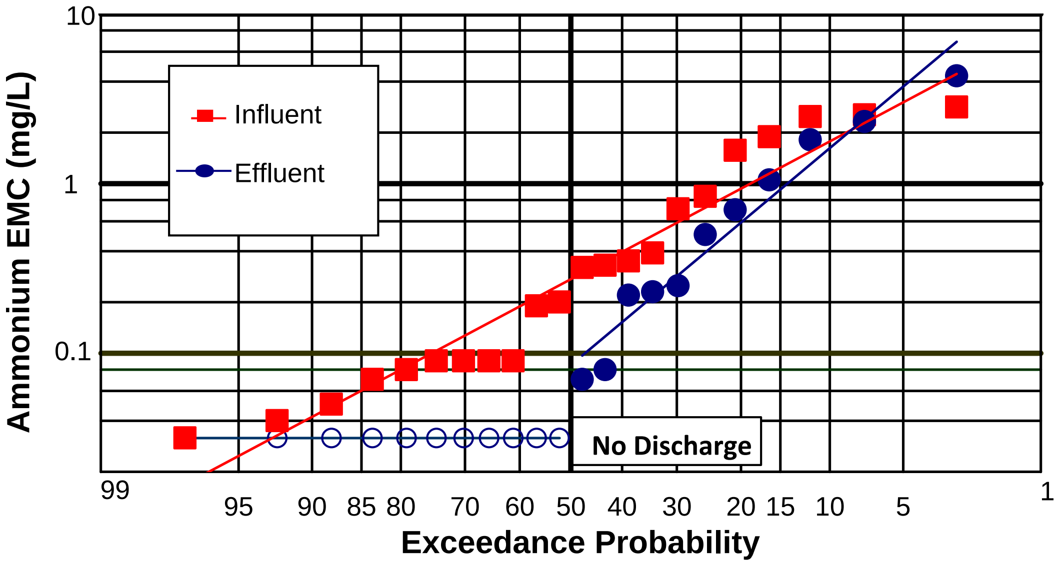


Figure 4-20. Probability Plot for Influent and Effluent Ammonium EMCs (22 Events) at the Hambleton Creek Study Site

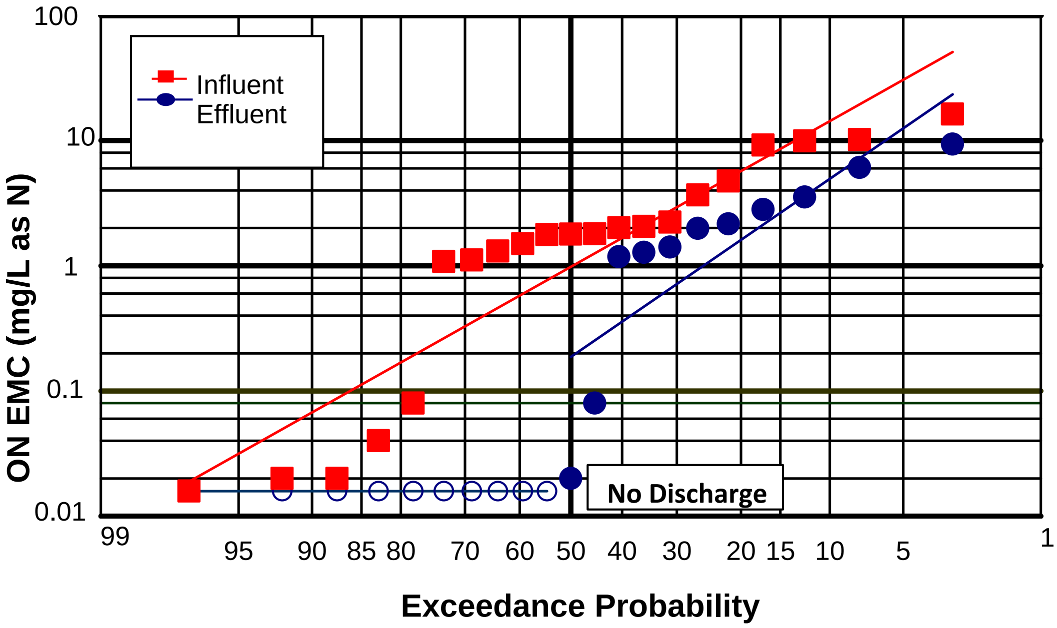


Figure 4-21. Probability Plot for Influent and Effluent ON EMCs (22 Events) at the Hambleton Creek Study Site

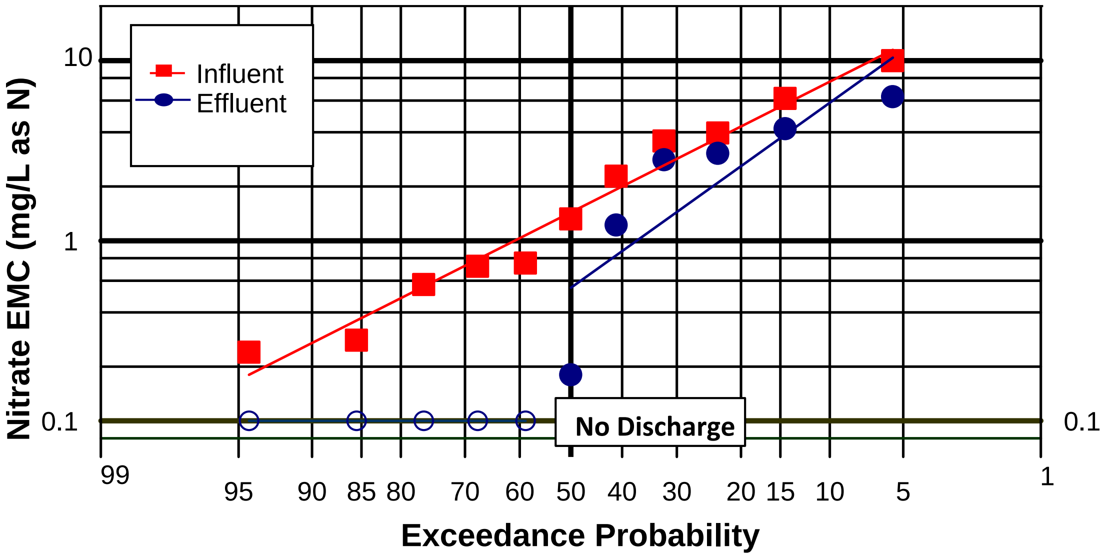


Figure 4-22. Probability Plot for Influent and Effluent Nitrate EMCs (11 Events) at the Hambleton Creek Study Site

Based on a two-sample t-test, the influent and effluent data sets for both TN and ON were found to be statistically different at α=0.05 taking the no flow data into account. The influent and effluent data sets for ammonium and nitrate were not determined to be statistically different with the no flow data taken into account. Not including the no flow data, no nitrogen data sets were found to be statistically different.

4.3.3 Speciation Removal Mechanisms, and Ultimate Fate of Nitrogen

Nitrogen speciation was most affected by fertilizing events. Following fertilization of the watershed, nitrate levels in the runoff would increase substantially, in some cases dominating the speciation. In June 2014, following fertilization, during which 4 storm events were captured, runoff nitrate EMCs averaged 40% of the total nitrogen concentration. In most cases, however, organic nitrogen was the dominant species. For storm events with complete nitrogen water quality speciation data (10 events), organic nitrogen averaged 60% of the total nitrogen EMCs. Ammonia ranged from 0.04 to 2.83 mg/L for storm events, which is a relatively small range when compared to organic nitrogen (1.08-16.28) and nitrate (0.28-9.97). The total masses measured into and out of the system for the 10 events with complete nitrogen speciation, as well as the corresponding removal rate for each species of nitrogen, are shown in Table 4-12.

Table 4-12 Summary of Nitrogen Speciation Masses Measured Into and Out of the Basin System and the Associated Removals for Each Species for Ten Events With Complete Nitrogen Speciation Data

	Volume	TSS	Total N	Organic N	Nitrate	Ammonium
Mass In*(kg)	$24x10^6$ L	20,000	151	77	61	14
Mass Out (kg)	$11x10^6$ L	6,000	53	36	18	2.5
Removal	54%	68%	65%	54%	70%	82%

*Mass In includes drainage area correction factor of 112/90 (See Section 1.3.2)

The removal of Organic N is equal to the volume reduction of 54% (Table 4-8); therefore, it can be assumed that the volume reduction caused by the basins is the primary mechanism for removal of Organic N. The removal of nitrate is significantly higher than the volume reduction (~15%); this possibly indicates some other treatment of nitrate is occurring within the basins, such as denitrification by microorganisms or uptake by plants between storm events. However, a definite conclusion as to which mechanism is taking place cannot be drawn from the data collected in the scope of this project.

Ammonium shows a much higher removal than any other contaminant or even the volume of runoff (~30% higher than volume reduction). The high removal rate of ammonium could be an indication of biological activity converting the ammonium to other species of nitrogen between storm events, such as nitrate which is then consequently removed from the runoff either through denitrification or leaching. It is worth noting, however, that the mass of ammonium measured during these ten events is only about 10% of the total ammonium mass measured entering the system. The removal rate of ammonium for the other 6 events is -10%, meaning that ammonium was exported from the system as opposed to being removed.

The ten events with complete nitrogen speciation were collected from March 30th, 2014 to September 26th, 2014. The majority of this time is within the growing period of the year, a time where significant biological activity could be expected within the basins. The 6 events where ammonium showed a negative removal rate of -10% occurred from October 16th, 2014 to December 12th, 2014. During this period, less plant growth and biological activity would be expected due to cooler temperatures. Therefore less conversion of ammonium to nitrate would be expected, and potential conversion of nitrate to ammonium may be expected. If ammonification was taking place in the basins during this period, an export of ammonium mass during storm events would be expected.

Table 4-13 shows the removals expected from SCMs that are frequently used in agriculture. Both contour buffer strips and riparian forest buffers exhibit low removals when compared to the removals shown by the cascading basin system in Table 4-12. Vegetated filter strips and no-till conditions show the possibility of high removal rates, up to 93% and 90.6% respectively. However, the range of removals associated with these two SCMs is quite broad, and therefore these SCMs may be less reliable to perform effectively. Further, Magette (1989) cited a TN removal for vegetated filter strips of 0%.

All of these SCMs are mainly targeted at removing TSS by capturing sediments and slowing runoff flows. There may be some nutrient uptake by the vegetated filter strips and the contour and riparian buffers, but these SCMs are not designed to retain much runoff and therefore the nutrient uptake should be minimal. Therefore, the main component of nitrogen that may be removed by these SCMs is the particulate portion, while the dissolved portion may pass through the SCMs unchanged.

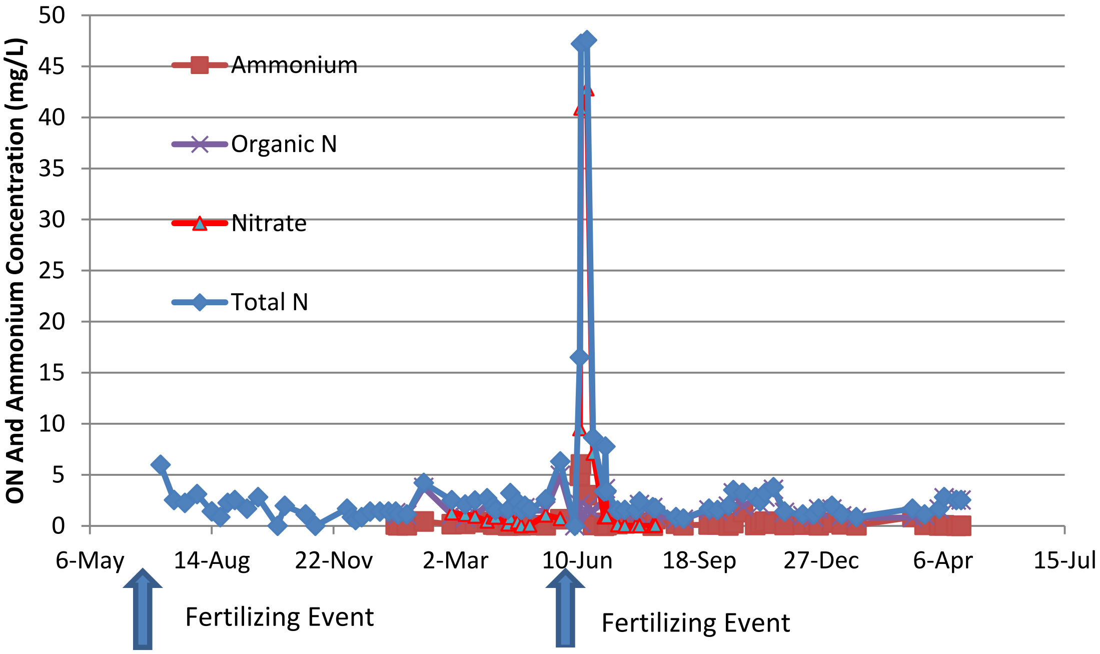
Table 4-13. Typical Total Nitrogen/Nutrient Mass Reduction Values for Frequently Used Agricultural SCMs

SCM	Source			
	EPA Report (2010) as cited by Merriman et al. 2009 (Total Nitrogen)	Ohio State University Agricultural BMPs Fact Sheet (2012) (Soluble Nutrients)	Ohio State University Agricultural BMPs Fact Sheet (2012) (Absorbed) Nutrients)	Magette (1989) (Total Nitrogen)
Contour Buffer Strip	14.5-20%			
Riparian Forest Buffer	37%	No Control to Low Effectiveness	Medium to High Effectiveness	
Vegetated Filter Strip	1-93%	No Control to Low Effectiveness	Low to Medium Effectiveness	0%
No-Till	-2.8-90.6%	No Control to Low Effectiveness	Medium to High Effectiveness	

The ultimate fate of nitrogen that entered the basin system, similar to phosphorus, was most likely dependent upon speciation. Any particulate forms of nitrogen would be removed via sedimentation. Nitrate is known to be highly mobile and therefore easily leaches into groundwater (Ledbetter, 2012). Therefore, the nitrate is most likely escaping the basins via infiltration. Nitrate could also be denitrified, especially during summer months when more microbial activity is expected. Ammonia and nitrate are the most bioavailable N species for plants, so these two species could be taken up by plant life directly and incorporated into biomass. Ammonia could also be oxidized to other forms of nitrogen if biological activity is occurring within the basins.

4.3.4 Nitrogen Concentration Within the Basins

Figure 4-23 shows the concentrations of ammonium, organic nitrogen, nitrate, and TN in Basin 1 over time. Very high concentrations of nitrate, almost 50 mg-N/L, were recorded in the basins in June 2014 following fertilizing. This was the only time during which nitrate dominated the speciation. For the remaining times, organic nitrogen almost always (~85% of the time) dominated the speciation within all of the basins.



Fertilizing Event

Fertilizing Event

Figure 4-23. Ammonium, ON, Nitrate, and TN Concentrations Within Basin 1 Over Time

Overall, the nitrogen concentrations in the basins, like the nitrogen concentrations for storm events, appear to be most affected by fertilizing events. Fertilizing not only affected the amount of nitrogen in the basins, but also the speciation as nitrate became the dominant nitrogen species following fertilizing.

4.3.5 Relationship Between Basin Nitrogen Concentrations and Input Concentrations

The CMFR/PFR analysis was conducted for nitrogen concentrations within Basins 2, 3, and 4. The input concentrations and basin concentrations as a function of time for all four basins are shown in Figure 4-24. Overall, one input type did not fit best to the basin concentration data for each basin, as shown by the statistics summarized in Table 4-14. Basin 2 most closely followed the PFR Input concentrations, while Basin 3 most closely followed the CMFR Input concentrations and Basin 4 was closest to the Average CMFR Input Concentrations. However, the T-values for the Average CMFR Input, with the exception of Basin 3, were 0.24 and 0.29. Both of these values are close to 0; only the PFR Input value for Basin 2 of 0.08 was lower. Further, the values for Basin 3 were all similar, ranging from 0.78 to 0.91; therefore while the CMFR Input did have the closest values, it was not as statistically significant as the values for Basins 2 and 4. These results, in conjunction with the results from the Phosphorus PFR/CMFR analysis, further support the fact that the Average CMFR Input values most closely follow the concentrations within the basins and therefore support that significant mixing in the basins occurs during storm events.

Table 4-14. Summary of the Absolute-Value of the T-Statistic Values For PFR, CMFR and Average CMFR Input Data Sets as Compared to the Concentrations Measured in Basins 2, 3, and 4 (α=0.05, *n*=[24,27])

	Basin 2	Basin 3	Basin 4
PFR Input	0.08	0.89	1.16
CMFR Input	0.66	0.78	0.69
Average CMFR Input	0.24	0.91	0.29

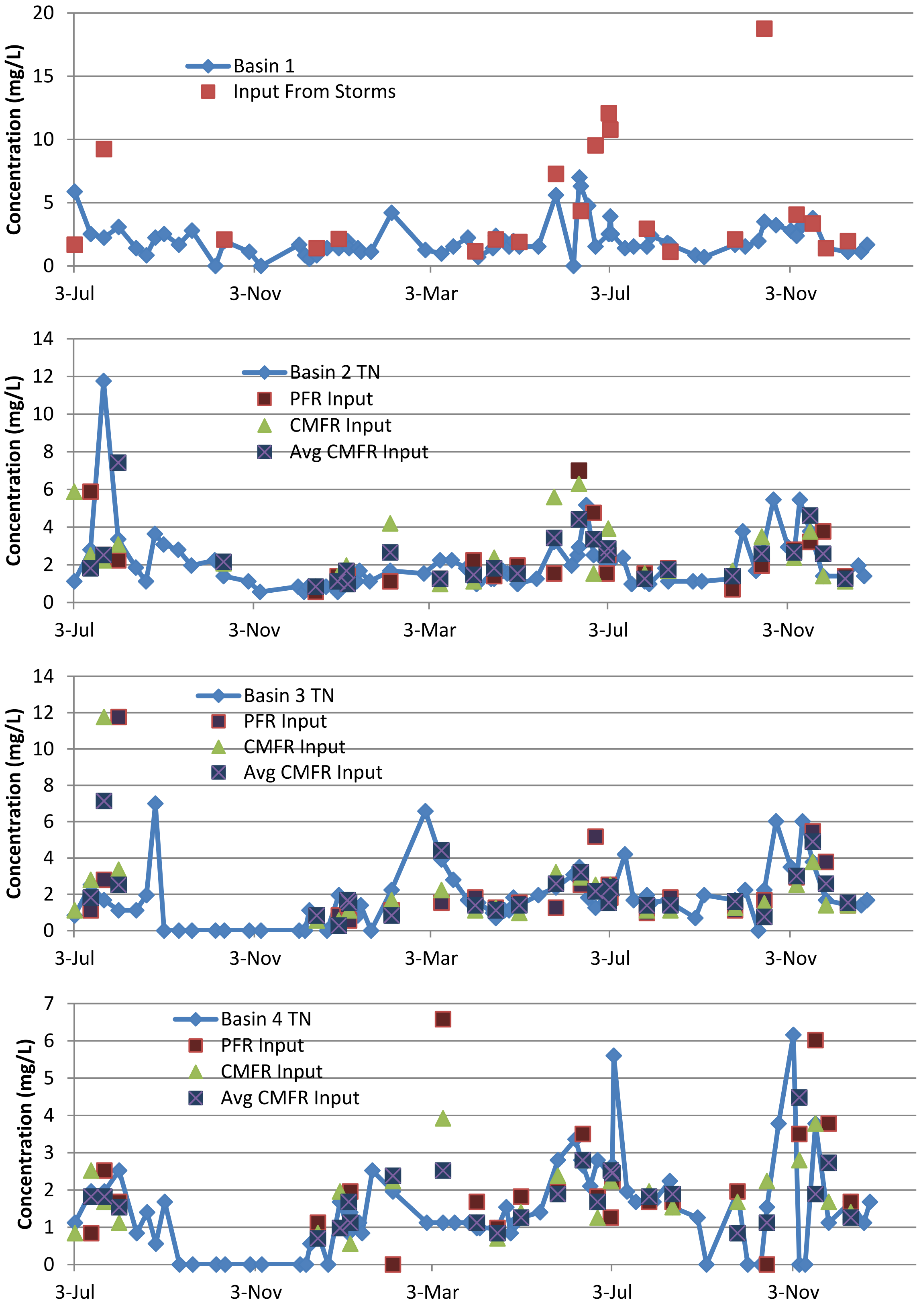


Figure 4-24. Concentration of Nitrogen In All Four Basins Over Time With Storm Input Concentrations and PFR/CMFR Predicted Input Concentrations

4.3.6 Conclusions

Overall, the season of the year appears to have the most effect on the speciation and removal of nitrogen. During the growing season, from March to August, very high removals of both ammonium and nitrate (82% and 70% respectively) were noted, supporting potential uptake by plants as well as removals through microbial activity. During the colder months, the removals of these pollutants was less efficient. The affect that the seasons may have on removal rates is explored further in Chapter 5. Fertilizing events also had a large impact on the speciation of nitrogen; following fertilizer application, large amounts of nitrate were recorded in the basins and in the stormwater runoff. Beyond the potential treatment during summer months, the main mechanism of removal for all species of nitrogen appears to be volume reduction.

The PFR/CMFR input analysis yielded similar results to the findings from phosphorus, although the results for nitrogen were less clear. Still, the nitrogen findings support the fact that there is significant mixing within the basins during a storm event.

4.4 Seasonal Analysis of TSS and Nutrient Removals and Variability of Storm Events

An analysis was conducted in which the storm events were categorized as either warm (April-September) or cold (October-March) and the removals for each category were calculated. Evidence of treatment outside of volume reduction would be expected during warmer months, or growing months, during which more biological activity may occur. The results of the analysis are shown in Table 4-15.

Of particular interest in this analysis is the treatment, if any, within the basin in addition to the volume reduction that is occurring. That is, the mass removals associated with each pollutant would be expected at least to be equivalent to the volume reduction. Any additional reduction beyond what is associated with volume reduction that is shown by the basin system could then be attributed to treatment within the basins, such as denitrification or nutrient uptake. For this reason, the reductions from both summer and winter were normalized by the associated volume reductions for each, (30% for summer and 60% for winter) in order to better compare estimated removals due to treatment from summer and winter. The last row for both summer and winter in Table 4-15, labeled “Difference from Volume Reduction,” represents the portion of the removal for each nutrient that would be attributed specifically to treatment within the basins, and not volume reduction.

In every case except DOP, the removal attributed to treatment is larger in the summer months than the winter months, as was expected. This shows that some removal is occurring during the summer in addition to the volume reduction. Further, with the exception of DOP, nitrate and ammonium, the reductions shown from winter do not differ significantly from the volume reduction of 60% for winter.

An analysis was also conducted to assess the variability of the storm events captured and the effect that this may have on the mass reductions. The storm events were ranked from largest influent volume to smallest influent volume. The largest storm event, which occurred on April 29th, 2014, was not included in this analysis because it was large enough to dominate and skew the results. The remaining storms were divided into two data sets based on size; the first data set was comprised of storm events ranked 1, 4, 5, 8, 9, 12, 13, 16, 17, 20, 21, and 24. The second data set consisted of storm events ranked 2, 3, 6, 7, 10, 11, 14, 15, 18, 19, 22, and 23. The mass reductions for the two data sets are shown in Table 4-16.

Table 4-16 also shows the difference between the mass reductions of the two data sets. 8 of the 12 pollutant mass reductions for the two data sets included within Table 4-16 were within 10% each other, showing very little variability between the two data sets. The three pollutants that were more than 10% different were DOP, ammonium and nitrate. Ammonium and nitrate have fewer data points included in the data sets compared to the other pollutants, which may explain the increased variability for these pollutants. It is also clear that by removing the large storm event from April 29th, 2014, the total removals for all pollutants were greatly impacted. Therefore this large storm event clearly has a large impact on the mass removals exhibited by the system.

Table 4-15. Summary of Concentrations, Masses, and Removals for Storm Events Classified as Summer (April-September) or Winter (October-March) at the Hambleton Creek Study Site

	Summer										
	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
Mean EMC In (mg/L)	2.84	5.70	1150	1.92	0.91	0.80	0.11	0.95	3.26	4.91	8.14
Mean EMC Out (mg/L)	2.05	4.86	850	1.47	0.58	0.37	0.20	0.96	3.51	4.37	7.78
Mass In (mg)	37x10^6	83x10^6	15x10^9	26x10^6	10x10^6	8.2x10^6	2.3x10^6	7.3x10^6	33x10^6	75x10^6	116x10^6
Mass Out (mg)	21x10^6	42x10^6	6.5x10^9	15x10^6	5.2x10^6	4.0x10^6	1.3x10^6	2.3x10^6	20x10^6	39x10^6	62x10^6
Total Mass Removal	44%	49%	57%	41%	49%	51%	45%	69%	40%	48%	46%
*Difference From Vol. Red.	14%	19%	27%	11%	19%	21%	15%	39%	10%	18%	16%
	Winter										
	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
Mean EMC In (mg/L)	1.02	3.05	150	0.79	0.23	0.20	0.13	0.52	0.28	2.64	3.07
Mean EMC Out (mg/L)	0.82	2.77	157	0.61	0.21	0.18	0.04	1.08	0.18	1.69	2.80
Mass In (mg)	16x10^6	46x10^6	2.5x10^9	12x10^6	3.6x10^6	3.0x10^6	2.7x10^6	6.6x10^6	0.32x10^6	39x10^6	46x10^6
Mass Out (mg)	6.1x10^6	14x10^6	1.2x10^9	5.0x10^6	1.1x10^6	0.9x10^6	0.23x10^6	5.0x10^6	0.34x10^6	9.4x10^6	15x10^6
Total Mass Removal	61%	69%	53%	59%	69%	70%	91%	25%	-6%	76%	68%
**Difference From Vol. Red.	1%	9%	-7%	-1%	9%	10%	31%	-35%	-66%	16%	8%

*Row approximates the portion of mass removal that can be attributed to treatment by subtracting the volume reduction of 30% from the total mass removal

**Row approximates the portion of mass removal that can be attributed to treatment by subtracting the volume reduction of 60% from the total mass removal

Table 4-16. Summary of Masses and Removals for Storm Events Divided into Two Data Sets Based on Ranking of Events by Influent Runoff Volume at the Hambleton Creek Study Site

	Ranking Set 1										
	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
Mass In (mg)	24x10^{6}	60x10^{6}	8x10^{9}	18x10^{6}	7x10^{6}	6x10^{6}	3x10^{6}	8x10^{6}	8x10^{6}	49x10^{6}	65x10^{6}
Mass Out (mg)	7x10^{6}	15x10^{6}	2x10^{9}	5x10^{6}	2x10^{6}	2x10^{6}	0.2x10^{6}	3x10^{6}	4x10^{6}	12x10^{6}	19x10^{6}
Total Mass Removal	71%	74%	74%	69%	76%	76%	94%	64%	49%	76%	71%
	Ranking Set 2										
	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
Mass In (mg)	28x10^{6}	69x10^{6}	10x10^{9}	21x10^{6}	7x10^{6}	2x10^{6}	2x10^{6}	6x10^{6}	26x10^{6}	63x10^{6}	94x10^{6}
Mass Out (mg)	7x10^{6}	17x10^{6}	3x10^{9}	6x10^{6}	1x10^{6}	0.8x10^{6}	0.6x10^{6}	4x10^{6}	6x10^{6}	12x10^{6}	23x10^{6}
Total Mass Removal	74%	75%	68%	71%	81%	84%	75%	37%	77%	80%	76%
Difference Between Mass Reduction of Set 1 and Set 2	3%	1%	6%	2%	5%	8%	19%	27%	28%	4%	5%

Chapter 5. Recommendations and Conclusions

5.1 Recommendations for Improving the Cascading Basin Design

The cascading basin system has proven to provide removals of TSS, nitrogen, and phosphorus from incoming stormwater that is draining off of the surrounding agricultural watershed. Most of these removals can be attributed largely to volume reduction associated with storage within the basins. Therefore, the size of the basins and the amount of runoff that the basins can store is primary among the design criteria for this system. The loading ratio, defined as the area of the watershed divided by the surface area of the BMP, for this basin system and its watershed is 200:1. According to the Pennsylvania Stormwater Best Management Practices Manual (2006), a loading ratio of 5:1 should be used for impervious drainage areas, and 8:1 for the total drainage area (pervious and impervious cover). The Maryland Department of the Environment Stormwater Design Manual (2009) states that for a shallow wetland, the surface area of the wetland should be at least 1.5% of the total drainage area (pervious and impervious cover). The Hambleton Creek loading ratio of 200:1 is significantly larger than the values typically used for impervious and total drainage areas. It is suggested that the basins be re-sized so that the loading ratio is at least 100:1, therefore doubling the surface area of the basins from 2,190 m^2 to 4,380 m^2.

Further, the amount of rainfall over the 112 acre watershed at the Hambleton Creek site that can be contained within the basins is 0.37 cm (0.14 inches). Infiltration basins, according to the Pennsylvania Stormwater Best Management Practices Manual (2006), should be sized to contain a 2-year, 3.81 cm (1.5 inch) storm event in urban watersheds. The Maryland Department of the Environment (MDE) Stormwater Design Manual (2009) states that for watersheds with less than 15% impervious cover, the BMP should be designed to store at least 0.2 inches of rainfall per acre. Therefore, following the typical guidelines for the design of a BMP provided by the Pennsylvania Stormwater Best Management Practices Manual (2006) and the MDE Stormwater Design Manual, the basins should be designed to hold a substantially larger volume. It is suggested to enlarge the size of the basins to store at least 0.51cm (0.2 in) of rainfall over the watershed, as opposed to 0.37 cm (0.14 in) which they can store now. This would increase the total volume of the basins from 1.65 million L to 2.3 million L. Resizing the basins to make them larger, or adding more basins in succession, is chief among the recommendations for improving the design. The larger the basins, the more likely that the system will be able to fully capture an event, and therefore the system will be expected to discharge less volume.

In addition to increasing the volume of water that the basins can store, the dimensions of the basins can be adjusted to possibly enhance processes such as sedimentation. There was little evidence of sedimentation within the basins during storm events; however, by manipulating the dimensions of the basins sedimentation may be promoted. Since Basin 1 receives the majority of the runoff initially, this basin could be redesigned to better capture sediments before discharging to subsequent basins. By deepening and lengthening Basin 1, sediments that reach the bottom of the basin may be less likely to resuspend with incoming water. Sediments will also have more time to settle in a longer basin.

Adding baffles to the basins could also help promote sedimentation, as well as reduce peak flows through the basins. Strips of gravel or rip-rap could be lined across the width of the basins. Figure 5-1 shows a schematic of a single basin and potential locations for baffles within this basin. These would help to slow the runoff as it passes through the basins reducing the peak flow as well as allowing more time for sedimentation. The material could also trap sediments as the runoff moves through the baffle. It is recommended to make the baffles as tall and as wide as the basins, and to be permeable enough so that runoff will still flow easily through them

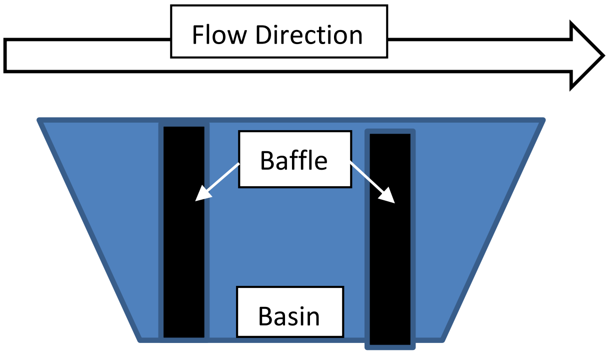


Figure 5-1. Schematic of Potential Baffle Modification to the Basins. Profile View of a Single Basin and Location of Potential Baffles

Plant life, particularly cattails, could also work as potential baffles. For the duration of this study, only Basins 1 and 2 contained cattails and in parts of those basins the cattails were sparse. Promoting cattail growth could have similar results to adding baffles made of rip-rap or gravel. Thick sections of cattails would slow the runoff as it passes through, reducing the peak flow. Cattails could also provide added nutrient uptake.

Beyond the recommendations given above, the basins could be engineered to perform under two different conditions. The first would be to engineer the basins to drain quickly, therefore maximizing the storage available for the next storm event. By maximizing the storage available for a storm event, the likelihood that the storm is completely captured is also maximized; this, therefore, will also minimize the amount of discharge for each storm event which may improve removal as volume reduction was the main mechanism of treatment for this study. To do this, the material in the bottom of the basins would be removed and replaced with sand and gravel to promote faster infiltration. Regular maintenance of the bottoms of the basins would also need to be performed as material builds up on the sand and gravel that may cause clogging. This maintenance may include digging up sediments that have settled in the bottoms of the basins, or even replacing the installed sand or gravel on a regular basis. By encouraging infiltration in the basins, less water would be stored for extended periods of time, thereby increasing the amount of runoff that could be contained during each storm event.

The second condition that the basins could be engineered to perform under would be to modify them to retain some level of water for an extended period of time, thereby enhancing the wetland-like qualities of the basins. For the duration of this research project, Basins 1 and 2 contained more water more often, while Basins 3 and 4 typically went longer without receiving an input. Therefore Basins 3 and 4 tended to dry out more frequently, which could explain the lack of cattails within these basins. By distributing the water retained in the system more evenly throughout all four of the basins, wetland-like properties could exist in all four of the basins and not just Basins 1 and 2. That is, cattail growth and microbial activity could be supported within all four basins, providing baffling, nutrient uptake, and potentially denitrification. In order to distribute the incoming stormwater evenly among the basins, it would be recommended that the basins be connected in some way to allow lower levels of water within the basins to cause a discharge from the basins. An example of how the basins could be connected is shown in Figure 5-2.

Figure 5-2. Schematic of Potential Method Connecting Two Basins Using an Underground Pipe

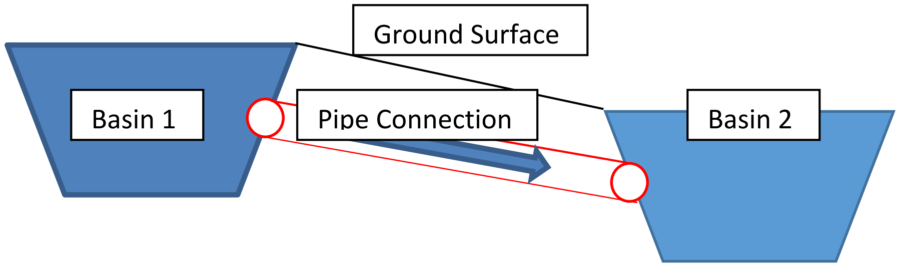


Figure 5-2 shows how two basins may be connected using an underground pipe system. By installing a pipe at some depth of the basin wall that connects to the subsequent basin, the basin will slowly discharge to the subsequent basin without having to reach full capacity. Depending on the sizing of the pipe and the depth of the pipe connection in the basins, the draining could take 2-4 hours from one basin to the next. Across all four of the basins, the delayed total draining time could be substantial. Should the basin fill, it will discharge overland to the following basin at the same rate as before the modification. Connecting all of the basins using this pipe modification would prevent Basins 1 and 2 from filling while Basins 3 and 4 do not receive any runoff; runoff that enters the basin system would be more evenly distributed among the four basins.

5.2 Recommendations for Future Research

It is clear that the cascading basin system provided reductions in the mass loads of TSS, nitrogen, and phosphorus as well as a reduction in volume of runoff. However, there is opportunity to improve this system by applying some of the modifications described in section 5.2. The following research options are recommended to succeed this project:

1. More measurements within the basins should be taken in order to more fully understand the mechanisms of treatment that may be taking place. These measurements may consist of dissolved oxygen readings, oxidation/reduction potential, or electrical conductivity. It may also be useful to monitor the pH within the basins as well as the pH of the incoming stormwater.
2. Re-sizing the basins as described in section 5.2 to better suit the size of the watershed is the primary modification recommended. Upon altering the size of the basins, it is further recommended that monitoring similar to the scope of this project be continued in order to quantify the effect that enlarging the basins has on pollutant reductions.
3. Further modifications as described in section 5.2 could be made to the system in addition to re-sizing the basins, although these modifications may be best implemented after the enlarged basins have been monitored for a period of time to better understand the effects that these modifications have directly. Upon implementation of further modification, monitoring similar in scope to this research project should be continued at the Hambleton Creek Site.

4. Lastly, an economic evaluation of the implementation of this SCM would be of great value to agricultural land owners and decision-makers. In addition to the system itself, the individual modifications could also be evaluated from an economic standpoint in order to determine which would be the most feasible to implement. This evaluation could be compared either to other agricultural SCMs, such as contour buffers or vegetated filter strips, or possibly even to urban bioretention and detention cells.

5.3 Conclusions

The efficiency of the cascading basin system at the Hambleton Creek Research Site was evaluated from June 25, 2013 to April 22, 2015 during which period 26 storm events were successfully sampled and tested for TSS, nitrogen and phosphorus. Overall, the cascading basin system reduced the incoming mass of all pollutants tested. The incoming volume of runoff was also reduced by the basin system, even though the storage volume and surface area of this system in relation to the size of the watershed were not sized according to convention. Given that the loading ratio of the site is much larger than would be recommended by both the Pennsylvania Stormwater BMPs Manual and the MDE Stormwater Design Manual, the volume reduction of 56% exhibited by the system is significant.

Overall, TSS exhibited a slightly more efficient removal rate than volume reduction (65% compared to 56%.) This may be evidence of sedimentation within the basins during storm events although the two values are similar in magnitude and sedimentation was not supported by the soil texture analysis. Between storm events, however, it is clear that settling of suspended solids from the water stored in the basins is occurring.

Nitrogen and phosphorus removal efficiencies were similar in magnitude to the reduction of runoff volume, therefore providing evidence that volume reduction is the primary mechanism for removal of the pollutants. However, the seasonal analysis provided some evidence of additional treatment occurring during the summer months. While this additional treatment was relatively small in comparison to the total removal efficiency (most ~10% compared to 40% total removal), it is promising that these treatments appear to exist within the basin system as they could potentially be enhanced through modifications to the design.

Appendix

Table A-1. Summary of Influent EMC Values For All Storm Events Measured at the Hambleton Creek Site

Date	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
7/3/2013	6.2	1.7	46	1.1	5.12	5.01	0.11			1.7	1.7
7/23/2013	1.9	9.2	77	0.45	1.45	0.74	0.71			9.2	9.2
10/13/2013	1.1	1.4	139	0.55	0.54	0.58	0			1.4	1.4
12/14/2013	0.2	1.4	50	0	0.24	0.16	0.08			1.4	1.4
12/29/2013	0.7	1.6	144	0.52	0.17	0.2	0			1.6	1.6
3/30/2014	1.3	1.2	89	1.24	0.06	0.05	0.01	0.05	0.28	1.1	1.43
4/15/2014	0.3	2.1	25	0.17	0.09	0.06	0.03	0.09	0.57	2.01	2.67
4/29/2014	0.6	1.9	140	0.35	0.23	0.16	0.07	0.08	0.75	1.82	2.65
5/16/2014	1.4	7.3	525	0.95	0.4	0.35	0.05	2.54	2.28	4.76	9.58
6/13/2014	1.4	4.3	516	1.23	0.18	0.16	0.02	2.83	9.97	1.47	14.27
6/19/2014	5.4	9.5	3336	5.13	0.25	0.19	0.06	0.33	6.16	9.17	15.66
6/26/2014	3.9	12.1	3841	2.66	1.2	1.15	0.05	1.9	3.57	10.2	15.67
7/3/2014	7.6	10.8	3710	6.23	1.38	1.43	0	0.84	3.96	9.96	14.76
7/28/2014	1.9	2.9	865	1.73	0.14	0.11	0.03	0.71	0.72	2.19	3.62
9/26/2014	1.73	2.1	343	1.45	0.28	0.2	0.08	0.04	1.32	2.06	3.42
10/16/2014	2.16	18.76	232	1.69	0.47	0.25	0.22	2.48		16.28	18.76
11/7/2014	1.17	4.06	117	0.7	0.47	0.43	0.04	0.39		3.67	4.06
11/17/2014	1.45	3.36	179	1.21	0.24	0.19	0.05	1.57		1.79	3.36
11/28/2014	0.33	1.4	146	0.09	0.23	0.24	0	0.32		1.08	1.4
12/8/2014	0.5	1.4	121	0.3	0.2	0.16	0.04	0.09		1.31	1.4
12/12/2014	1.24	1.96	290	1.08	0.16	0.13	0.03	0.19		1.77	1.96
1/5/2015	1.29	1.96	150	1.14	0.18	0.15	0.03	0.2		1.76	1.96
3/13/2015	1.29	1.12	209	1.2	0.09	0.06	1.2	0.35		0.77	1.12
3/16/2015	0.81	1.96	172	0.73	0.08	0.06	0.02	0		1.96	1.96
3/22/2015	0.69	1.12	61	0.57	0.13	0.08	0.04	0.09		1.03	1.12
4/22/2015	1.74	4.48	427	1.59	0.15	0.07	0.08	0.09		4.39	4.48

Table A-2. Summary of Effluent EMC Values For All Storm Events Measured at the Hambleton Creek Site

Date	TP	TKN	TSS	PP	DP	DIP	DOP	NH4	NO3	ORG N	TN
7/23/2013	1.45	2.52	210.32	0.06	1.39	0.52	0.87				2.52
3/30/2014	1.44	1.51	283.7	1.34	0.1	0.08	0.03	0.23	0.18	1.28	1.69
4/29/2014	1.42	2.89	299.6	1.02	0.4	0.31	0.09	0.08	1.22	2.81	4.11
5/16/2014	0.52	4.48	119	0.23	0.28	0.23	0.01	2.32	2.81	2.16	7.29
6/13/2014	0.83	3.22	333.5	0.61	0.22	0.15	0.07	1.81	6.3	1.41	9.52
6/19/2014	4.69	9.87	3028.5	4.45	0.24	0.16	0.08	0.5	4.18	9.37	14.05
7/3/2014	3.37	6.16	1118.8	2.45	0.93	0.87	0.06	0.07	3.05	6.09	9.21
11/28/2014	0.92	7.56	125.5	0.36	0.56	0.51	0.05	4.02		3.54	7.56
12/8/2014	0.32	1.4	119.3	0.17	0.15	0.13	0.02	0.22		1.18	1.4
12/12/2014	0.59	2.24	66.6	0.42	0.17	0.16	0.01	0.25		1.99	2.24
3/13/2015	0.54	1.68	186	0.35	0.19	0.12	0.08	1.05		0.63	1.68
3/16/2015	1.12	2.24	159	1.01	0.11	0.09	0.02	0.7		1.54	2.24

Table A-3. Summary of Height Measurements and Concentrations of Grab Samples From Basin 1 From the Hambleton Creek Study Site

Date	Height	TSS	TP	TDP	DRP	PP	DOP	TKN	Nitrite	Nitrate	NH4	Organic N	Total N
7/3/2013	24	34.57	4.11	1.73	2	2.38	0	5.88	0.1				5.98
7/14/2013	24	14.1	3.02	3.47	1.81	0	1.67	2.52	0.013				2.533
7/23/2013	24	83.3	2.18	1.34	0.52	0.84	0.82	2.24	0.001				2.241
8/2/2013	24	18.71	0.83	0.6	0.61	0.23	0	3.08	0.018				3.098
8/14/2013	19.2	8.16	0.21	0.08	0.11	0.13	0	1.4	0.011				1.411
8/21/2013	17.7	2.95	0.15	0.23	0.21	0	0.01	0.84	0.008				0.848
8/27/2013	15.3	19.1	0.31	0.1	0.05	0.21	0.05	2.24	0.008				2.248
9/2/2013	8.1	12.4	0.27	0.13	0.09	0.14	0.03	2.52	0.008				2.528
9/12/2013	8.7	34.46	0.17	0.1	0.06	0.07	0.04	1.68	0.003				1.683
9/21/2013	6	13.33	0.09	0.07	0.04	0.02	0.03	2.8	0.002				2.802
10/7/2013	0	0	0	0	0	0	0	0	0				0
10/13/2013	18	35.24	0.39	0.38	0.29	0.01	0.09	1.96	0.008				1.968
10/30/2013	4.5	0.3	0.15	0.05	0.04	0.1	0.01	1.12	0				1.12
11/7/2013	0	0	0	0	0	0	0	0	0				0
12/3/2013	7.2	18.9	0.17	0.09	0.15	0.08	0	1.68	0				1.68
12/7/2013	7.2	13	0.07	0	0	0.07	0	0.84	0				0.84
12/10/2013	22.8	32.2	0.27	0.12	0.19	0.15	0	0.56	0				0.56
12/15/2013	22.8	83.1	0.45	0.13	0.19	0.32	0	0.84	0				0.84
12/22/2013	13.2	6.5	0.19	0.12	0.18	0.07	0	1.4					1.4
12/30/2013	21.6	34.6	0.29	0.18	0.21	0.11	0	1.4					1.4
1/6/2014	22.8	33.7	0.23	0.11	0.14	0.12	0	1.4					1.4
1/12/2014	22.8	26.98	0.28	0.2	0.2	0.08	0	1.4			0.12	1.28	1.4
1/14/2014	18	25.31	0.21	0.14	0.14	0.07	0	1.12			0.05	1.07	1.12
1/21/2014	6	17.53	0.22	0.16	0.15	0.06	0.01	1.12			0.05	1.07	1.12
2/4/2014	21	26.5	0.3	0.18	0.18	0.12	0	4.2			0.43	3.77	4.2
2/27/2014	14.4	31.63	0.14	0.04	0.03	0.1	0.01	1.26		1.25	0.16	1.1	2.51

3/10/2014	18.6	28.14	0.18	0.04	0.03	0.14	0.01	0.98		1.11	0.19	0.79	2.09
3/18/2014	12	127.78	0.54	0.05	0.04	0.49	0.01	1.54		0.94	0.35	1.19	2.48
3/28/2014	8.4	166.39	0.84	0.07	0.03	0.77	0.04	2.24		0.46	0.38	1.86	2.7
4/2/2014	19.2	13.93	0.1	0.06	0.05	0.04	0.01	1.12		0.86	0.13		
4/4/2014	16.8	8.21	0.08	0.05	0.03	0.03	0.02	0.7		0.84	0.09		
4/14/2014	8.4	5	0.11	0.06	0	0.05	0.06	1.4		0.18	0.03	1.37	1.58
4/16/2014	21.6	76.35	0.41	0.1	0.1	0.31	0	2.38		0.82	0.05	2.33	3.2
4/22/2014	12	22.86	0.17	0.06	0.04	0.11	0.02	1.96		0.38	0.14	1.82	2.34
4/25/2014	7.2	12	0.09	0.03	0.02	0.06	0.01	1.54		0	0.04	1.5	1.54
4/28/2014	4.8	12.38	0.15	0.07	0.04	0.08	0.03	1.96			0.18	1.78	1.96
5/2/2014	21.6	20.98	0.23	0.11	0.11	0.12	0	1.54		0.06	0.06	1.48	1.6
5/15/2014	4.8	3.94	0.09	0.03	0.02	0.06	0.01	1.54		1.05	0.05	1.49	2.59
5/27/2014	6	27.74	0.32	0.18	0.11	0.14	0.07	5.6		0.7	0.64	4.96	6.3
6/8/2014	0	0	0	0	0	0	0	0				0	0
6/12/2014	21.6	92.73	1.3	0.77	0.71	0.53	0.06	7		9.5	4.9	2.1	16.5
6/13/2014	21.6	32.2	0.34	0.2	0.19	0.14	0.01	6.3		40.9	6.01	0.29	47.2
6/18/2014	16.8	15.62	0.16	0.09	0.05	0.07	0.04	4.76		42.8	3	1.76	47.56
6/23/2014	18	46.19	0.22	0.04	0.04	0.18	0	1.54		7.1	0.08	1.46	8.64
7/2/2014	16.2	45	0.92	0.79	0.76	0.13	0.03	2.52		0.86	0	2.52	3.38
7/3/2014	21	195.3	1.25	0.65	0.65	0.6	0	3.92		3.85	0.28	3.64	7.77
7/4/2014	28.8	523.37	2.1	0.68	0.63	1.42	0.05	2.52		0.9	0.07	2.45	3.42
7/13/2014	15	51.4	0.4	0.03	0.08	0.37	0	1.4		0.1	0.17	1.23	1.5
7/19/2014	18	28.89	0.27	0.06	0.06	0.21	0	1.54		0.02	0.23	1.31	1.56
7/28/2014	20.4	24.26	0.27	0.04	0.04	0.23	0	1.54		0	0.28	1.26	1.54
7/31/2014	18.6	29.9	0.18	0	0.02	0.18	0	2.38		0	0.29	2.09	2.38
8/11/2014	12	14.39	0.12	0.03	0.02	0.09	0	1.82		0	0.02	1.8	1.82
8/13/2014	20.4	19.5	0.21	0.07	0.06	0.14	0	1.68		0.05	0.66	1.02	1.73
8/30/2014	9.6	2	0.08	0.05	0	0.03	0.05	0.84			0.2	0.64	0.84
9/5/2014	4.8	3.76	0.06	0.05	0	0.01	0.05	0.7			0.05	0.65	0.7
9/26/2014	20.4	1.18	0.93	0.21	0.13	0.72	0.08	1.68			0.12	1.56	1.68

10/3/2014	12.6	32.57	0.19	0.11	0.01	0.08	0.1	1.54			0.12	1.42	1.54
10/12/2014	20.4	43.98	0.5	0.16	0.06	0.34	0.1	1.96			0.03	1.93	1.96
10/16/2014	21.6	68.29	0.59	0.16	0.1	0.43	0.06	3.5			0.27	3.23	3.5
10/24/2014	20.4	17.73	0.36	0.16	0.13	0.2	0.03	3.22			1.33	1.89	3.22
11/3/2014	19.8	57.29	0.9	0.44	0.39	0.46	0.05	2.8			0.08	2.72	2.8
11/7/2014	21.6	42.57	0.48	0.19	0.16	0.29	0.03	2.38			0.28	2.1	2.38
11/11/2014	17.4	32.84	0.28	0.21	0.16	0.07	0.05	3.22			0.41	2.81	3.22
11/18/2014	21.6	34.83	1.06	0.5	0.38	0.56	0.12	3.78			0.21	3.57	3.78
11/27/2014	21.6	42.13	0.47	0.29	0.27	0.18	0.02	1.4			0.08	1.32	1.4
12/12/2014	21	11.77	0.52	0.16	0.16	0.36	0	1.12			0.11	1.01	1.12
12/21/2014	12	8.4	0.36	0.19	0.17	0.17	0.02	1.12			0.29	0.83	1.12
12/25/2014	22.2	69.5	0.95	0.31	0.3	0.64	0.01	1.68			0.04	1.64	1.68
1/5/2015	21.6	54.21	1.02	0.22	0.19	0.8	0.03	1.96			0.32	1.64	1.96
1/13/2015	24	53.8	0.74	0.18	0.15	0.56	0.03	1.12			0.14	0.98	1.12
1/25/2015	24	65.86	0.47	0.07	0.06	0.4	0.01	0.84			0.05	0.79	0.84
3/12/2015	20	145.56	1.21	0.18	0.12	1.03	0.06	1.68			0.87	0.81	1.68
3/22/2015	20	41.38	0.38	0.1	0.07	0.28	0.03	1.12			0.09	1.03	1.12
4/3/2015	12	34.62	0.21	0.1	0.06	0.11	0.04	1.68			0.03	1.65	1.68
4/7/2015	12	87.37	0.34	0.13	0.06	0.21	0.07	2.8			0.05	2.75	2.8
4/17/2015	18	18.4	0.25	0.16	0.07	0.09	0.09	2.52			0	2.52	2.52
4/21/2015	24	13.78	0.31	0.19	0.09	0.12	0.1	2.52			0	2.52	2.52

Table A-4. Summary of Height Measurements and Concentrations of Grab Samples From Basin 2 From the Hambleton Creek Study Site

Date	Height	TSS	TP	TDP	DRP	PP	DOP	TKN	Nitrite	Nitrate	NH4	Organic N	Total N
7/3/2013	32	28.4	2.14	1.47	1.5	0.67	0	1.12	0.11				1.23
7/14/2013	32	30.32	2.2	1.68	1.44	0.53	0.24	2.8	0.015				2.815
7/23/2013	32	119.06	1.73	0.89	0.33	0.84	0.56	11.76	0.002				11.762
8/2/2013	32	27.9	0.37	0.23	0.41	0.15	0	3.36	0.044				3.404
8/14/2013	30.6	82.9	0.2	0.11	0.05	0.09	0.05	1.85	0.008				1.858
8/21/2013	28.8	9.57	0.11	0.18	0	0	0.18	1.12	0.007				1.127
8/27/2013	26.1	15.67	0.22	0.06	0.05	0.14	0.01	3.64	0.007				3.647
9/2/2013	23.7	16.26	0.52	0.42	0.56	0.1	0	3.08	0.007				3.087
9/12/2013	19.2	28.66	0.07	0.03	0.02	0.03	0.01	2.8	0.002				2.802
9/21/2013	16.2	12.74	0.03	0.07	0.02	0	0.03	1.96	0.002				1.962
10/7/2013	12	25.94	0.12	0.07	0.04	0.06	0.03	2.24	0.003				2.243
10/13/2013	24	37.7	0.19	0.21	0.18	0	0.01	1.4	0.003				1.403
10/30/2013	17.7	4.9	0.09	0	0	0.09	0	1.12	0				1.12
11/7/2013	13.2	7.1	0.08	0	0	0.08	0	0.56	0				0.56
12/3/2013	9.6	18	0.13	0	0	0.13	0	0.84	0				0.84
12/7/2013	10.8	20.6	0.1	0	0.01	0.1	0	0.56	0				0.56
12/10/2013	33.6	25.7	0.31	0.14	0.21	0.17	0	0.84	0				0.84
12/15/2013	34.8	49.3	0.33	0.08	0.17	0.25	0	0.56	0				0.56
12/22/2013	28.8	23.9	0.18	0.07	0.03	0.11	0.04	0.84					0.84
12/30/2013	33.6	44.4	0.3	0.19	0.26	0.11	0	0.56					0.56
1/6/2014	34.8	46.5	0.25	0.14	0.16	0.11	0	1.12					1.12
1/12/2014	34.8	245.32	0.34	0.23	0.22	0.11	0.01	1.12			0.13	0.99	1.12
1/14/2014	31.2	37.1	0.23	0.13	0.14	0.1	0	1.68			0.07	1.61	1.68
1/21/2014	22.8	29.21	0.19	0.13	0.12	0.06	0.01	1.12			0.06	1.06	1.12
2/4/2014	34.8	44.7	0.34	0.17	0.16	0.17	0.01	1.68			0.46	1.22	1.68
2/27/2014	28.8	48.7	0.17	0.04	0.02	0.13	0.02	1.54		1.81	0.2	1.34	3.35

3/10/2014	31.2	199	0.64	0.05	0.03	0.59	0.02	2.24		0.83	0.73	1.51	3.07
3/18/2014	25.2	128.95	0.58	0.03	0.01	0.55	0.02	2.24			1.07	1.17	2.24
3/28/2014	24	187.86	0.76	0.03	0.01	0.73	0.02	1.82		0.47	0.56	1.26	2.29
4/2/2014	31.8	25.99	0.15	0.05	0.05	0.1	0	1.12		0.52	0.14	0.98	1.64
4/4/2014	31.2	29.44	0.17	0.05	0.03	0.12	0.02	0.98		1.42	0.24	0.74	2.4
4/14/2014	14.4	39.87	0.2	0.05	0.01	0.15	0.04	1.26		1	0.07	1.19	2.26
4/16/2014	21.6	33.23	0.18	0.06	0.01	0.12	0.05	1.26		1.4	0.04	1.22	2.66
4/22/2014	18	20.43	0.15	0.04	0.03	0.11	0.01	1.68		2.51	0.25	1.43	4.19
4/25/2014	12	31.24	0.16	0.04	0.04	0.12	0	1.54		0.03	0.34	1.2	1.57
4/28/2014	4.8	30.71	0.18	0.05	0.05	0.13	0	1.54		0.05	0.39	1.15	1.59
5/2/2014	33	49.2	0.35	0.15	0.14	0.2	0.01	0.98		0.07	0.12	0.86	1.05
5/15/2014	24	13.88	0.12	0.02	0	0.1	0.02	1.26		0.01	0.09	1.17	1.27
5/27/2014	24	32.22	0.15	0.07	0	0.08	0.07	3.22		0.66	0	3.22	3.88
6/8/2014	14.4	20.1	0.14	0.04	0	0.1	0.04	1.96		0.67	0	1.96	2.63
6/12/2014	33.6	276.95	0.96	0.37	0.3	0.59	0.07	2.52		7.39	0.9	1.62	9.91
6/13/2014	33.6	130.1	0.61	0.17	0.18	0.44	0	2.94		27.5	2.83	0.11	30.44
6/18/2014	28.8	20.2	0.09	0.02	0.03	0.07	0	5.18		26.03	3.76	1.42	31.21
6/23/2014	30	282.55	1.09	0.11	0.11	0.98	0	2.52		4.62	1.24	1.28	7.14
7/2/2014	28.2	49.19	0.34	0.14	0	0.2	0.14	1.82		0.08	0	1.82	1.9
7/3/2014	32.4	160.3	0.94	0.35	0.32	0.59	0.03	2.52		2.3	0	2.52	4.82
7/4/2014	32.4	416.57	2.21	0.73	0.66	1.48	0.07	2.1		2.17	0.04	2.06	4.27
7/13/2014	27	141.9	0.78	0.13	0.09	0.65	0.04	2.38		0.02	0.59	1.79	2.4
7/19/2014	29.4	78.1	0.24	0.05	0.04	0.19	0.01	0.98		0	0.12	0.86	0.98
7/28/2014	31.8	33.23	0.31	0.05	0.05	0.26	0	1.12		0.04	0.05	1.07	1.16
7/31/2014	29.4	23.9	0.16	0.03	0.03	0.13	0	0.98		0.04	0.23	0.75	1.02
8/11/2014	22.8	49.8	0.25	0.18	0.05	0.07	0.13	1.82		0	0.02	1.8	1.82
8/13/2014	32.4	34	0.22	0.05	0.05	0.17	0	1.12		0.07	0.2	0.92	1.19
8/30/2014	21.6	17.82	0.16	0.07	0.01	0.09	0.06	1.12			0.27	0.85	1.12
9/5/2014	19.2	7.47	0.63	0.12	0.02	0.51	0.1	1.12			0	1.12	1.12
9/26/2014	32.4	202.7	1.08	0.17	0.05	0.91	0.12	1.26			0.07	1.19	1.26

10/3/2014	27	90.49	0.52	0.14	0.06	0.38	0.08	3.78			0.11	3.67	3.78
10/12/2014	22.8	25.9	0.22	0.18	0.03	0.04	0.15	1.68			0.09	1.59	1.68
10/16/2014	33.6	110.2	0.61	0.11	0.03	0.5	0.08	2.52			0.17	2.35	2.52
10/24/2014	32.4	51.31	0.4	0.12	0.04	0.28	0.08	5.46			3.14	2.32	5.46
11/3/2014	32.4	100	0.68	0.23	0.16	0.45	0.07	2.94			0.94	2	2.94
11/7/2014	33.6	14	0.32	0.16	0.14	0.16	0.02	2.52			1.09	1.43	2.52
11/11/2014	29.4	17.17	0.29	0.14	0.09	0.15	0.05	5.46			1.84	3.62	5.46
11/18/2014	33.6	121.61	1.04	0.21	0.16	0.83	0.05	3.78			0.54	3.24	3.78
11/27/2014	33.6	96.59	0.46	0.27	0.24	0.19	0.03	1.4			0.09	1.31	1.4
12/12/2014	33	27.79	0.66	0.16	0.11	0.5	0.05	1.4			0.11	1.29	1.4
12/21/2014	25.2	31.19	0.58	0.16	0.13	0.42	0.03	1.96			0.86	1.1	1.96
12/25/2014	34.8	68.23	0.81	0.24	0.24	0.57	0	1.4			0	1.4	1.4
1/5/2015	33.6	44.54	0.63	0.21	0.17	0.42	0.04	1.68			0.52	1.16	1.68
1/13/2015	36	66.7	0.71	0.19	0.16	0.52	0.03	0.84			0.29	0.55	0.84
1/25/2015	36	63.27	0.43	0.06	0.05	0.37	0.01	0.56			0	0.56	0.56
3/12/2015	30	415.57	2.8	0.13	0.09	2.67	0.04	2.24			0.7	1.54	2.24
3/22/2015	30	43.7	0.38	0.11	0.07	0.27	0.04	1.4			0.55	0.85	1.4
4/3/2015	28.8	93.01	0.24	0.09	0.06	0.15	0.03	1.68			0.17	1.51	1.68
4/7/2015	22.8	79.29	0.32	0.11	0.06	0.21	0.05	2.8			0	2.8	2.8
4/17/2015	13.2	51.68	0.39	0.12	0.04	0.27	0.08	2.52			0	2.52	2.52
4/21/2015	36	105.36	0.74	0.32	0.19	0.42	0.13	3.08			0	3.08	3.08

Table A-5. Summary of Height Measurements and Concentrations of Grab Samples From Basin 3 From the Hambleton Creek Study Site

Date	Height	TSS	TP	TDP	DRP	PP	DOP	TKN	Nitrite	Nitrate	NH4	Organic N	Total N
7/3/2013	32	11.11	1.61	1.27	1.19	0.33	0.08	0.84	0.03				0.87
7/14/2013	32	19.7	1.94	1.46	1.28	0.48	0.18	2.52	0.01				2.53
7/23/2013	32	143.3	0.67	0.78	0.19	0	0.59	1.68	0.002				1.682
8/2/2013	32	35.77	0.29	0.12	0.15	0.17	0	1.12	0.027				1.147
8/14/2013	18.6	6.94	0.19	0.03	0.08	0.16	0	1.12	0.008				1.128
8/21/2013	12.9	0.52	0.12	0.12	0.08	0	0.04	1.96	0.007				1.967
8/27/2013	6	65.1	0.67	0.51	0.63	0.16	0	7	0.008				7.008
9/2/2013	0	0	0	0	0	0	0	0	0				0
9/12/2013	0	0	0	0	0	0	0	0	0				0
9/21/2013	0	0	0	0	0	0	0	0	0				0
10/7/2013	0	0	0	0	0	0	0	0	0				0
10/13/2013	0	0	0	0	0	0	0	0	0				0
10/30/2013	0	0	0	0	0	0	0	0	0				0
11/7/2013	0	0	0	0	0	0	0	0	0				0
12/3/2013	0	0	0	0	0	0	0	0	0				0
12/7/2013	0	0	0	0	0	0	0	0	0				0
12/10/2013	31.2	34.4	0.34	0.16	0.26	0.18	0	1.12					1.12
12/15/2013	33.6	52	0.38	0.15	0.19	0.23	0	0.84					0.84
12/22/2013	0	0	0	0	0	0	0	0					0
12/30/2013	33	99.4	0.31	0.15	0.18	0.16	0	1.96					1.96
1/6/2014	33	46.9	0.26	0.12	0.13	0.14	0	0.56					0.56
1/12/2014	33.6	60.3	0.41	0.24	0.24	0.17	0	0.84			0.13	0.71	0.84
1/14/2014	24	54.74	0.31	0.2	0.19	0.11	0.01	1.4			0.12	1.28	1.4
1/21/2014	0	0	0	0	0	0	0	0			0	0	0
2/4/2014	30.6	59.48	0.4	0.24	0.21	0.16	0.03	2.24			0.7	1.54	2.24
2/27/2014	22.8	32.4	0.13	0.04	0.03	0.09	0.01	6.58		2.44	0.22	6.36	9.02

3/10/2014	13.2	232.2	1.26	0.15	0.14	1.11	0.01	3.92		1.59	1.53	2.39	5.51
3/18/2014	7.2	86.9	0.88	0.12	0.06	0.76	0.06	2.8		1.22	0.54	2.26	4.02
3/28/2014	13.2	78.08	0.45	0.05	0.03	0.4	0.02	1.68		0.18	0.35	1.33	1.86
4/2/2014	30	31.5	0.2	0.07	0.05	0.13	0.02	1.12		0.94	0.11	1.01	2.06
4/4/2014	27.6	27.08	0.17	0.05	0.06	0.12	0	1.54		1.11	0.14	1.4	2.65
4/14/2014	15	8.34	0.08	0.07	0	0.01	0.07	0.98		0.52	0.04	0.94	1.5
4/16/2014	14.4	6.38	0.06	0.03	0	0.03	0.03	0.7		0.98	0	0.7	1.68
4/22/2014	10.2	10.82	0.09	0.02	0.02	0.07	0	1.12		0.05	0.2	0.92	1.17
4/25/2014	8.4	10.51	0.08	0.01	0.01	0.07	0	1.12		0.04	0.09	1.03	1.16
4/28/2014	6.6	26.67	0.26	0.04	0.02	0.22	0.02	1.82		0.14	0.03	1.79	1.96
5/2/2014	33	54.95	0.38	0.21	0.19	0.17	0.02	1.4		0.1	0.2	1.2	1.5
5/15/2014	16.8	9.69	0.18	0.08	0.07	0.1	0.01	1.96		0.22	0.28	1.68	2.18
5/27/2014	15	22.02	0.28	0.16	0.02	0.12	0.14	2.38		0.77	0.63	1.75	3.15
6/8/2014	8.4	61.92	0.4	0.16	0.02	0.24	0.14	3.08		0.86	0	3.08	3.94
6/12/2014	25.2							3.5		1.58		3.5	5.08
6/13/2014	33.6	99.8	0.47	0.17	0.17	0.3	0	2.8		20.54	2.77	0.03	23.34
6/18/2014	21.6	37.69	0.12	0.02	0.03	0.1	0	1.82		12.1	0.75	1.07	13.92
6/23/2014	25.2	292.35	1.02	0.16	0.17	0.86	0	1.26		3.9	1.02	0.24	5.16
7/2/2014	21	120.75	0.45	0.16	0.01	0.29	0.15	2.24		1.95	0.73	1.51	4.19
7/3/2014	32.4	334.38	1.01	0.39	0.3	0.62	0.09	2.52		2.42	0.1	2.42	4.94
7/4/2014	32.4	209.9	1.19	0.55	0.52	0.64	0.03	1.96		2.56	0	1.96	4.52
7/13/2014	18.6	156.63	1.09	0.31	0.29	0.78	0.02	4.2		0.34	2.47	1.73	4.54
7/19/2014	23.4	50.62	0.37	0.16	0.1	0.21	0.06	1.68		0.05	0.19	1.49	1.73
7/28/2014	27.6	23.13	0.33	0.14	0.09	0.19	0.05	1.96		0.04	0.1	1.86	2
7/31/2014	22.2	24.79	0.2	0.06	0.05	0.14	0.01	1.54		0.04	0.13	1.41	1.58
8/11/2014	12	43.4	0.27	0.03	0.03	0.24	0	1.68		0	0.18	1.5	1.68
8/13/2014	32.4	29.7	0.15	0.08	0.06	0.07	0.02	1.54		0.1	0.11	1.43	1.64
8/30/2014	11.4	15.88	0.15	0.08	0.01	0.07	0.07	0.7			0.06	0.64	0.7
9/5/2014	8.4	2.53	0.83	0.37	0.2	0.46	0.17	1.96			0.01	1.95	1.96
9/26/2014	29.4	105.96	0.99	0.3	0.18	0.69	0.12	1.68			0.19	1.49	1.68

10/3/2014	6	28.1	0.3	0.1	0	0.2	0.1	2.24			0	2.24	2.24
10/12/2014	0	0	0	0	0	0	0	0				0	0
10/16/2014	32.4	71.94	0.69	0.14	0.09	0.55	0.05	2.24			0.15	2.09	2.24
10/24/2014	28.8	45.71	0.41	0.14	0.09	0.27	0.05	6.02			3.3	2.72	6.02
11/3/2014	28.8	59.41	0.46	0.18	0.09	0.28	0.09	3.5			1.95	1.55	3.5
11/7/2014	19.1	19.1	0.32	0.12	0.09	0.2	0.03	2.8			2.12	0.68	2.8
11/11/2014	13.8	9.09	0.1	0.03	0	0.07	0.03	6.02			0.6	5.42	6.02
11/18/2014	33.6	99	0.66	0.18	0.14	0.48	0.04	3.78			0.7	3.08	3.78
11/27/2014	34.2	81.28	0.36	0.2	0.19	0.16	0.01	1.68			0.28	1.4	1.68
12/12/2014	28.8	22.45	0.75	0.16	0.13	0.59	0.03	1.4			0.11	1.29	1.4
12/21/2014	13.8	12.96	0.58	0.29	0.25	0.29	0.04	1.4			0.45	0.95	1.4
12/25/2014	34.2	70.53	0.75	0.2	0.18	0.55	0.02	1.68			0.01	1.67	1.68
1/5/2015	25.2	23.4	0.56	0.24	0.17	0.32	0.07	1.68			0.27	1.41	1.68
1/13/2015	34.2	69.9	0.93	0.21	0.14	0.72	0.07	2.24			0.47	1.77	2.24
1/25/2015	34.2	77.8	0.4	0.07	0.06	0.33	0.01	0.56			0	0.56	0.56
3/12/2015	30	690.17	4.74	0.13	0.07	4.61	0.06	2.8			0.77	2.03	2.8
3/22/2015	26	25	0.35	0.09	0.05	0.26	0.04	0.28			0	0.28	0.28
4/3/2015	24	59.3	0.29	0.11	0.06	0.18	0.05	1.4			0.01	1.39	1.4
4/7/2015	12	73.44	0.3	0.13	0.06	0.17	0.07	1.68			0.01	1.67	1.68
4/17/2015	8.4	8.76	0.19	0.16	0.07	0.03	0.09	1.12			0	1.12	1.12
4/21/2015	34.2	92.35	0.51	0.14	0.07	0.37	0.07	2.52			0	2.52	2.52

Table A-6. Summary of Height Measurements and Concentrations of Grab Samples From Basin 3 From the Hambleton Creek Study Site

Date	Height	TSS	TP	TDP	DRP	PP	DOP	TKN	Nitrite	Nitrate	NH4	Organic N	Total N
7/3/2013	32	2.84	0.62	0.32	0.15	0.31	0.17	1.12	0.03				1.15
7/14/2013	32	43.83	1.83	1.35	1.21	0.48	0.14	1.96	0.009				1.969
7/23/2013	32	107.53	0.72	0.61	0.31	0.11	0.3	1.96	0.002				1.962
8/2/2013	32	41.1	0.27	0.16	0.19	0.11	0	2.52	0.014				2.534
8/14/2013	19.2	26.46	0.2	0.08	0	0.12	0.08	0.84	0.008				0.848
8/21/2013	15.3	16.34	0.17	0.03	0	0.14	0.03	1.4	0.007				1.407
8/27/2013	10.5	18.4	0.26	0.02	0	0.24	0.02	0.56	0.007				0.567
9/2/2013	4.8	36.9	0.35	0.12	0.11	0.23	0.01	1.68	0.008				1.688
9/12/2013	0	0	0	0	0	0	0	0	0				0
9/21/2013	0	0	0	0	0	0	0	0	0				0
10/7/2013	0	0	0	0	0	0	0	0	0				0
10/13/2013	0	0	0	0	0	0	0	0	0				0
10/30/2013	0	0	0	0	0	0	0	0	0				0
11/7/2013	0	0	0	0	0	0	0	0	0				0
12/3/2013	0	0	0	0	0	0	0	0	0				0
12/7/2013	0	0	0	0	0	0	0	0	0				0
12/10/2013	13.2	17.02	0.33	0.24	0.22	0.09	0.02	0.56	0				0.56
12/15/2013	21.6	22.2	0.25	0.04	0.15	0.21	0	0.84	0				0.84
12/22/2013	0	0	0	0	0	0	0	0	0				0
12/30/2013	13.2	84	0.45	0.26	0.38	0.19	0	1.68					1.68
1/6/2014	7.2	30	0.22	0.1	0.09	0.12	0.01	1.4					1.4
1/12/2014	28.8	85.21	0.89	0.66	0.64	0.23	0.02	1.12			0.22	0.9	1.12
1/14/2014	21.6	52.58	0.35	0.22	0.22	0.13	0	0.84			0.22	0.62	0.84
1/21/2014	10.8	23.43	0.26	0.17	0.17	0.09	0	2.52			0.12	2.4	2.52
2/4/2014	27	94.49	0.49	0.2	0.21	0.29	0	1.96			0.47	1.49	1.96

2/27/2014	22.8	34.39	0.14	0.03	0.03	0.11	0	1.12		0.82	0.35	0.77	1.94
3/10/2014	18.6	69.7	0.28	0.04	0.03	0.24	0.01	1.12		1.39	0.47	0.65	2.51
3/18/2014	16.8	62.2	0.41	0.03	0.1	0.38	0	1.12			0.09	1.03	1.12
3/28/2014	17.4	30.51	0.18	0.04	0.01	0.14	0.03	1.12		1.63	0.06	1.06	2.75
4/2/2014	27.6	31.22	0.18	0.07	0.07	0.11	0	0.98		0.94	0.22	0.76	1.92
4/4/2014	26.4	19.51	0.14	0.05	0.03	0.09	0.02	0.98		1.14	0.17	0.81	2.12
4/14/2014	21.6	3.77	0.1	0.04	0	0.06	0.04	0.98		0.52	0.09	0.89	1.5
4/16/2014	22.8	32.04	0.05	0.02	0	0.03	0.02	0.98		0.79	0	0.98	1.77
4/22/2014	19.8	48.24	0.03	0	0	0.03	0	1.54		0	0	1.54	1.54
4/25/2014	18.6	5.05	0.03	0	0	0.03	0	0.84		0.010597	0	0.84	0.850597
4/28/2014	17.4	14.27	0.09	0	0.01	0.09	0	1.12		0.07	0.03	1.09	1.19
5/2/2014	28.2	63.3	1.49	0.13	0.15	1.36	0	1.26		0.73	0.45	0.81	1.99
5/15/2014	24	8.94	0.08	0	0	0.08	0	1.4		0.16	0.24	1.16	1.56
5/27/2014	21	21.78	0.19					2.8					2.8
6/8/2014	17.4	44	0.36	0.14	0	0.22	0.14	3.36		0.35			3.71
6/12/2014	19.2	38.79	0.24	0.13	0	0.11	0.13	2.8		0.72	0.67	2.13	3.52
6/13/2014	28.8	123.1	0.48	0.13	0.12	0.35	0.01	2.66		13.72	1.82	0.84	16.38
6/18/2014	23.4	20.62	0.1	0	0.01	0.09	0	2.1		8.58	0.92	1.18	10.68
6/23/2014	25.2	291.1	1.08	0.13	0.14	0.95	0	2.8		2.14	1.32	1.48	4.94
7/2/2014	20.4	81.06	0.31	0.07	0	0.24	0.07	2.38		0.55	0.4	1.98	2.93
7/3/2014	28.8	184.15	0.85	0.24	0.15	0.61	0.09	2.66		0.58	0.56	2.1	3.24
7/4/2014	28.8	353.3	1.45	0.48	0.42	0.97	0.06	5.6		2.43	0.1	5.5	8.03
7/13/2014	18	130.51	0.58	0.08	0.06	0.5	0.02	1.96		0.71	0.66	1.3	2.67
7/19/2014	19.8	54.4	0.33	0.05	0.04	0.28	0.01	1.68		0.07	0.21	1.47	1.75
7/28/2014	12	47.27	0.27	0.04	0.02	0.23	0.02	1.68		0	0.06	1.62	1.68
7/31/2014	7.2	68.74	0.27	0.21	0.04	0.06	0.17	1.68		0	0.05	1.63	1.68
8/11/2014	4.8	42.53	0.33	0.25	0.06	0.08	0.19	2.24		0	0	2.24	2.24
8/13/2014	25.2	25.61	0.35	0.12	0.09	0.23	0.03	1.54		0.05	0.11	1.43	1.59
8/30/2014	2.4	2.71	0.08	0.07	0	0.01	0.07	1.26			0.17	1.09	1.26
9/5/2014	0	0	0	0	0	0	0	0				0	0

9/26/2014	4.8	5.33	0.47	0.15	0.05	0.32	0.1	1.96			0.51	1.45	1.96
10/3/2014	0	0	0	0	0	0	0	0				0	0
10/12/2014	0	0	0	0	0	0	0	0				0	0
10/16/2014	8.4	59.39	0.61	0.24	0.19	0.37	0.05	1.54			0.13	1.41	1.54
10/24/2014	20.4	26.84	0.3	0.12	0.04	0.18	0.08	3.78			1.36	2.42	3.78
11/3/2014	2.8	65	1.22	0.51	0.49	0.71	0.02	6.16			2.98	3.18	6.16
11/7/2014	0	0	0	0	0	0	0	0			0	0	0
11/11/2014	0	0	0	0	0	0	0	0			0	0	0
11/18/2014	7.2	67.68	0.82	0.32	0.28	0.5	0.04	3.78			0.55	3.23	3.78
11/27/2014	28.8	104.26	0.35	0.15	0.14	0.2	0.01	1.12			0.27	0.85	1.12
12/12/2014	24	95.11	0.7	0.15	0.13	0.55	0.02	1.68			0.07	1.61	1.68
12/21/2014	14.4	20.52	0.45	0.17	0.14	0.28	0.03	1.12			0.24	0.88	1.12
12/25/2014	28.2	53.4	0.56	0.14	0.13	0.42	0.01	1.68			0.38	1.3	1.68
1/5/2015	15.6	10.2	0.42	0.18	0.13	0.24	0.05	0.84			0.62	0.22	0.84
1/13/2015	28.8	77.7	0.73	0.19	0.14	0.54	0.05	1.4			0.44	0.96	1.4
1/25/2015	28.8	86.7	0.49	0.09	0.06	0.4	0.03	0.56			0	0.56	0.56
3/12/2015		209.23	1.16	0.09	0.07	1.07	0.02	1.68			0.43	1.25	1.68
3/22/2015		22.02	0.35	0.08	0.05	0.27	0.03	0.56			0.17	0.39	0.56
4/3/2015	19.2	29.6	0.09	0.07	0.04	0.02	0.03	2.52			0	2.52	2.52
4/7/2015	14.4	20.9	0.11	0.07	0.04	0.04	0.03	1.68			0	1.68	1.68
4/17/2015	16.8	4.58	0.1	0.09	0.04	0.01	0.05	1.4			0	1.4	1.4
4/21/2015	28.8	41.98	0.3	0.19	0.08	0.11	0.11	1.96			0	1.96	1.96

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