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Analysis of Stormwater Runoff from Permeable Friction Course

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Analysis of Stormwater Runoff from Permeable Friction Course

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Dedication

I dedicate this thesis to my mom and dad for supporting all I’ve ever done.

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I would like to thank the Texas Department of Transportation for funding the project. My time spent researching and writing would certainly have been more difficult if it had not been for the patience and positive attitudes of my advisors: Dr. Michael Barrett and Dr. Randall Charbeneau. And lastly, my graduate school experience would not have been complete without the camaraderie shared by my stormwater teammates and fellow EWRE students. My grad school experience was exactly as I hoped it to be.

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Abstract

Analysis of Stormwater Runoff from Permeable Friction Course

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Recently, the Texas Department of Transportation began using Permeable Friction Course (PFC), a 5 cm overlay of porous pavement that is applied over conventional pavement. PFC was initially developed because it allows water to drain off the surface of roads much more rapidly, thus reducing visual impairment due to splash and spray as well as reducing the risk of hydroplaning. While investigating the water quality of stormwater runoff, researchers at the University of Texas discovered that PFC caused a reduction in many common stormwater pollutant concentrations. Monitoring of stormwater at one site has been ongoing for 5 years without any indication of a decline in water quality. A second location provided paired samples to analyze the particle size distribution. Results show a significant reduction in the mass of particles commonly associated with heavy metals and nutrient loads. A third location was chosen based on tests indicating it to have a lower hydraulic conductivity relative to other locations. The paired samples provided a comparison of runoff quality at a site believed to be heavily clogged. The results show PFC continues to produce significantly lower runoff pollutant concentrations despite the decreased hydraulic conductivity.

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Chapter 1 Introduction

1.1 Overview

Permeable Friction Course (PFC) is a 5 cm overlay of porous pavement that is applied over conventional asphalt. PFC is a bituminous mixture similar to conventional pavements except made up of only coarse aggregate (no fine aggregates). The lack of fine aggregates allows the asphalt to develop voids and become permeable. Traditionally, porous pavements have been used in low traffic areas as a form of runoff volume control. PFC is different than other porous pavements or concrete because it is overlaid on top of conventional pavement.

PFC was initially developed because it allows water to drain off the surface of the roads, into the voids of the pavement, then flow out of the edges of the roadway. The draining of water provides many safety benefits such as the reduction of visual impairment due to water spray as well as reducing the risk of hydroplaning (Van der Zwan et al., 1990). It is has been found in recent studies that porous overlays can be used to reduce the concentrations of various pollutants in stormwater runoff (Berbee et al., 1999; Barrett and Shaw, 2007).

The lifespan of PFC is of upmost importance. The ability for PFC to perform as designed is dependent on the extent of clogging that occurs over time. Sediment and vehicle debris collects in the roadway. This debris fills the voids, decreases the hydraulic conductivity, and prevents water from draining into the overlay.

Stormwater runoff controls are an important part of protecting watersheds and aquifers. Over the Edwards Aquifer region the Texas Commission on Environmental Quality (TCEQ) requires 80% removal of total suspended solids (TSS) that result from new development. In order to gain permission from TCEQ to construct roads, Texas Department of Transportation (TxDOT) must prove that 80% of the TSS introduced by the road is removed (Texas Administrative Code, 2005). Traditional methods of reducing TSS concentrations include detention ponds, wet ponds, and filtration basins. These methods are expensive, require substantial right-of-way, and ongoing maintenance to ensure proper performance. Treatment methods must be proven effective before they may be considered a Best Management Practice (BMP).

There have been multiple previous studies examining the stormwater quality at Loop 360. The initial study examined the benefits of vegetative buffer strips along the sides of the roadway. Seven months into monitoring, Loop 360 was repaved using PFC. It was discovered that the runoff from PFC was drastically cleaner (Kearfott et al., 2005). Monitoring of the site continued for the next five years (Barrett and Shaw, 2007; Stanard et al., 2008). This study is a continuation of that earlier research.

1.2 Objectives

The purpose of this project is to determine the extent and limitations of the water quality benefits of PFC. The goals of this project include:

- Continued monitoring of developed sites to evaluate longevity

- Laboratory analysis of samples
- Collection of laboratory results
- Development of new sites to determine affect of hydraulic conductivity on quality
- Evaluation of particle size distributions (PSD)
- Statistical analysis of data
- Determine independent variables that impact stormwater quality

Chapter 2 Literature Review

2.1 Introduction

The following chapter presents a literature review of articles dealing with the water quality benefits of PFC. Previous studies conducted by the Center for Water Resources are introduced as background and motivation for the current project. Also included are articles dealing with the quality of conventional stormwater, primarily particle size distributions.

2.2 Stormwater Quality Benefits

The quality of urban runoff and benefits of PFC have largely been studied in the Netherlands. Berbee et al. (1999) studied the difference between the quality of runoff from conventional and pervious pavements. Two sites were developed to monitor the runoff from both impervious and pervious pavements. Both sites were standard north-south, four lane roads with hard shoulders, separated by a median with a rigid barrier. The pervious pavement was 50mm thick and 3 years old. Runoff was collected over a period of one week and then analyzed for various pollutant concentrations. Two sites were sampled for a period of over one year. The results documented significantly lower pollutant concentrations in runoff from pervious pavement compared to impervious. The most drastic improvements in water quality were found in heavy metal (lead, copper, zinc) and total suspended solid concentrations. The results are summarized in Table 1.

Table 1: Summary of Pollutant Concentration from Berbee et al. (1999)

Pollutant (units)	Impervious	Pervious
Suspended Solids (mg/L)	153-354	2-70
Nitrogen, Kjeldahl, Total (mg/L)	2-3	0.3-0.5
Chemical Oxygen Demand (mg/L)	143-149	16-18
Copper (μg/L)	91-163	14-107
Lead (μg/L)	51-106	2-22
Zinc (μg/L)	225-493	18-133

Berbee et al. (1999) also examined the effectiveness of additional treatment on the runoff from both the PFC and conventional pavements. Results showed reduced treatment efficiency for pervious pavement runoff because of the already low pollutant concentrations. The poor treatment efficiency of pervious pavement runoff has implications in the cost benefit analysis of stormwater quality. It may not be cost effective to provide additional treatment for PFC runoff.

Similarly, Pagotto et al. (2000) compared the quality of runoff between pavement types in France. The research site was originally conventional pavement but was replaced in 1996 with an overlay of 30 mm porous pavement. The runoff from a bridge was diverted to a flow meter and sampled. Flow weighted samples were taken and rain information was recorded. Factors that could lead to changes in water quality were taken largely into account. The effects of seasonal variations were a primary concern and for this reason, only storms that occurred between June and November were compared. The results showed a major reduction in total suspended solids and heavy metals. Results showed the mean value of TSS reduced from 46 mg/L to 8.7 mg/L, an 81% reduction.

For heavy metals, copper reduced 35%, lead reduced 78%, zinc reduced 66%, and cadmium reduced 69%. Table 2 shows the mean concentration values.

Table 2: Pollutant Concentrations from Pagotto et al. (2000)

Pollutant (units)	Impervious	Pervious
Suspended Solids (mg/L)	46	8.7
Nitrogen, Kjeldahl, Total (mg/L)	2.1	1.2
Chemical Oxygen Demand (mg/L)	80	80
Copper, total (μg/L)	30	20
Lead, total (μg/L)	40	8.7
Zinc, total (μg/L)	228	77
Cadmium, total (μg/L)	0.88	0.28
Copper, dissolved (μg/L)	19	16
Lead, dissolved (μg/L)	3.3	2.2
Zinc, dissolved (μg/L)	140	54
Cadmium, dissolved (μg/L)	0.32	0.13

Pagotto et al. (2000) postulated that the retention of particles was the main cause of improved quality. The retained sediment in the porous pavement may function as a filtration system. Furthermore, the retention of smaller particle sizes reduces the concentrations of pollutants bound to sediment in the runoff discharged. Also, they proposed that adsorption occurs within the porous media; either to the pavement itself or to trapped sediment.

2.3 Particle Size Distributions

The particle size distribution of runoff is crucial to multiple aspects of water quality. Sediments are considered to be a large storage area for pollutants and if specific pollutants are of concern, knowing their association with various size ranges has major treatment design implications.

Kayhanian et al. (2005) examined particle size distributions in stormwater runoff and the concentration of pollutants within various particle size ranges. Three sites were instrumented in the Los Angeles area and were monitored for three years. Kayhanian et al. (2005) reports that particles in stormwater runoff may range from 0.1 µm to over 1000 µm with a majority of particles below 30 µm. A large fraction of heavy metals (copper, lead, and zinc) were associated with particles in size range 8 µm to 20 µm. In regards to particle sizes specifically, small particles comprise a majority of the number of particles in stormwater runoff but a small percentage of the total mass. Particles with diameters less than 10 µm make up 90% of the number of particles but their mass makes up only 10%.

Sansalone and Buchberger (1997) researched the relationship between suspended particle and metal concentrations in stormwater runoff. Samples were obtained from interstate I-75 in Cincinnati, Ohio where the average daily traffic is 150,000 vehicles. Metal concentrations were calculated and separated by the corresponding particle size. The results are summarized in Table 3. The results show that metal concentrations increase with a decrease in particle size. The highest zinc and copper concentrations are found in the 25-38 µm range. Lead concentrations are comparable in all size ranges under 150 µm.

Table 3: Metal concentrations separated by particle size

Particle Size (microns)	Zinc (μg/g)	Lead (μg/g)	Copper (μg/g)
4750-9500	36	9	14
2000-4750	524	59	14
850-2000	220	44	46
425-850	302	56	209
250-425	314	83	121
150-250	593	187	217
75-150	1141	332	323
63-75	1290	311	374
45-63	1207	326	394
38-45	1326	291	398
25-38	1410	303	478

Heavy metals are not the only constituent that shows a strong affinity for certain particle size ranges. Vaze and Chiew (2004) showed that 60% of the total phosphorus (TP) was attached to particles with a diameter between 11 μm and 150 μm while 40-50% of the attached phosphorus was adsorbed onto particles with a diameter 11 μm and 53 μm. Also, total nitrogen (TN) was found attached to particles with diameters between 11 μm and 150 μm. Even though half of surface pollutants are coarser than 300 μm, less than 10% of TP or TN is attached to particles larger than 300 μm.

2.4 Developing a Model to Predict Water Quality

Irish et al. (1995) studied the variables that affect the quality of stormwater runoff. A rainfall simulator was developed to evaluate the impact of varying conditions on quality. Samples were taken from 35 simulated storms as well as 23 natural storms. Statistical analysis proved the simulated and natural rainfalls to be homogenous. Possible causal variables were identified and evaluated using multiple linear regression analysis.

Table 4 identifies pollutants and the variables deemed statistically significant in their prediction.

Table 4: Variables affecting pollutant concentrations from Irish et al. (1995)

	Storm Length	Storm Vol.	Storm Int.	Traffic Count	ADP	Ant. Traffic Count	Prev. Storm Duration	Previ. Storm Vol.	Prev.Storm Int.
Iron		x	x		x				
TSS		x	x		x				x
Zinc	x	x				x	x	x	x
COD	x	x	x		x	x			
Phosphorus	x	x	x			x			
Nitrate		x	x			x			
BOD_5		x	x	x		x			
Lead		x	x	x					x
Copper	x	x		x					
Oil and Grease		x		x					

The resulting equation to determine TSS concentrations is:

$$TSS(\mathrm{g/m^2}) = 0.2556 + 0.3068(Flow) + 2.0181(Intensity) + 0.0037(ADP) - 2.9865(PINT)$$

Where *Flow* is the volume of runoff per unit area. *Intensity* is *Flow* divided by duration. *ADP* is the antecedent dry period in number of hours. *PINT* is previous storms *Intensity*. The modeled TSS values were plotted against the observed TSS values to obtain the graph in Figure 1. The resulting R^2 value is 0.93.

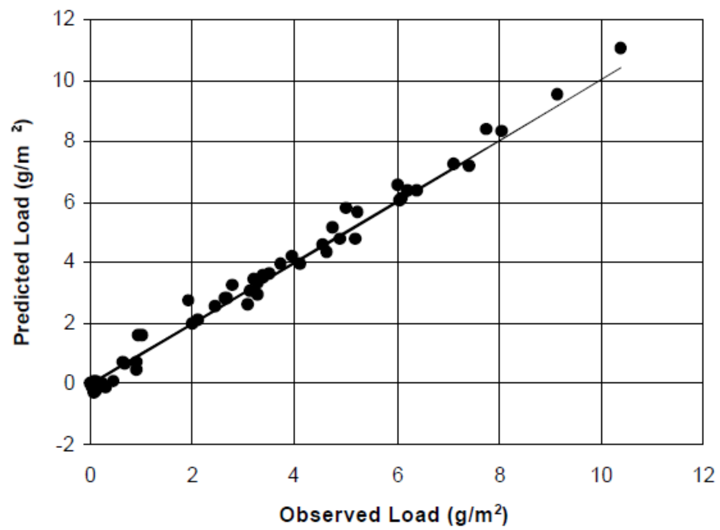


Figure 1: Predicted vs Observed Load from Irish et al. (1995)

Irish et al. (1995) notes that despite the absence of traffic counts in the regression model for TSS, there is a positive correlation between traffic counts and TSS loads. The average concentration of TSS for simulations when traffic is present was 291 mg/L while the no-traffic simulation averaged 67 mg/L.

Robien et al. (1997) modeled dissolved and particle-bound pollutants in urban runoff. Two study sites were sampled between 1990 and 1991 in Bayreuth, Germany.

The sampling sites are located at two lane roadways that host 6,000 and 16,000 vehicles per day. An automatic sampling system was used. Multiple linear regression was used to develop relationships between pollutant load and independent variables. Total runoff and antecedent dry period were chosen as the independent variables. For suspended solid load, total runoff was found to be significant at both locations at p-values between 0.01 and 0.001. Antecedent dry period was found to be significant at a p-value between 0.01 and 0.001 for one location and 0.05 and 0.01 for the second location.

2.5 Studies Conducted by the Center for Research in Water Resources

The Center for Research in Water Resources (CRWR) began studying the water quality impacts of PFC in 2004. Kearfott et al. (2005) studied the effect of vegetated filter strips along the edge of roadway pavement. During the study, one of the study sites was overlain with PFC. The presence of PFC was found to be statistically significant compared to conventional pavement (93.2% decrease in TSS). The findings of Kearfott et al. lead the CRWR to begin multiple research projects involving PFC. Candaele et al. (2008) studied the hydraulic properties of PFC. The study included the verification of the clogging phenomenon. Three study locations all reported reductions in hydraulic conductivity and effective porosity as the pavement aged. It is believed that the reductions could affect the long term efficiency of PFC in improving water quality. Stanard et al. (2008) evaluated the effects of PFC on water quality. The study evaluated the water quality impacts as well as the rainfall/runoff relationship. The current investigation was established to extend the progress made by Stanard et al. (2008).

Stanard et al. (2008) reported that the average concentrations recorded before Loop 360 was paved with PFC are similar to average concentrations found in other reports. The average concentrations from impervious pavement as reported Irish et al. (1995) were compared to those found at Loop 360 in Table 5.

Table 5: Comparison of mean concentrations Stanard et al. (2008)

Constituent	High-traffic Site	Low-traffic Site	Loop 360 Site 1
TSS (mg/L)	202	142	117.8
Total P (mg/L)	0.42	0.13	0.13
COD (mg/L)	149	48	64
Total Copper (µg/L)	38	10	26.84
Total Lead (µg/L)	99	41	12.57
Total Zinc (µg/L)	237	77	167.4

Stanard et al. (2008) reported regression equations showing the relationship between concentration and time. A crucial aspect of evaluating PFC performance is predicting when the benefits will end. Stanard et al. (2008) examined, in detail, the concentration of total copper and the graph is found in Figure 2. It was reported that it would take 1.4 years from March 2008 for the total copper concentrations of runoff from PFC to reach that of conventional hot mix asphalt (29.4 µg/L).

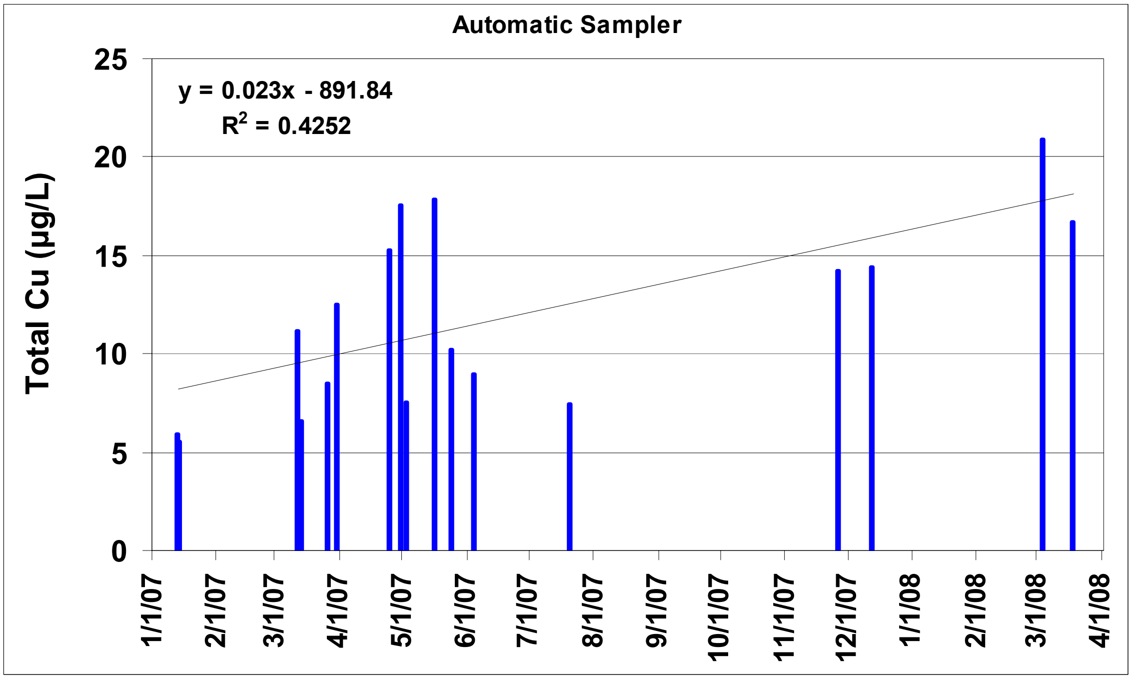


Figure 2: Total Cu versus time (Stanard, et al (2008))

Chapter 3 Materials and Methods

3.1 Site Descriptions

3.1.1 Overview

There are three sites used in this study. Two of the sites are found on State Highway Loop 360 near FM 2222 in Austin, TX. The third site is located on FM 620 near Cornerwood Drive in Round Rock, TX. Satellite images of the three sites are found in Figure 3 and Figure 4.

Figure 3: Satellite Images of Sites 1 and 2 (Google Maps, 2009)

Figure 4: Satellite Images of Site 3 Passive Samplers (Google Maps, 2009)

Loop 360 is paved with PFC from Lake Austin to US 183 except at traffic signals and bridges. RR 620 is paved with PFC from IH 35 to the intersection at Cornerwood Dr. The 2005 average annual daily traffic (AADT), as estimated by TxDOT, for Loop 360 between Spicewood Springs Road and RM 2222 was 48,000. The AADT for RR 620 between Wyoming Springs Dr. and FM 734 was 32,000. (CAMPO, 2007)

3.1.2 Site 1

Site 1 is located on the shoulder of southbound Loop 360. Water quality was monitored since March 2004 prior to the installation of PFC in October 2004. Passive samplers were used to monitor stormwater runoff until the system was replaced with an active sampler in December 2006.

3.1.3 Site 2

Site 2 is located 0.3 miles south of Site 1 on the shoulder of the northbound lane near Lakewood Drive. The passive samplers are located about 200 feet apart, one each for PFC and conventional pavement. TxDOT feared that the deceleration and acceleration that occurs at intersections would lead to rapid deterioration of PFC and concluded that conventional asphalt would remain at the locations of traffic lights. The proximity of the two samplers allowed for pair samplings to occur where conditions (rainfall depth, storm intensity, traffic counts, etc.) could be assumed homogenous.

3.1.4 Site 3

Site 3 is located on either side of Cornerwood Drive the southbound shoulder of RR 620. The two passive samplers are located about 450 feet apart. Candaele et al. (2008) determined that the hydraulic conductivity and effective porosity of PFC at RR 620 is much lower than that at Loop 360. The goal of adding this third research site was to observe the differences in water quality for a pavement that does not drain properly. The hypothesis is that as permeability of PFC decreases the water quality approaches that of conventional pavement.

3.2 Site 1 Setup

An active sampler was installed in December 2006 in lieu of the existing GKY FirstFlush samplers in order to gain more specific information about rainfall events. An active sampler allows monitoring of quantity as well as quality.

The stormwater collection system was constructed to act like a gutter on the shoulder of the road. It is made up of six 10 foot sections of 4 inch diameter PVC pipe that are connected with rubber joints. A quarter circle of the cross section was cut laterally along the pipe to create an entrance for water runoff. Plastic flashing was used to allow runoff to enter the PVC pipe. The flashing has a 1" overhang which is placed within the opening in the PVC pipe. Flashing was secured to the pavement using silicone. The pipe runs along the edge of the pavement until it makes a 90 degree turn and runs underground in a completely closed PVC pipe. The underground pipe runs for about 20 feet before emptying into an H-flume.

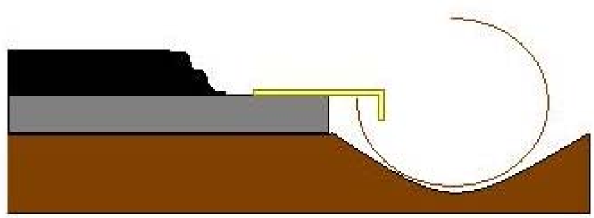


Figure 5: Cross section of collection system

An ISCO 4230 Bubbler Flow Meter monitors the depth of water runoff in the H-flume approach and calculates the corresponding flow rate. Just downstream of the bubble flow meter the runoff flows into a container where samples can be drawn using an

ISCO 3700 Portable Sampler. The samples are pumped through a Teflon coated suction line into a 10L Nalgene bottle.

A secure storage box is located onsite to house the sampling equipment and bubble flow meter. It is powered by a 12-volt marine battery that is charged by a solar panel. An ISCO 674 Rain Gauge is located onsite and is connected to the flow meter. The rain gage is a tipping bucket which measures rainfall in 0.01 inch increments. Rainfall data is sent to the flow meter every 5 minutes. Photographs of the Loop 360 site are found in Figure 6 and Figure 7. For more detailed information regarding the design, installation, and programming of the active sampler refer to Stanard et al. (2008).

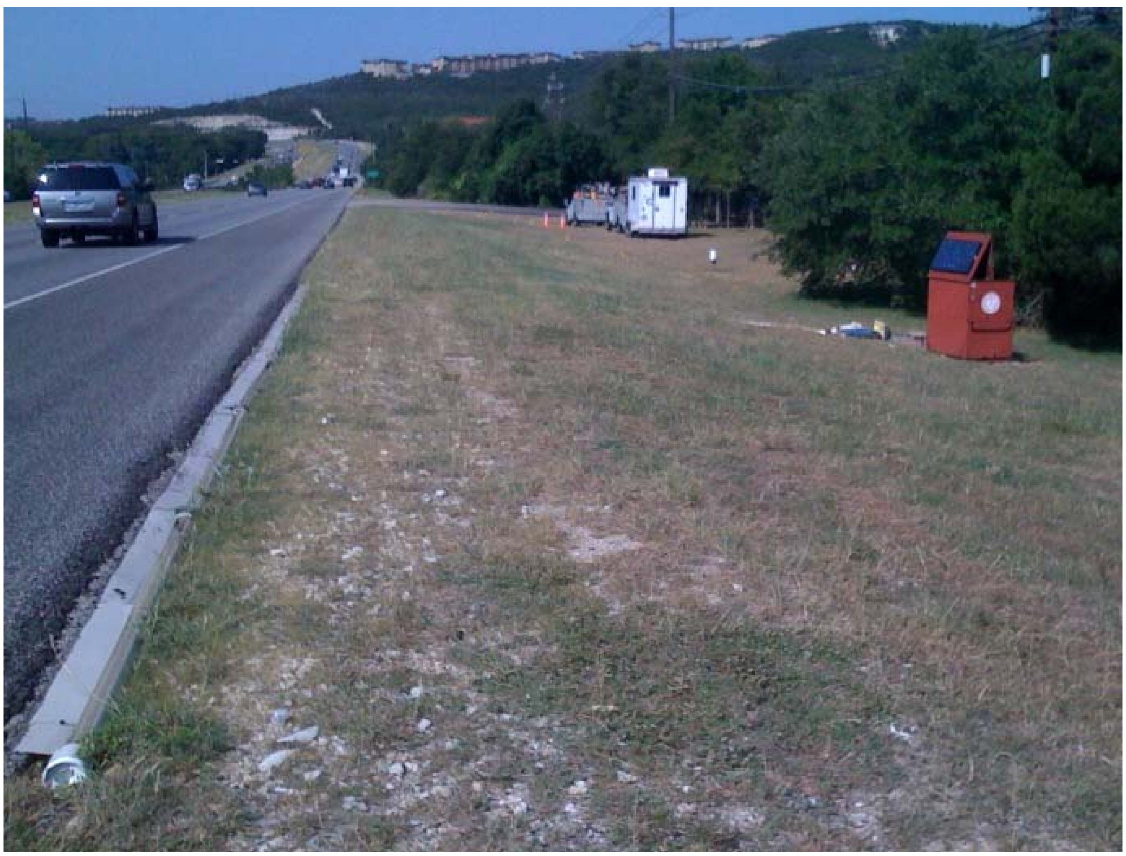


Figure 6: Loop 360 sampling site

Figure 7: Flume and Sampling Box at Loop 360

3.3 Site 2 Setup

Two GKY First Flush samplers were installed in March 2007. The first flush samplers have five holes in the top of the lid to allow runoff to flow into the containers. Inside each sampler is a 4 L plastic container that can be easily removed. Once the containers are full, buoyant plastic flaps seal the holes.

The locations for the samplers were chosen so that neither would be affected by the close proximity of the transition from PFC to conventional pavement. The samplers were installed by digging a hole on the edge of the pavement, filling it with concrete, and insuring that the boxes were level so that water would be naturally collected. Silicone was used to create a level transition from the pavement to the boxes and to fill any holes that might divert water from the box. Photographs of the passive samplers at Site 2 are found in Figure 8.

Figure 8: Passive Samplers at Loop 360, PFC (Left) and Conventional Pavement (Right)

3.4 Site 3 Setup

Site 3 passive samplers were installed in January 2009 on the shoulder of RR 620. Setup is very similar to that of Site 2. Locations for samplers were based on the closest combination of paired sampling as well as ease of access. Both boxes are located adjacent to parking lots. Photos of the RR 620 site are found in Figure 9.

Figure 9: Passive Samplers at RR 620, PFC (Left) and Conventional Pavement (Right)

3.5 Sampling Procedure

Prior to rain events the site was prepared for sampling. For the active sampler on Loop 360, a battery powered leaf blower was used to clean the PVC pipes and flume of debris. The sampling box was wiped clean and a new 10L Nalgene bottle was placed in the storage box. The sampler was programmed to begin sampling. The rain gauge was checked for clogging and all tubing was checked for proper connections. For the passive samplers, roadside debris was cleared and the boxes were cleaned of any dirt and any residual water was removed. Clean sampling boxes were placed in the samplers and lids were tightened to secure a level surface for water to enter the boxes.

After the storms, all the sampling containers were removed and secured with a lid. The samples from RR 620 and the active sampler at Loop 360 were taken to the Lower

Colorado River Authority (LCRA) lab in Austin for analysis. The paired samples from Loop 360 were used to compare particle size distributions (PSD). The samples were taken to the Center for Research in Water Resources where they were split using a Dekaport Cone Sample Splitter, found in Figure 10. A 1L representative sample of both PFC and conventional pavements were packed with gel ice packs and mailed to the University of Alabama for particle size analysis by Dr. Robert Pitt.

Figure 10: Dekaport Cone Sample Splitter

3.6 Analytical Procedures

The samples were delivered to the LCRA lab as soon as possible. If the lab was closed post-sampling, the samples were stored in a cold room at 4°C and delivered as soon as the lab was open. Table 6 contains the parameters and methods used by the LCRA lab for analyzing the samples.

Table 6: Parameters and Methods for Analysis

Parameter	Units	Method	Practical Quantification Limit
Total Suspended Solids	mg/L	E160.2	1.0
Total Kjeldahl Nitrogen (TKN)	mg/L	E351.2	0.40
Nitrate and Nitrite as N (NO_3^+/NO_2)	mg/L	E353.2	0.04
Total Phosphate as P	mg/L	E365.4	0.02
Dissolved Phosphate as P	mg/L	E365.4	0.02
Chemical Oxygen Demand (COD)	mg/L	E4104.4	70
Total Copper (Cu)	µg/L	E200.8	2.00
Dissolved Copper	µg/L	E200.8	1.02
Total Lead (Pb)	µg/L	E200.8	1.00
Dissolved Lead	µg/L	E200.8	1.02
Total Zinc (Zn)	µg/L	E200.8	5.00
Dissolved Zinc	µg/L	E200.8	4.08

The Practical Quantification Limit represents the minimal limit at which concentrations can be accurately quantified. Concentrations less than these amounts are said to be "Not Detected" (ND).

3.7 Statistical Methods

Laboratory results were compiled using Microsoft Excel. Various environmental factors and event specific data were collected for each data point. The following variables were quantified: age of pavement, event rainfall amount, storm duration, average intensity, cumulative rainfall at site, time of storm, day of week, season, antecedent dry period, volume of event, traffic counts during rainfall, and peak runoff. Most of these parameters were derived from the hydrograph produced at the research site which will be discussed in detail later.

The Data Toolpack in Excel was used to do a linear regression analysis on the set of data to gain an initial basic understanding. More in depth investigation took place with the use of Minitab Statistical Software to perform forward, backward, and stepwise linear regression. The basis for removal or acceptance, depending on the type of regression, was taken to be an alpha value of 0.20.

A few data points were removed while creating this model. Data points that were removed were done so on a basis of inconsistent data (inaccurate flow or rainfall measurements) or outlier data that could be explained. Causes of outlier points include problems with the physical site such as an ant hill spilling into the box.

Chapter 4 Results

4.1 Rainfall Data

A total of 11 rain events were sampled from April 2008 to July 2009. The automatic sampler at Site 1 has sampled 26 storms in total. Since the installation of passive samplers at Site 3, five rain events have been sampled. For Site 2, five samples were analyzed for particle size distributions. Table 7 summarizes the 11 rain events from which samples were gathered. Note that the rainfall and runoff values for Site 3 are unknown.

Table 7: Summary of sampled storm events

Storm Date	Rainfall (in.)	Runoff (L)	Sample Location
4/18/2008	0.95*	-	1
8/6/2008	0.25*	-	1
10/15/2008	1.35	3828	1
11/12/2008	0.44	-	2
1/6/2009	0.43	1934	1,2
2/9/2009	0.93	2940	1,2,3
3/13/2009	2.04*	5524	1,3
3/26/2009	-	-	3
4/12/2009	0.35	1246	1,3
6/11/2009	1.23	3191	1,2,3
7/1/2009	0.79	2128	1, 2

*Denotes USGS rain gauge values (LCRA, 2009)
- Data missing or unavailable

4.2 Site 1 Results

Monitoring of water quality at this site began in March 2004 prior to the construction of PFC. Twenty-one storms were monitored using the GKY FirstFlush sampling system before the installation of the automatic sampler in December 2006. A total of 47 storms have been sampled since the construction of PFC. The results of the sampling prior to the installation of the automatic sampler can be found in Barrett and Shaw (2007). These results are also included in the graphs evaluating the relationship between concentration and time.

The concentrations of pollutants from the 26 storms since the installation of the automatic sampler are found in Table 8. Dates marked with an asterisk (*) indicate the samples are taken from Stanard et al. (2008). Concentrations below the detectable limit are labeled as less than the detection limit (i.e., <1).

Table 8: Results from Site 1

Date	TSS (mg/L)	TKN (mg/L)	NO2/NO3 (mg/L)	P_{total} (mg/L)	$P_{dissolved}$ (mg/L)	COD (mg/L)	Cu_{Total} (µg/L)	Pb_{Total} (µg/L)	Zn_{Total} (µg/L)	Cu_{Diss} (µg/L)	Pb_{Diss} (µg/L)	Zn_{Diss} (µg/L)
1/13/07*	11	0.163	0.08	< 0.02	< 0.02	30	5.89	< 1	11.8	3.47	< 1	9.63
1/14/07*	2	1.18	0.26	< 0.02	< 0.02	63	5.49	< 1	25.8	4.40	< 1	23.20
3/11/07*	11	0.434	0.25	< 0.02	< 0.02	42	11.20	1.01	27.4	8.31	< 1	18.90
3/13/07*	4	0.261	0.05	< 0.02	< 0.02	32	6.60	1.17	17.8	4.46	< 1	12.90
3/26/07*	2	5.45	0.14	0.052	< 0.02	25	8.53	< 1	20.9	7.06	< 1	16.40
3/30/07*	8	0.692	0.1	0.063	< 0.02	49	12.50	1.45	28.1	8.03	< 1	17.90
4/25/07*	3	0.462	0.52	0.074	0.045	61	15.30	< 1	15.9	11.50	< 1	11.50
4/30/07*	8	0.555	0.32	0.055	< 0.02	80	17.60	< 1	22.0	12.50	< 1	18.20
5/3/07*	6	0.39	0.18	0.024	< 0.02	23	7.51	< 1	8.09	5.01	< 1	6.17
5/16/07*	2	1.29	0.72	0.069	0.03	86	17.80	< 1	13.4	16.10	< 1	17.20
5/24/07*	4	0.482	0.12	< 0.02	< 0.02	57	10.20	< 1	24.9	8.40	< 1	12.70
6/4/07*	8	0.479	0.21	0.038	< 0.02	35	8.96	< 1	10.5	5.95	< 1	5.44
7/20/07*	13	0.114	0.03	0.062	< 0.02	37	7.45	< 1	18.7	4.05	< 1	8.02
11/26/07*	3	0.586	0.43	0.064	0.046	66	14.20	< 1	14.8	12.50	< 1	9.72
12/12/07*	10	0.865	0.28	< 0.02	< 0.02	42	14.40	1.33	19.4	10.40	< 1	8.31
3/3/08*	7	1.37	0.97	0.053	0.042	93	20.90	< 1	21.2	17.80	< 1	12.00
3/18/08*	29.0	0.791	0.22	< 0.02	0.052	50	16.7	1.42	35.2	8.39	< 1	6.9
4/18/08	23.3	1.22	0.26	< 0.02	0.092	72	16.1	1.32	23.1	11.8	< 1	11.7
8/6/08	2.0	1.83	0.79	0.028	0.113	166	35.4	< 1	20.1	34.6	< 1	13.4
10/15/08	4.0	0.422	0.07	0.023	< 0.02	54	10.7	< 1	15.9	7.75	< 1	6.91
1/6/09	2.4	0.526	0.32	0.032	0.033	40	11.2	< 1	9.16	8.82	< 1	< 4.08
2/9/09	4.2	0.755	0.37	< 0.02	0.148	55	13.9	< 1	10.7	13.5	< 1	6.27
3/13/09	3.2	0.795	0.4	0.021	0.043	46	8.93	< 1	10.3	8.54	< 1	7.49
4/12/09	8.4	1.33	0.79	0.03	0.052	85	22.3	< 1	12.7	16.3	< 1	7.09

Table 8, continued

Date	TSS (mg/L)	TKN (mg/L)	NO2/NO3 (mg/L)	P_{total} (mg/L)	$P_{dissolved}$ (mg/L)	COD (mg/L)	Cu_{Total} (µg/L)	Pb_{Total} (µg/L)	Zn_{Total} (µg/L)	$Cu_{Dissolved}$ (µg/L)	$Pb_{Dissolved}$ (µg/L)	$Zn_{Dissolved}$ (µg/L)
6/11/2009	23.3	4.51	0.07	0.034	0.273	75	20.3	< 1	27.8	10.3	< 1	12
7/1/2009	8.7	0.916	0.35	< 0.02	0.052	74	17.1	< 1	12	14.1	< 1	8.4

*- Results reported in Stanard et al. (2008)

The mean concentrations, percent reduction, and corresponding p-values for Site 1 are found in Table 9. The Conventional Asphalt concentrations are the results obtained prior to the installation of PFC. The most significant reductions are found in TSS and total copper, lead, and zinc. Only dissolved copper showed a statistically significant increase in concentration.

Table 9: Comparison of Conventional and PFC for Site 1

Constituent	Conventional Asphalt	PFC	Reduction %	p-values
TSS (mg/L)	117.8	8.93	92	0.016
TKN (mg/L)	1.13	1.09	4	0.845
NO_3^+/NO_2 (mg/L)	0.43	0.39	9	0.883
Total P (mg/L)	0.13	0.08	38	0.097
Dissolved P (mg/L)	0.06	0.06	4	0.921
COD (mg/L)	64	62.15	3	0.886
Total Copper (μg/L)	26.84	13.89	48	0.008
Dissolved Copper (μg/L)	5.94	10.74	-81	0.044
Total Lead (μg/L)	12.57	1.48	88	0.028
Dissolved Lead (μg/L)	< 1.0	< 1.0	NA	NA
Total Zinc (μg/L)	167.4	28.52	83	0.002
Dissolved Zinc (μg/L)	47.06	21.18	55	0.138

The changes of concentration over time are of interest. A graph of TSS concentration is presented in Figure 11. The first five events were samples taken from conventional pavement. Overall, there is a 92% reduction in TSS concentration in runoff from PFC as compared to conventional hot mix asphalt.

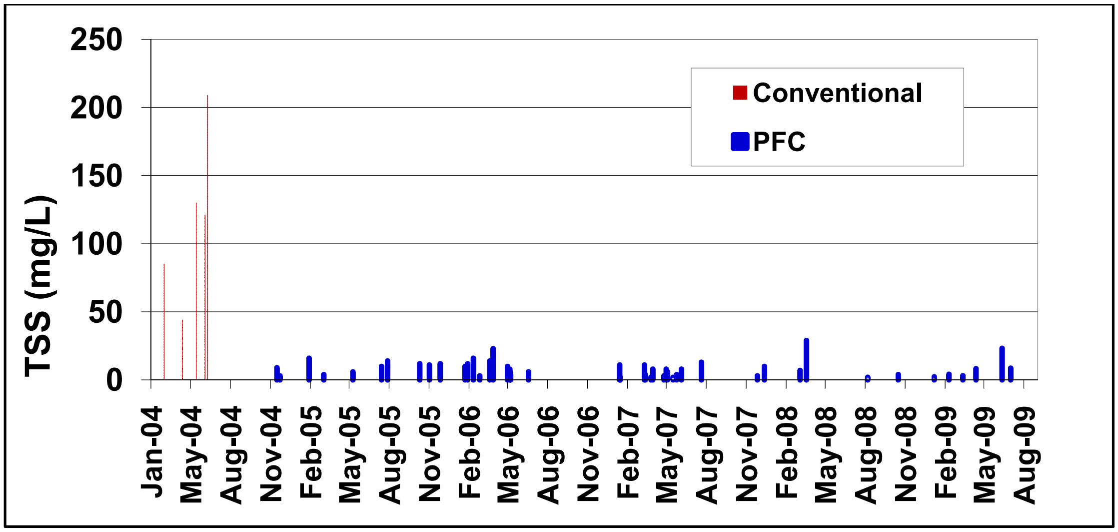


Figure 11: TSS concentrations over time

As another example, the concentration of zinc is shown in Figure 12. Total zinc concentrations of runoff from PFC were reduced by 83%. Concentration versus time graphs for each individual constituent are found in Appendix A.

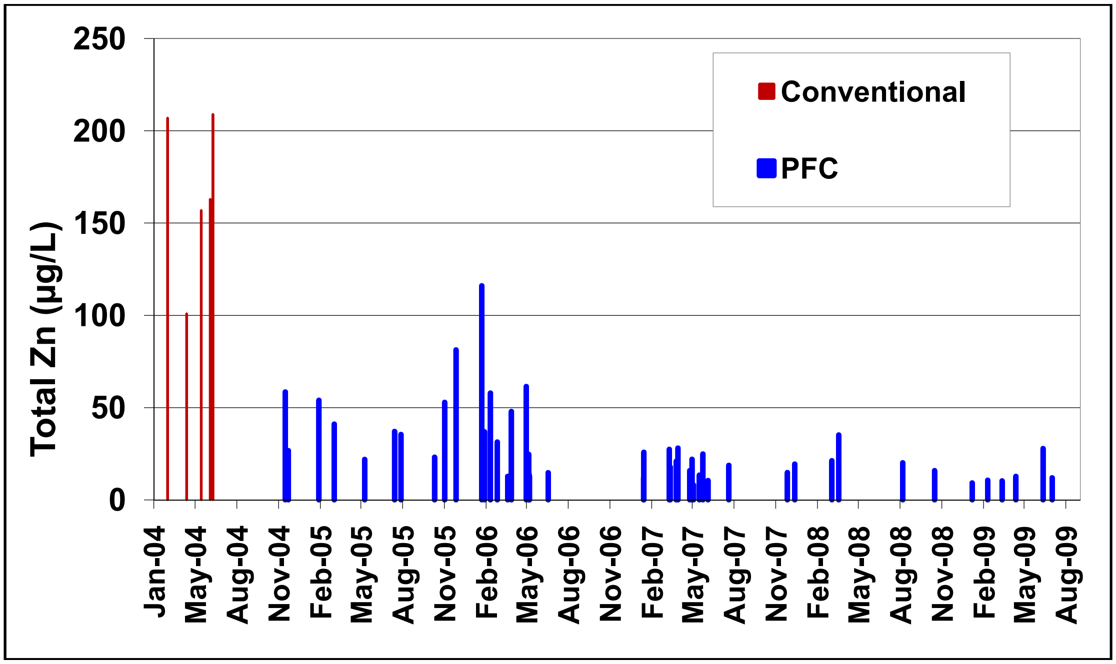


Figure 12: Total Zinc concentrations over time

The relationship between performance and age is very important. Extending the research and gathering more samples provides further insight into the relationship between time and quality. As reported in the literature review, Stanard et al. (2008) predicted it would take 1.4 years from March 2008 for total copper in runoff from PFC to reach that of conventional pavement. With the addition of nine samples since March 2008, an extended graph is created. Figure 13 contains the updated information and reveals that total copper concentrations is less sensitive to time than previously estimated. A comparison of the slopes reveals that concentrations are not increasing as rapidly. The p-value of the slope for the regression of total copper is 0.016. The new regression line indicates that it will take 2.8 years from the last sample to reach a value of 29.4 μg/L. The time for TSS concentrations to approach 118 mg/L was 18 years as reported by Stanard et al. (2008). The significance of the updated slope for the regression on TSS is 0.373. This reveals that TSS concentrations are relatively constant and are not changing with time. While these results tell us that the inclusion of more data reveals greater insight into the lifespan of data, the estimation of water quality based on age of pavement severely over predicts the life of the pavement. A more rigorous statistical analysis of the impacts of water quality is found in Section 4.5 Regression Analysis.

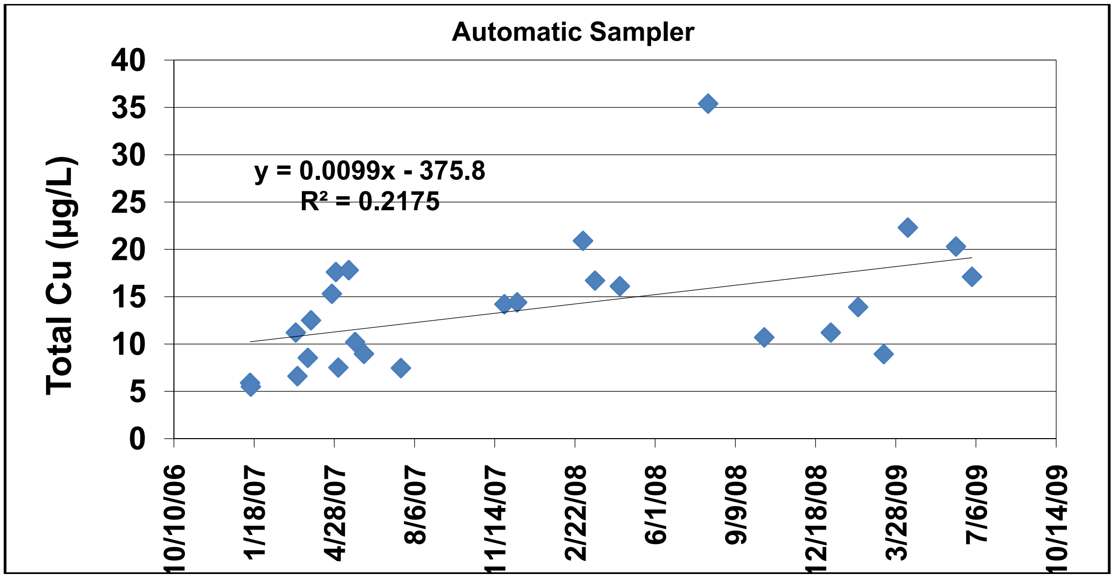


Figure 13: Total Cu versus time

4.3 Site 2 Results

The samples were taken from Site 2 from the fall 2008 to the summer of 2009. A total of six paired samples were shipped to the University of Alabama. The samples were analyzed for particle size distributions (PSD) in order to gain more insight in the differences in the two pavements.

A primary goal of the PSD analysis is to determine what particle size range comprises a majority of the total mass. For the purposes of this research an upper limit of 75 µm is established. The decision to place an upper limit is based on findings that pollutants are correlated to very fine particles. Also, larger particles are more likely to settle and thus have lower potential for pollutant transport. Table 10 reveals that the majority of TSS from PFC runoff is comprised of particles ranging from 0.45-3 µm. For HMA, the majority of mass is comprised of particles ranging from 12-30 µm. The average mass contribution from 12-30 µm particles for PFC is 15.9%. As previously stated in the literature review, metals have shown an affinity for particles ranging from 8-20 µm and nutrients have shown to range from 11-53 µm.

Table 10: Average percent mass by size range

	average % of mass		% finer	
Particle Size (µm)	PFC	HMA	PFC	HMA
< 0.45	0.0	0.0	0.0	0.0
0.45 < x < 3	30.8	6.1	32.5	5.3
3< x < 12	23.5	25.1	54.3	28.9
12< x < 30	16.0	37.4	70.2	68.4
30< x < 60	24.2	26.0	94.1	94.6
60< x < 75	5.6	5.4	100.0	100.0

The differences in specific size ranges between PFC and HMA is also valuable. The results found in Table 11 indicate that the largest reduction in concentration is found in the size range 12-30 µm. Figure 14 is the graphical representation of the data in Table 11. The overall reduction of TSS is similar to that found at other sites at an average total reduction of 89.6%. Detailed graphs of the particle size distribution can be found in Appendix B- Particle Size Distributions.

Table 11: Comparison of average concentrations by size range

Particle Size (µm)	PFC (mg/L)	Conventional (mg/L)	% Reduction	pvalue
0.45 < x < 3	2.08	3.86	46.3%	0.5309
3< x < 12	1.62	19.86	91.8%	0.0367
12< x < 30	1.16	27.03	95.7%	0.0216
30< x < 60	2.75	16.06	82.9%	0.0367
60< x < 75	0.61	2.41	74.8%	0.0367

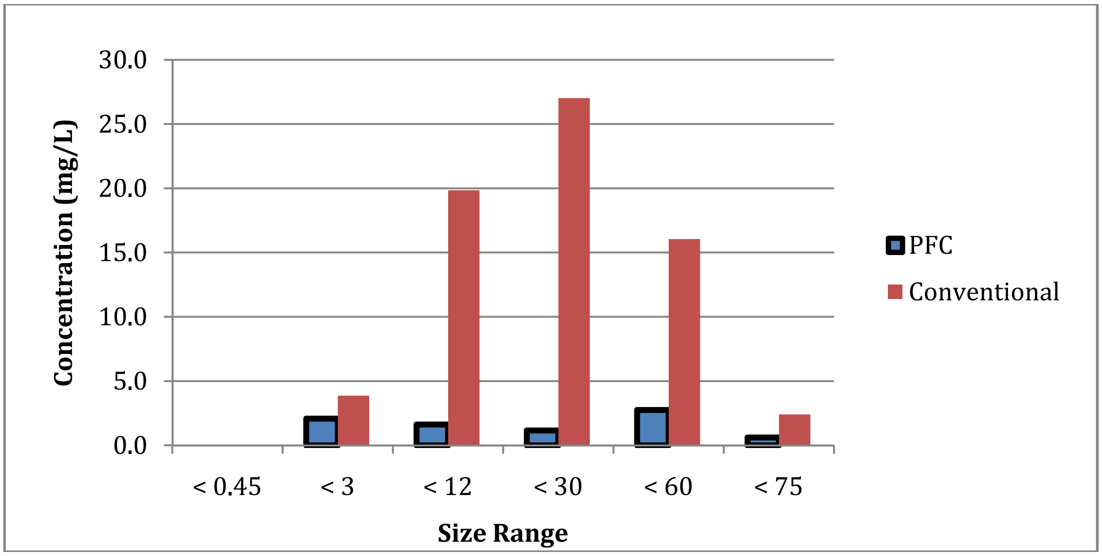


Figure 14: Comparison of average concentrations by size range

Particle size distributions can also be analyzed by the number of particles in each size range. All particles were assumed to have a density of 2.65 g/cm^2. Particles were estimated to have a spherical shape with a radius half of the particle size. The midpoint of each size range was used in the calculation of particle counts (i.e.; 1.5 μm radius for all particles between 0.45 and 3 μm in diameter). Using the average density, an estimate of the mass of a single particle was calculated. The average concentration allows for the calculation of number of particles per liter of runoff. The results are presented in Figure 15. The percent reduction is unchanged from the mass concentration comparison, as expected, but this alternative calculation provides further information.

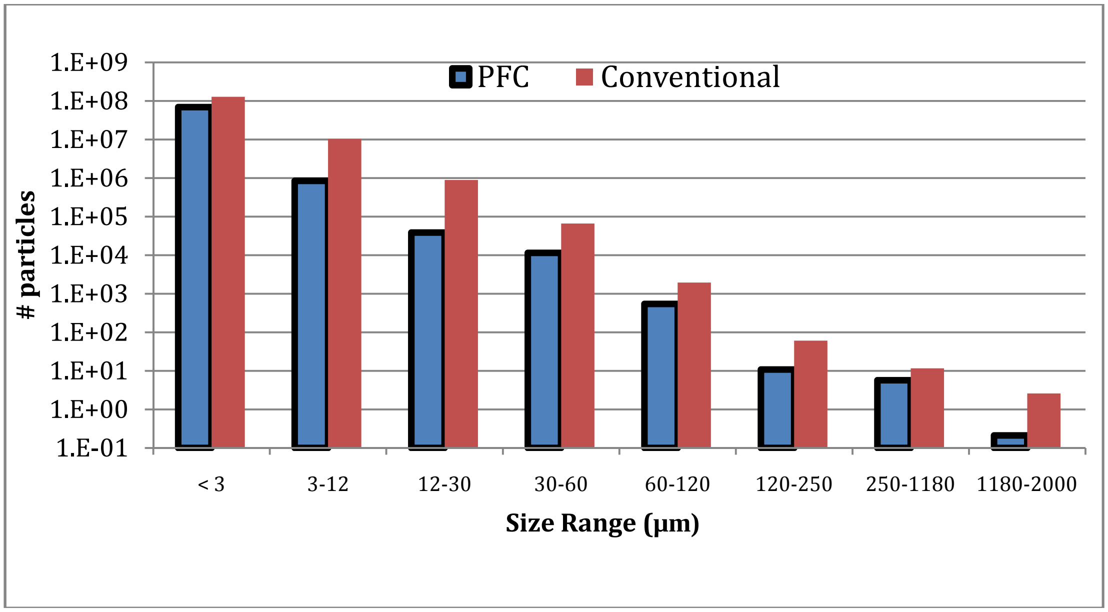


Figure 15: Number of particles within each size range

The results support the findings reported in the literature review that while the mass contribution of the fine particles is small, they comprise a majority of the particles in the runoff. About 92% of the particles in runoff from conventional pavement have a diameter of less than 3 μm while 98.6% of the particles in PFC derived runoff have diameters of less than 3 μm. In comparison, 16.3% and 15.6% of the mass is contributed from particles less than 12 μm for PFC and HMA, respectively. In regards to metal and nutrient sorption, the average total surface area of all particles was calculated. The total surface area of particles with diameters less than 75 μm for PFC runoff is 17.9 cm^2/L compared to 375 cm^2/L for HMA.

These results allow the comparison of current treatment practices to the use of PFC. Kim and Sansalone (2008) evaluated hydrodynamic separation as a treatment option for stormwater. The process is more efficient for larger particles, however, the results showed an average removal efficiency of 16.7% for particles ranging from 25 to 75 μm. The process had a negligible impact on particles between 1-25 μm. Li et al. (2006) examined the treatment capabilities of using a two-compartment settling tank. The most efficient treatment design provided a 45% reduction in particle sizes 2-10 μm. Kang et al. (2007) evaluated the ability to treat stormwater by means of coagulation-flocculation in a sedimentation column. The results showed a 90% reduction in the number of particles less than 30 μm. These comparisons show that PFC, which removes roughly 90% of particles, performs at least as well as some current treatment options.

4.4 Site 3 Results

The results from Site 3 allow a comparison to be made between conventional HMA and PFC pavements. The results also provide insight into the relationship between hydraulic conductivity and quality. In 2009, core samples were taken from RR 620 and Loop 360. The cores were tested for hydraulic conductivity and porosity. The average porosity for RR 620 was found to be 15% while Loop 360 was found to be 19% (Charbeneau, 2009). The null hypothesis for the Mann-Whitney Test is that the hydraulic conductivities of the two sites are the same. It was determined that the null hypothesis is to be rejected and the two samples are significantly different. The differences in hydraulic conductivity could be used to explain any differences in the runoff pollutant concentration. The results from five storms sampled from February to June 2009 are found in Table 12.

Table 12: Results from Site 3

Date	*Surface*	*TSS*	*TKN*	*NO2/NO3*	P_{Total}	$P_{dissolved}$	*COD*	Cu_{Total}	Pb_{Total}	Zn_{Total}	$Cu_{Dissolved}$	$Pb_{Dissolved}$	$Zn_{Dissolved}$
		(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(mg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)	(µg/L)
2/9/2009	HMA	31.2	0.757	0.14	0.034	0.063	38	8.07	4.45	43.1	5.14	ND	5.76
3/12/2009	HMA	85.2	5.25	1.69	0.03	0.163	245	43.3	14	217	28.1	ND	86.4
3/26/2009	HMA	186	1.98	0.24	ND	0.215	70	25.8	23.7	161	6.99	1.1	21.8
4/12/2009	HMA	146	1.62	0.3	0.037	0.177	82	20.4	25.4	176	5.42	ND	14.2
6/12/2009	HMA	574	2.91	0.17	0.022	0.532	109	24.8	29.4	185	6.03	ND	7.07
2/9/2009	PFC	3.7	0.708	0.23	0.04	0.052	39	7.53	ND	19.4	7.25	ND	19.4
3/12/2009	PFC	5.2	0.533	0.44	ND	0.029	23	7.34	ND	34.6	4.82	ND	18.1
3/26/2009	PFC	36	0.943	0.35	ND	0.076	52	14.1	3.07	54.8	5.78	ND	12.3
4/12/2009	PFC	48	0.9	0.3	ND	0.065	41	10.7	1.67	9.14	5.44	ND	9.14
6/12/2009	PFC	9	1.65	0.36	0.03	0.1	58	14.7	ND	31	10	ND	17.9

Site 3 was chosen based on the results of porosity and permeability tests. Nearby construction sites caused heavier vehicles to frequently use the road, leaving debris along the way. These activities caused an overall increase in TSS concentration. Due to the small data set, median concentrations are reported in Table 13.

Table 13: Comparison from Site 3

Constituent	HMA	PFC	Reduction %	p-values
TSS (mg/L)	146	9	-94%	0.037
TKN (mg/L)	1.98	0.9	-55%	0.095
NO_3^+/NO_2 (mg/L)	0.24	0.35	46%	0.346
Total P (mg/L)	0.177	0.065	-63%	0.06
Dissolved P (mg/L)	0.032	0.035	9%	0.53
COD (mg/L)	82	42	-49%	0.095
Total Copper (µg/L)	24.8	10.7	-57%	0.06
Dissolved Copper (µg/L)	6.03	5.78	-4%	1
Total Lead (µg/L)	23.7	2.37	-90%	0.022
Dissolved Lead (µg/L)	1.1	< 1.0	NA	NA
Total Zinc (µg/L)	176	31	-82%	0.004
Dissolved Zinc (µg/L)	14.2	17.9	26%	1

The Wilcoxon Sign Rank test was used to determine if the concentrations of pollutants could be considered significantly different. The results show that all conventional pavement and PFC at RR 620 are significantly different except for nitrates/nitrites, dissolved phosphorus, and dissolved metals (copper, lead, and zinc).

While the concentration of pollutants is higher for PFC the overall reduction is similar to that of Loop 360. Table 14 compares the median concentrations of pollutants for passive samplers at Site 2 as reported by Stanard (2008) to the Site 3 concentrations. The increase in concentrations between PFC and HMA is not proportional. The last column in the table shows that the pollutant reduction is similar at both locations.

Table 14: Comparison of Loop 360 Passive Samplers to RR 620

Constituent	Site 2 PFC	Site 3 PFC	Increase %	Site 2 HMA	Site 3 HMA	Increase %	Reduction %	
							Site 3	Site 2
TSS (mg/L)	12.5	9	-28%	131.5	146	11%	-94%	-90%
TKN (mg/L)	0.49	0.9	84%	0.9	1.98	120%	-55%	-46%
NO_3^+/NO_2 (mg/L)	0.21	0.35	67%	0.16	0.24	50%	46%	31%
Total P (mg/L)	0.05	0.07	30%	0.11	0.177	61%	-63%	-55%
Dissolved P (mg/L)	0.02	0.03	75%	0.02	0.032	60%	9%	0%
COD (mg/L)	59.0	42	-29%	70	82	17%	-49%	-16%
Total Cu (µg/L)	11.4	10.7	-6%	28.4	24.8	-13%	-57%	-60%
Dissolved Cu (µg/L)	8.2	5.8	-30%	4.99	6.03	21%	-4%	65%
Total Pb (µg/L)	1.77	2.37	34%	10.2	23.7	132%	-90%	-83%
Dissolved Pb (µg/L)	<1.0	< 1.0	NA	1.09	1.1	1%	NA	NA
Total Zn (µg/L)	19.6	31	58%	134	176	31%	-82%	-85%
Dissolved Zn (µg/L)	10.3	17.9	74%	11.3	14.2	26%	26%	-9%

The same analysis using the average concentrations yields different percent changes but results in the same conclusion. Site 3 demonstrates that PFC continues to provide improved water quality despite the reduction in hydraulic conductivity. Further monitoring is required to determine an estimate of hydraulic conductivity that represents PFC failure.

4.5 Regression Analysis

There are multiple environmental factors that cause water quality to be different for each event. Understanding what causes these differences will help to further predict future water quality. For these reasons, a multiple linear regression model was developed to determine what factors were statistically significant in impacting water quality.

4.5.1 Model Development

The goal of the regression analysis was to develop a model to predict the TSS and metal concentration of stormwater runoff from PFC. The model was developed using multiple linear regression (MLR). MLR models go further than simple linear regression model by claiming that the dependent variable, Y, is dependent upon multiple independent variables, i.e. $Y= \beta + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 \ldots \beta_n X_n$. Including more possible explanations (X_n) for variations in Y will improve the model but the goal is to best accurately describe the phenomenon with the fewest number of independent variables. Thus, there is a tradeoff between model size and model accuracy.

The majority of data used in the model was gathered from the hydrograph and hyetograph recorded by the ISCO sampling system. From these graphs the following data were collected: storm rain amount (in.), peak flow rate (L/s), storm intensity (in./5 minutes), time of day, and day of the week and month, storm duration. Variables also included in the model were age of the pavement, antecedent dry period, cumulative rainfall at the site, and traffic counts during the storm. The Lower Colorado River Authority monitors rainfall at Bull Creek and Loop 360. Historical rainfall data was used to calculate antecedent dry period (days) and cumulative rainfall (in.). Only data that occurred during sampling was taken into consideration. For example, if sampling ended before the storm, the rainfall amount was scaled back to the amount that occurred during sampling. An example of the hydrograph and hyetograph is found in Figure 16.

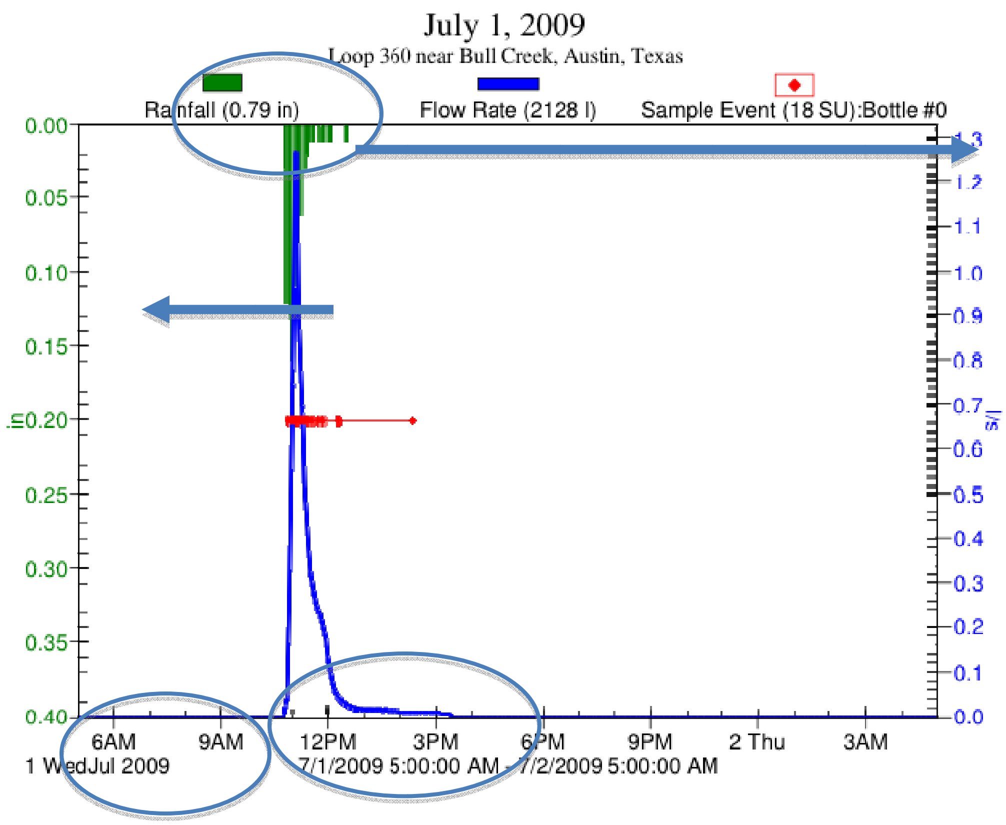


Figure 16: Data from hydrograph and hyetograph

Traffic counts were developed by combining two sets of data. GRAM Traffic Counting, Inc. conducted a study in 2007 of traffic counts during an average weekday on Loop 360. While the exact location of the traffic counts was approximately 5 miles south of Site 1, the counts were assumed to be the same. A study of traffic along Mopac Expressway was compared to that of Loop 360. The weekday counts of Loop 360 were found to follow the same hourly trends of Mopac Expressway. Weekend traffic counts for Loop 360 are unknown and were obtained by scaling the Mopac Expressway weekend data. Figure 17 shows the relationship between hourly traffic counts of Loop 360 and Mopac Expressway.

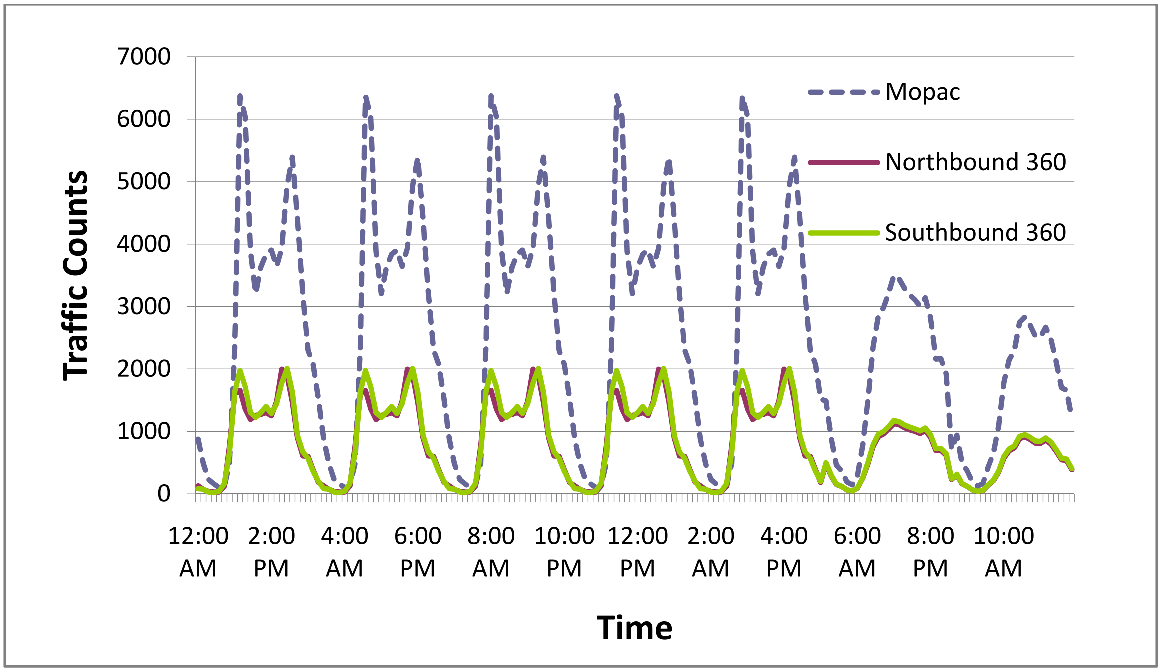


Figure 17: Traffic counts for Mopac Expressway and Loop 360

Irish et al. (1995) reported a difference in pollutant concentrations depending on the presence of traffic during the simulation. The importance of traffic was evaluated by first including the estimated traffic counts in the data and then by including the log of the traffic counts. The hypothesis being that there is an exponential relationship between quality and traffic; there is little difference between 800 vehicles in a storm and 3000, but a large difference between 500 and 800.

Brodie (2007) studied the relationship between suspended particle load and rainfall intensity. It was discovered that the modification of average rainfall intensity to the square of intensity improved the correlation. It has been postulated that the square of intensity is a measure of the total kinetic energy and thus, the total potential for disturbance of sediments. For these reasons, the square of average intensity was used in the multiple linear regression.

A major criterion of multiple linear regression is that the independent variables be completely independent and not correlated to each other. Upon further inspection it was determined that a few of the chosen variables were correlated. Pavement age and cumulative rainfall at the site are heavily correlated. Also, peak runoff rate is correlated with the peak rainfall intensity. And finally, average intensity is dependent on the event rainfall amount. The variables were analyzed and the variables with higher p-values were removed from the model. There are slight differences in variables between automatic and passive samplers based on the p-values. The final variables used in the model were: pavement age, antecedent dry period, event rain amount, peak flow rate (intensity squared for passive samplers), and the base log of the traffic counts.

4.5.2 Results

The choice of model parameters was influenced by past studies of the factors affecting stormwater quality runoff from conventional pavement. For this reason, conventional pavement was analyzed first in order to determine the strength of data and develop a basis for comparison. The TSS concentrations from the passive sampler located adjacent to the conventional pavement at Loop 360 were analyzed using storm data collected by the ISCO equipment located a short distance away. Due to variability in lab measurements and other sampling procedures (measurements themselves are said to be only 95% accurate) the data set was analyzed at a significance level of α=0.20. The equation resulting from backward elimination regression is:

$$TSS\left(\frac{mg}{L}\right) = -565.2 + 4.8ADP + 0.43AGE + 88Log\,Traffic \quad R^2 = 55.07\; S_e = 82.05\; F = 3.27$$

(-1.89) (1.57) (2.32) (1.93)

The numbers in parenthesis are the t-statistics associated with the coefficient for each variable. Figure 18 shows the relationship between modeled and observed data for conventional pavement. The straight line represents a perfect model.

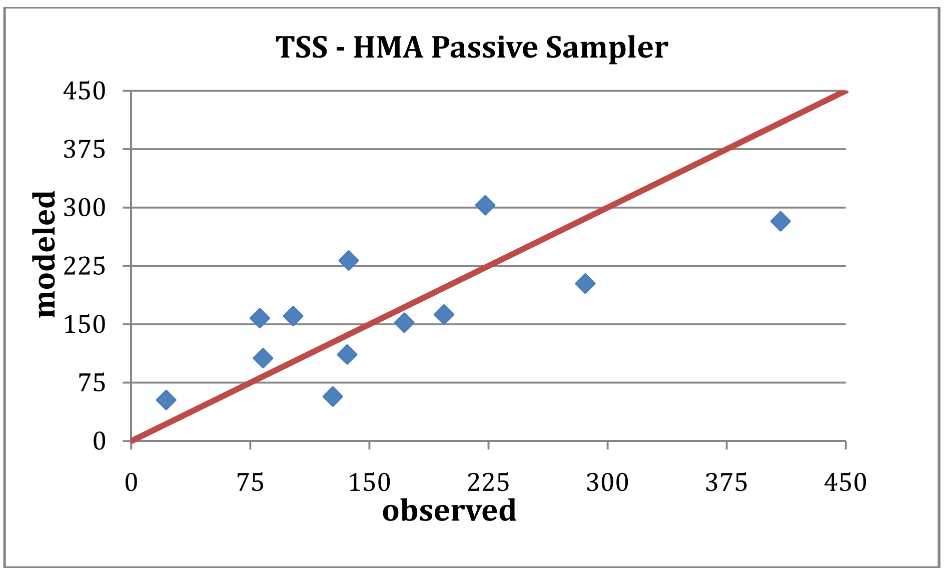


Figure 18: Modeled versus observed data for conventional pavement

The process was repeated for Site 1 PFC data collected by the active sampler site on Loop 360. Again, the stepwise regression was run at a significance level of α=0.20. The following results were obtained.

$$TSS(\frac{mg}{L}) = \underset{(0.321)}{0.619} + \underset{(1.53)}{0.135 ADP} + \underset{(5.59)}{4.47\ Peak\ Runoff} \quad R^2 = 67.77\ S_e = 4.48\ F = 15.8$$

Figure 19 shows the relationship between the results of the model and the observed data for PFC.

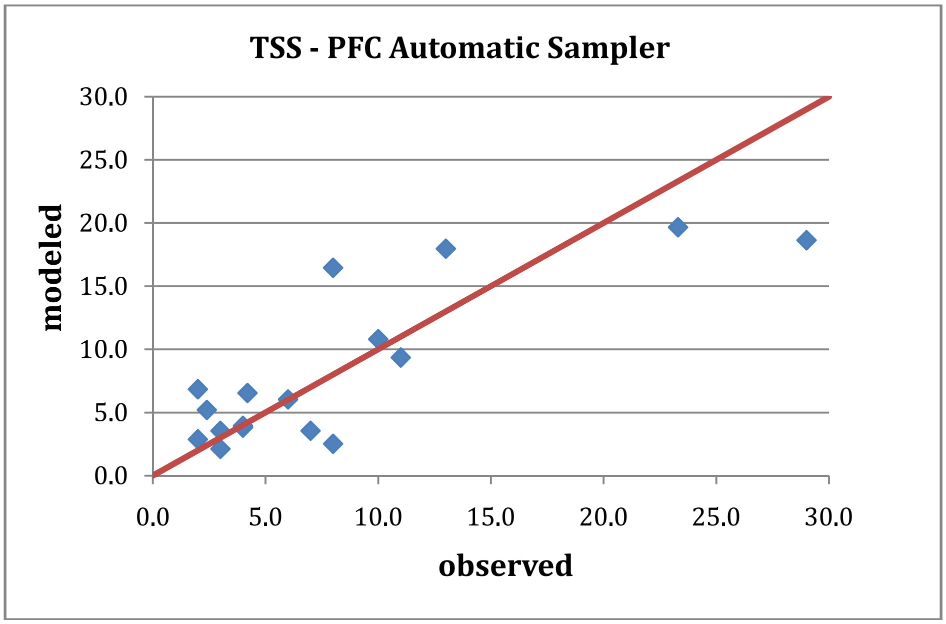


Figure 19: Modeled versus observed data for PFC automatic sampler

The process was repeated for the PFC passive sampler. The results were expected to be similar to that of the automatic sampler but were not. Figure 20 shows the relationship between the results of the model and the observed data for PFC. The significance level was set to be α=0.15 and regression equation is:

$$TSS(\frac{mg}{L}) = \underset{(0.341)}{1.45} + \underset{(1.72)}{0.516 ADP} + \underset{(2.2)}{9.19 Rain\ Depth} \quad R^2 = 56.41\ S_e = 4.4\ \ F = 4.63$$

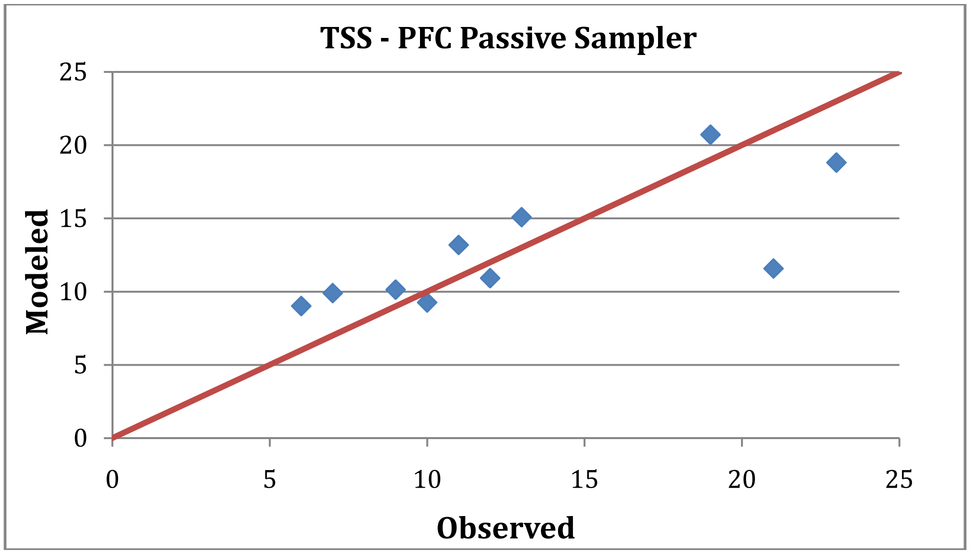


Figure 20: Modeled versus observed data for PFC passive sampler

The differences between the two PFC relationships can best be explained by the first flush phenomenon. While the automatic sampler takes aliquots throughout the duration of the storm, the passive sample collects the first three liters. It is very possible that the passive samplers were filled with water before the peak runoff rate was reached. Also, for all three constituents at the automatic sampler, the coefficient on the rain depth variable is negative. These results follow the theory that there is a fixed amount of pollutants available for mobilization during a storm and a larger storm volume allows for dilution to occur. The total load of pollutants may be the same for two storms but volume increases cause an overall dilution. The passive samplers would not be affected by changes in rain depth. A student's t-test reveals that the TSS data collected from the passive sampler and automatic samplers for PFC are not homogenous. The results of the t-test are found in Table 15. With the null hypothesis that the two data sets can be grouped together, the low p-values indicate that we can reject the null hypothesis.

Table 15: Testing for homogeneity between sampling systems

t-Test: Two-Sample Assuming Unequal Variances		
	PFC auto	*PFC Passive*
Mean	5.9	13.1
Variance	14.1	34.99
Observations	10	10
Hypothesized Mean Difference	0	
df	15	
t Stat	-3.24968	
P(T<=t) one-tail	0.002693	
t Critical one-tail	1.75305	
P(T<=t) two-tail	0.005387	
t Critical two-tail	2.13145	

The regression was again run using the total particulate copper and zinc concentrations for the PFC at Site 1. Interestingly, the results reveal a strong correlation between traffic counts and metals. For example purposes we will evaluate the automatic sampler. The regression equation for total particulate zinc (total – dissolved) at α=0.15 is:

$$Zinc\ \left(\frac{\mu g}{L}\right) = -13.33 + 3.29 PeakRunoff + 5.26 Log\ Traffic \quad R^2 = 54.65\ S_e = 4.99\ \ F = 8.44$$

(-1.7) (3.65) (2.24)

Table 16 compares each pavement type, independent variables, and the variables affecting pollutant concentration.

Table 16: Variable affecting pollutant concentration

Pavement and Sampler Type	Pollutant	Pavement Age (days)	Rain Depth (in.)	Log Traffic Counts	Antecedent Dry Period (days)	Peak Runoff Rate (L/s)	Peak Rainfall Rate Squared (in./5min)^2
HMA Passive Sampler	TSS	0.43		88	4.8		
	Zinc	0.254		73	2.37		-915
	Copper			16.7			
PFC Automatic Sampler	TSS				0.134	4.45	
	Zinc			5.4		3.26	
	Copper					1.13	
PFC Passive Sampler	TSS		8.2		0.54		
	Zinc			6.1			
	Copper		-2.7	1.74	0.153		

The conclusions of the regression analysis can be summarized as follows:

- Passive samplers are affected largely by their inability to fully sample large storms and, consequently, the samples tend to have higher concentrations than the automatic samplers.
- Antecedent dry period negatively impacts stormwater quality.
- Except copper for the PFC automatic sampler, all metal concentrations, are directly related to the number of vehicles that pass during the event. These results support the hypothesis that motor vehicles are an important source of metal contamination of stormwater.
- Unlike conventional pavement, TSS concentrations in PFC are not impacted by traffic counts. It is possible that PFC captures a majority of the particles generated from vehicles or that it prevents the generation of pollutants by eliminating the splash and spray effect and thus, traffic counts do not affect TSS concentration.

- The log of traffic counts is statistically significant while regular traffic counts are not. These results support the belief that the first *N* vehicles have a greater impact than vehicles that arrive at a later time. That is, a curve of traffic counts and water quality would have the shape of the curve found in Figure 21.

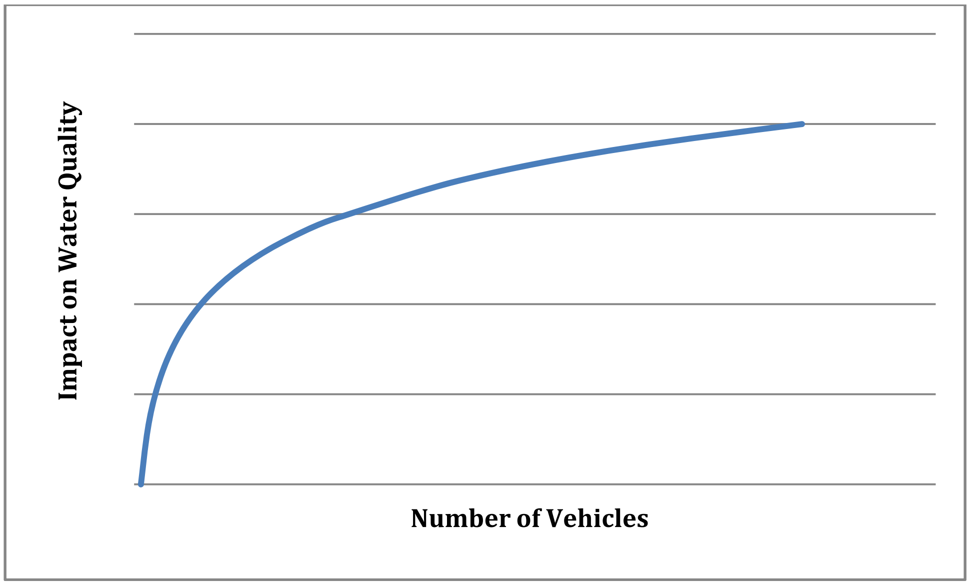


Figure 21: Theoretical relationship between traffic counts and water quality

Chapter 5 Conclusions

Porous asphalt overlays are proving to be a versatile new development. The ability to provide safer driving conditions in wet weather by eliminating the splash and spray effect and the prevention of hydroplaning promise many safety benefits. The added benefit of improved water quality is becoming better understood.

A common concern of PFC is the lifespan of the water quality benefits. Site 1 at Loop 360 has been monitored for over 5 years, including 6 months prior to the installation of PFC. The runoff from conventional pavement and PFC were compared. The results show a drastic improvement due to the installation of PFC. TSS concentrations were reduced by 92% while copper, lead, and zinc were reduced 48%, 88%, and 83% respectively. Results do not indicate any trends toward a decline in water quality.

Site 2 provided paired samples for the analysis of particle size distribution. Past research studies document a strong correlation between fine particles and pollutant concentration. PSD results show that PFC removes many of the particles in the size range 3-60 μm.

Site 3 provided insight into the water quality of runoff from a location where lab and field tests indicate a lower hydraulic conductivity. The results also showed a significant reduction in TSS and total metal concentrations. Interestingly, while the runoff from conventional pavement was more polluted than Site 2, the runoff from PFC remained relatively unchanged between the two sites. If decrease in hydraulic conductivity is to be an indicator of failure, Site 3 has yet to approach such a threshold. Further monitoring of hydraulic conductivity as well as water quality should be conducted in order to observe failure.

Multiple linear regression analysis was used to evaluate the variables that affect water quality. Regression equations were developed for TSS, particulate copper and particulate zinc concentrations for Site 1 and Site 2. Antecedent dry period and the log of traffic counts tend to be the two largest factors in affecting water quality. Automatic samplers capture the effect of the peak flow rate that results from runoff. Passive samplers are not affected by runoff rate due to its limited container volume.

The end of life of the pavement is still yet to be determined. Site 1 shows no indication of deterioration and should be monitored further to observe any changes. Site 3 has too few samples to draw any concrete conclusions. The lack of monitoring equipment at Site 3 (i.e.; rain gauge, etc.) makes it difficult to ascertain any explanations for the differences between storms. Samples from Site 3 should be analyzed for PSD in order to gain insight to any differences between Site 2 and Site 3. Initial studies of PFC focused on the difference between PFC and conventional pavement. As knowledge about these differences grows, it is important to research the differences in PFC based on quantifiable parameters such as hydraulic conductivity.

Appendix A- Site 1 Time Series Data

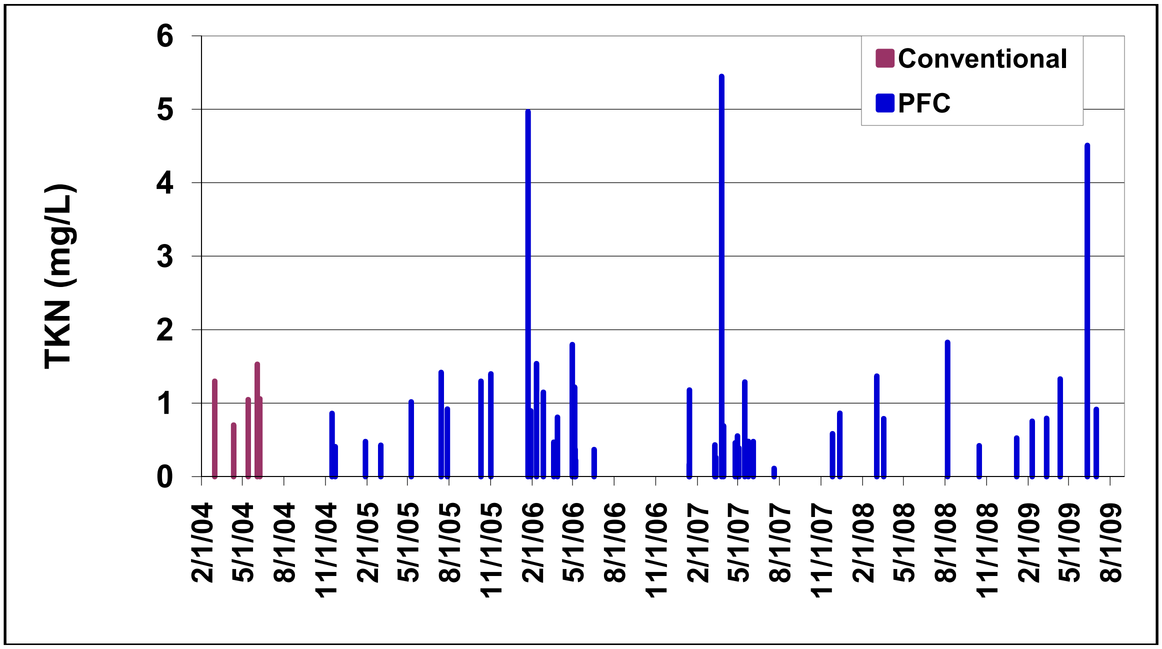


Figure A-1: TKN concentration over time at Site 1

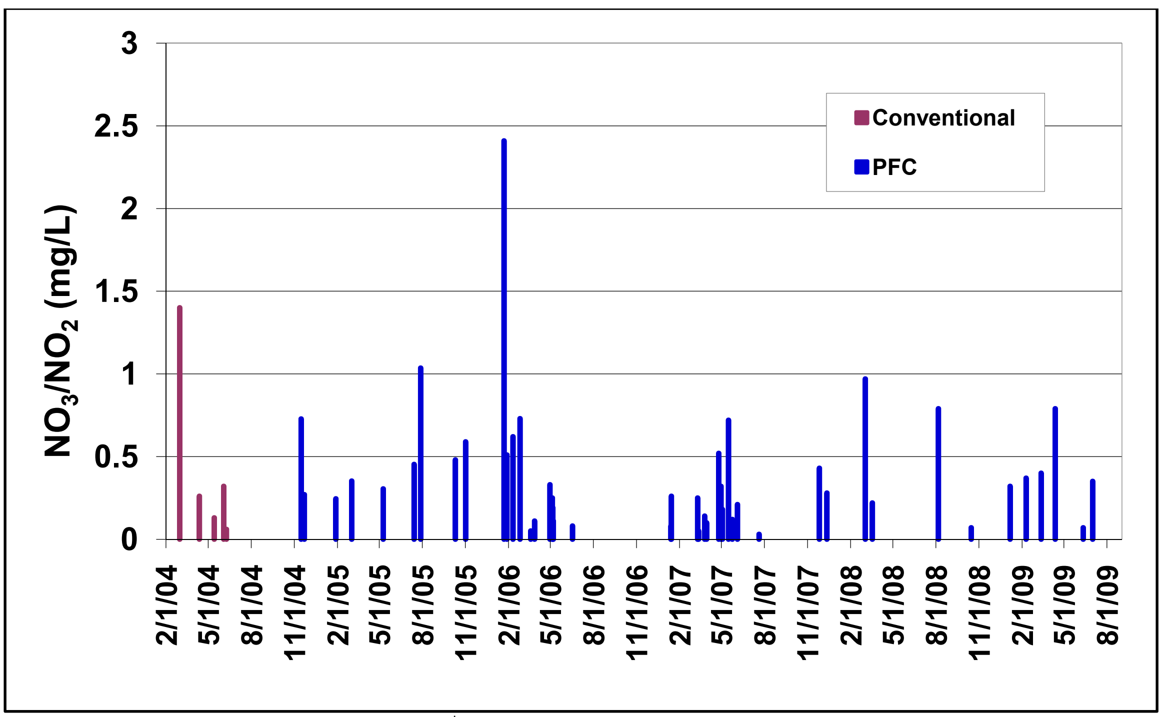


Figure A-2: NO_3^+/NO_2 concentration over time at Site 1

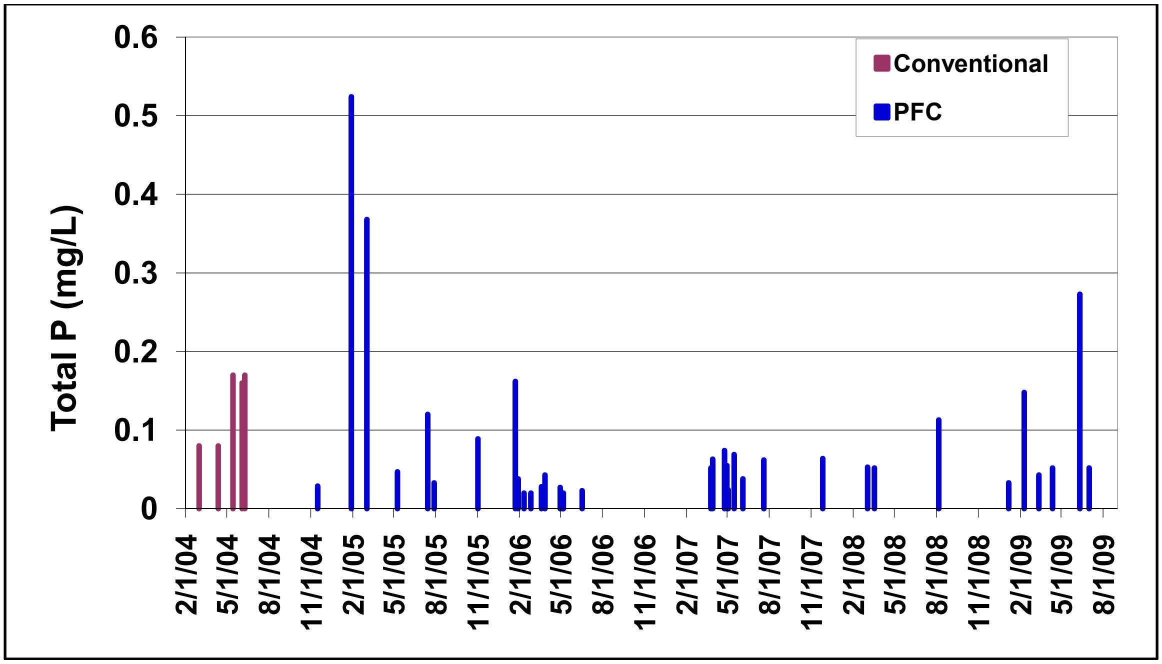


Figure A-3: Total P concentration over time at Site 1

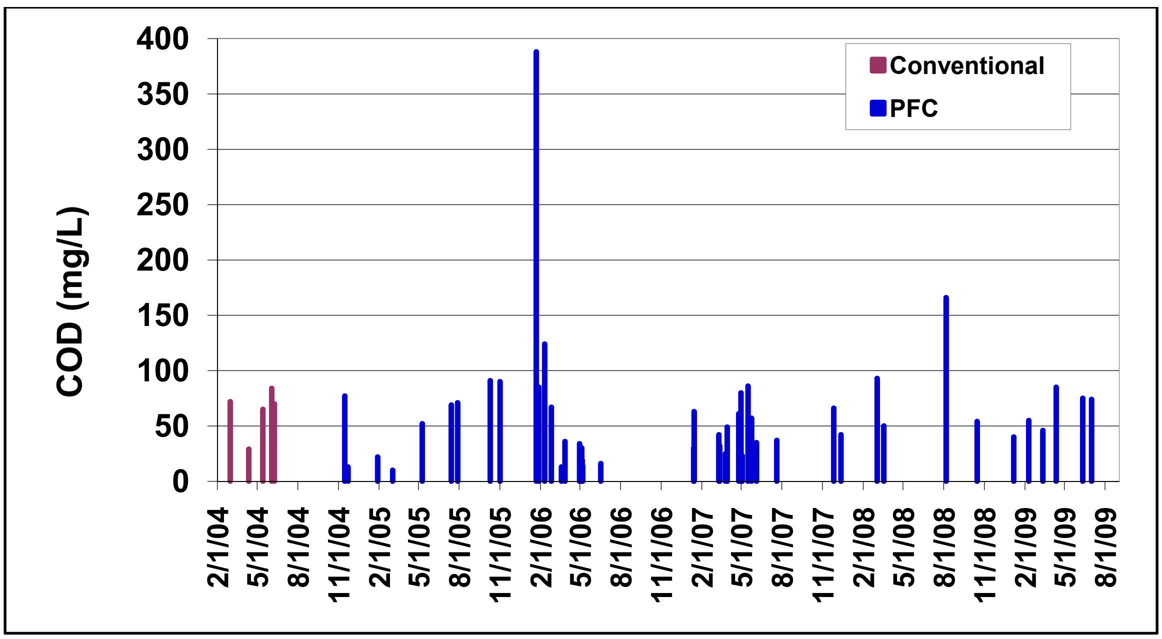


Figure A-4: COD concentration over time at Site 1

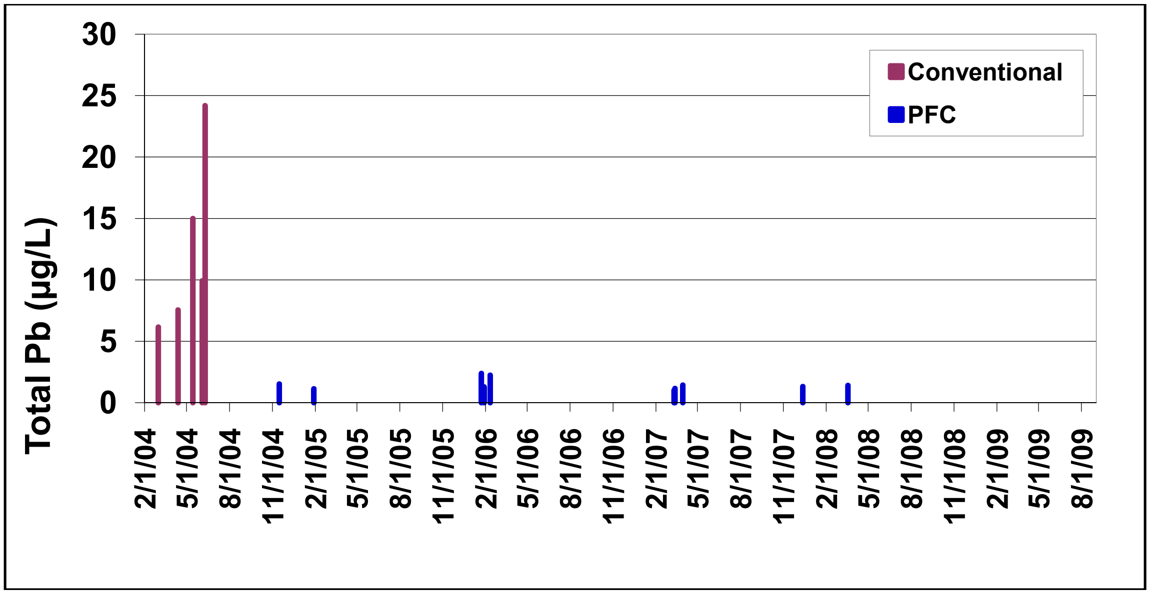


Figure A-5: Total Pb concentration over time at Site 1

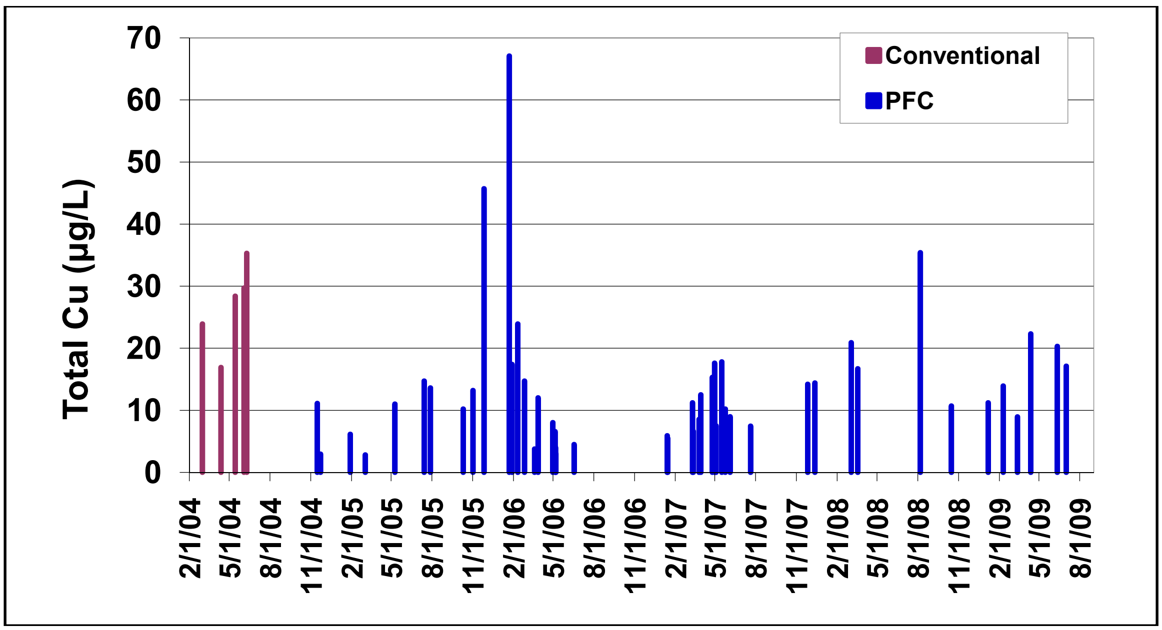


Figure A-6: Total Cu concentration over time at Site 1

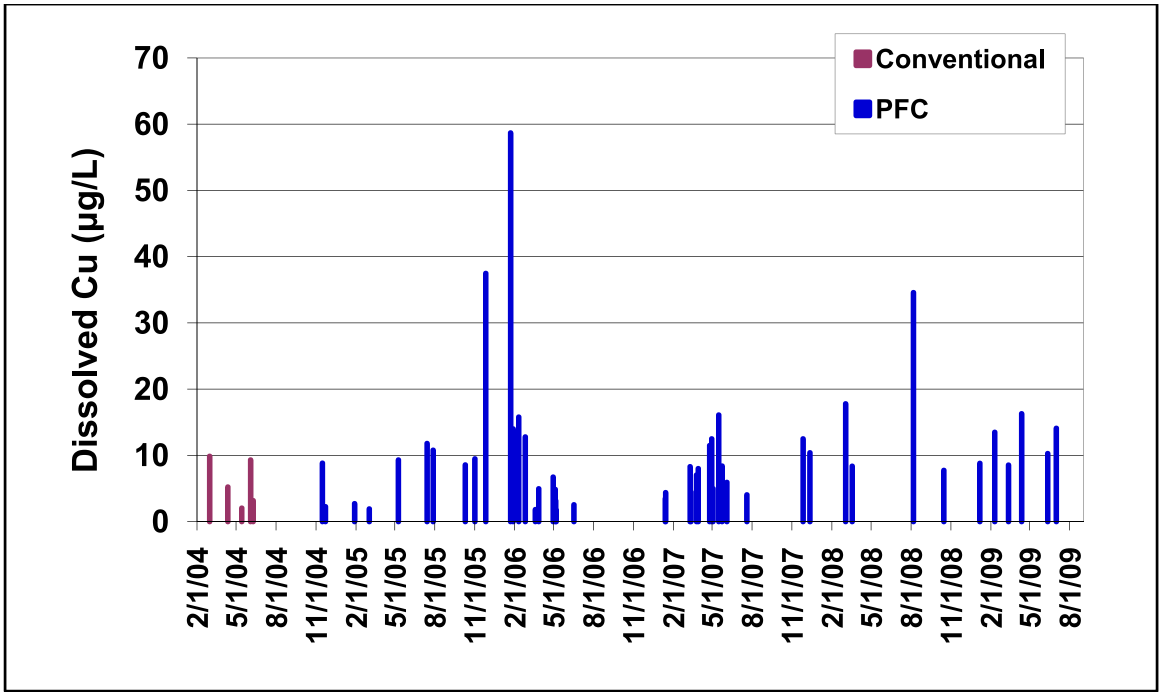


Figure A-7: Dissolved Cu concentration over time at Site 1

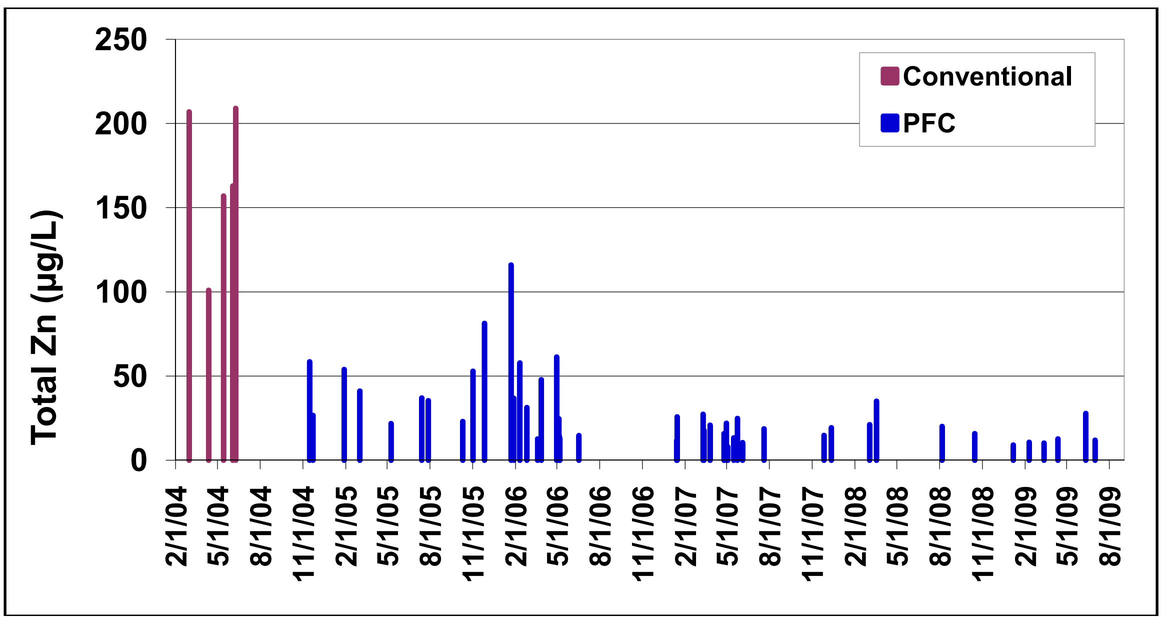


Figure A-8: Total Zn concentration over time at Site 1

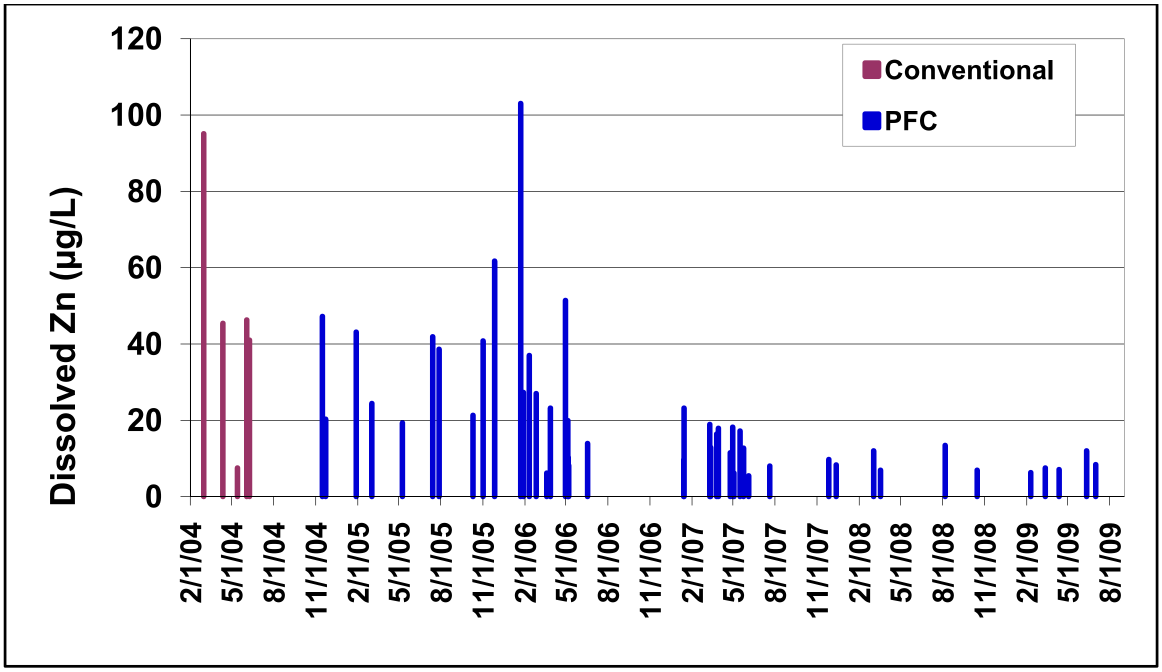


Figure A-9: Dissolved Zn concentration over time at Site 1

Appendix B- Particle Size Distributions

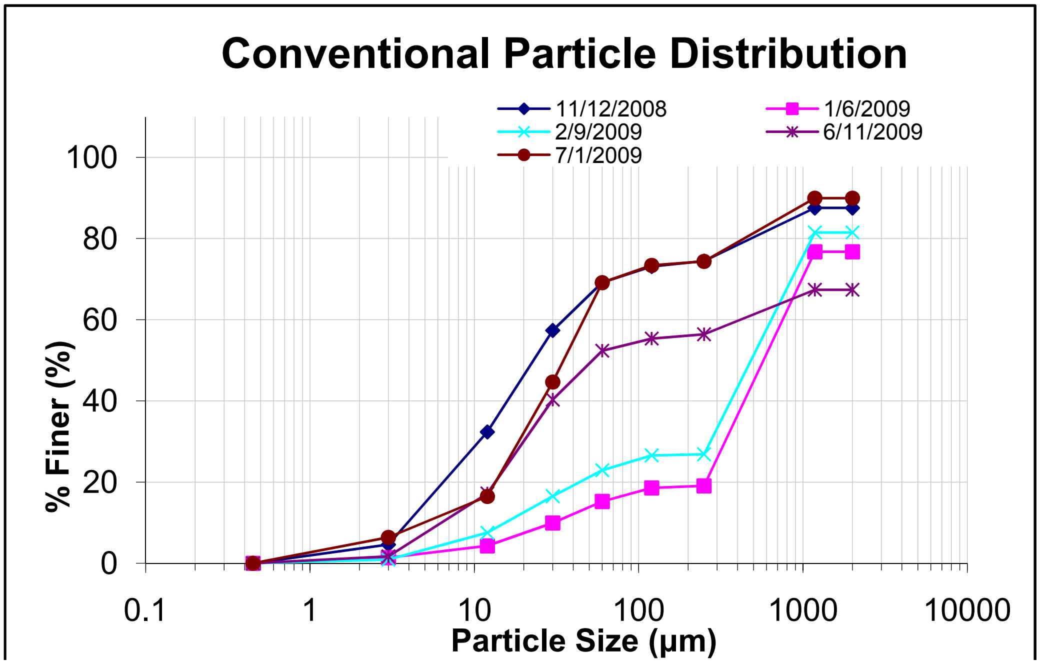


Figure B-1: Particle Size Distribution for Conventional Pavement

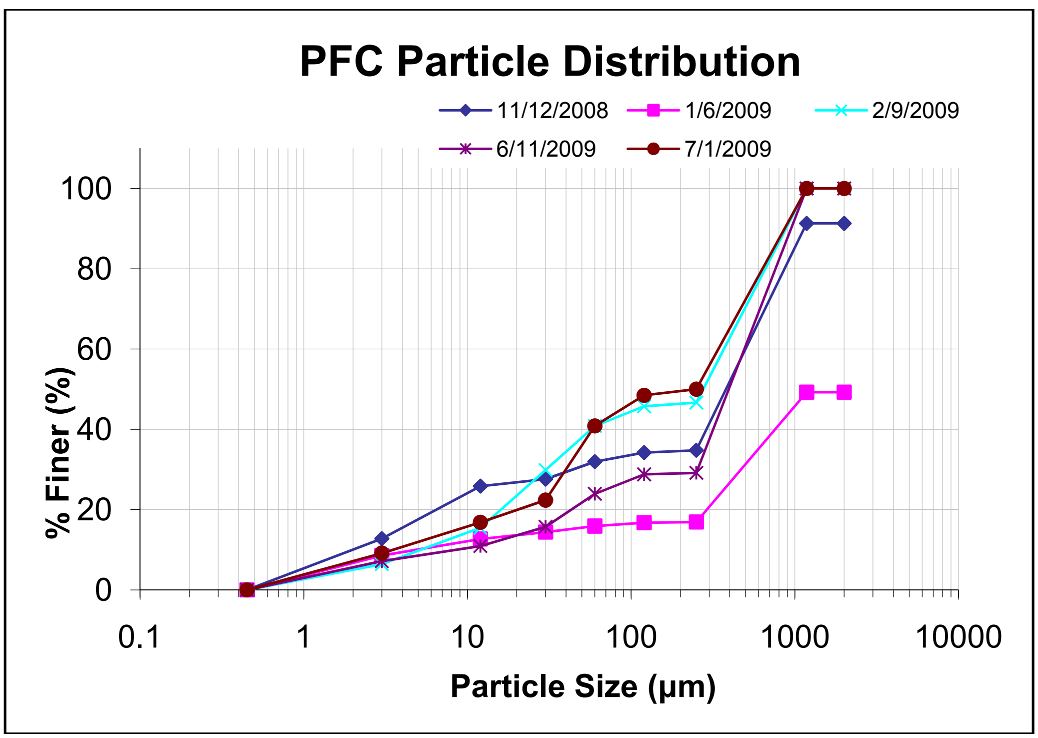


Figure B-2: Particle Size Distribution for PFC

Appendix C- Minitab Multiple Linear Regression Results

Table C-1: Raw Data for Regression Analysis

Date	PFC Automatic Sampler	PFC Passive Sampler	HMA Passive Sampler	Age (days)	Rain Event (in.)	Intensity (in./hr)	Cum. Rain (in.)	ADP (days)	Runoff (L/s)	Peak Hyeta (in./5min)	Log Traffic
3/11/07	*		*	861	0.8	0.291	69.2	45	1.4	0.10	3.333
3/13/07	*		*	863	1.13	0.283	71.8	2	0.65	0.16	3.830
3/26/07	*	*	*	876	1.36	0.259	73.6	13	1	0.09	3.715
4/25/07	*	*	*	906	0.37	0.370	76.5	8	0.41	0.12	2.828
4/30/07	*	*	*	911	0.49	0.392	76.9	5	0.27	0.05	3.824
5/3/07	*	*	*	914	0.97	0.647	78.7	2	1.15	0.09	3.463
5/16/07	*	*	*	927	0.46	0.204	79.4	5	0.35	0.04	2.507
5/24/07	*	*	*	935	0.89	0.396	80.5	2	0.64	0.10	3.700
6/4/07	*	*	*	946	1.43	0.817	85.2	5	1.7	0.18	2.808
7/20/07	*	*	*	992	1.1	1.780	94.8	3	3.8	0.26	2.933
11/26/07	*	*	*	1121	0.86	0.287	104.4	1	0.3	0.05	3.595
12/12/07	*	*	*	1137	0.93	0.744	105.7	16	1.8	0.18	3.444
3/3/08	*			1219	0.3	0.300	107.4	15	0.2	0.06	3.498
10/15/08	*			1445	0.71	0.406	122.1	8	0.5	0.13	3.028
1/6/09	*			1528	0.37	0.247	123.4	29	0.15	0.02	3.056
2/9/09	*			1562	0.83	0.302	124.4	34	0.3	0.07	3.556
6/11/09	*			1684	1.23	1.230	135.1	19	3.7	0.27	2.968

*indicates the sample locations where the data is used

Minitab Output Results

PFC - Passive Sampler Results

Zinc

Results for: pfcpassive.XLS

Stepwise Regression: zinc versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.15

Response is zinc on 5 predictors, with N = 10

Step                   1        2        3        4        5
Constant          -21.24   -20.66   -20.31   -20.19   -11.01

age                0.013    0.012    0.012    0.011
T-Value             0.93     0.98     1.03     0.96
P-Value            0.403    0.373    0.341    0.369

raintotal            1.6
T-Value             0.34
P-Value            0.748

traffic counts       5.3      5.7      5.7      5.7      6.1
T-Value             2.12     2.84     3.08     3.19     3.46
P-Value            0.102    0.036    0.022    0.015    0.009

ADP                -0.17    -0.16    -0.16
T-Value            -0.69    -0.71    -0.79
P-Value            0.528    0.508    0.461

runoff              -0.5     -0.2
T-Value            -0.37    -0.24
P-Value            0.728    0.823

S                   3.63     3.30     3.03     2.94     2.93
R-Sq               69.24    68.33    67.98    64.67    60.01
R-Sq(adj)          30.79    42.99    51.97    54.57    55.01
Mallows Cp           6.0      4.1      2.2      0.6     -0.8
PRESS            343.729  239.415  207.374  133.767  103.312
R-Sq(pred)          0.00     0.00     0.00    22.09    39.83
```

Copper

Stepwise Regression: copper versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.15

Response is copper on 5 predictors, with N = 10

Step                   1        2        3
Constant           1.793   -1.899   -1.081

age              -0.0047
T-Value            -0.81
P-Value            0.464

raintotal           -4.5     -4.0     -2.7
T-Value            -1.64    -1.55    -1.66
P-Value            0.175    0.182    0.148

traffic counts      2.52     2.20     1.74
T-Value             1.94     1.84     1.85
P-Value            0.124    0.124    0.114

ADP                0.180    0.164    0.153
T-Value             1.74     1.67     1.65
P-Value            0.157    0.156    0.149

runoff              0.52     0.38
T-Value             0.86     0.68
P-Value            0.440    0.527

S                   1.47     1.42     1.35
R-Sq               60.61    54.18    49.95
R-Sq(adj)          11.37    17.52    24.92
Mallows Cp           6.0      4.7      3.1
PRESS            64.4882  46.5075  35.8931
R-Sq(pred)          0.00     0.00     0.00
```

TSS

PFC passive Stepwise Regression: TSS versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.15

Response is TSS on 5 predictors, with N = 10

Step                  1        2        3        4
Constant         -7.097   -7.337   -4.658    2.542

age               0.003    0.003
T-Value            0.12     0.16
P-Value           0.908    0.878

raintotal           6.2      6.5      6.5      8.2
T-Value            0.87     1.24     1.35     1.92
P-Value           0.432    0.269    0.224    0.097

traffic counts      2.8      2.7      2.8
T-Value            0.70     0.79     0.91
P-Value           0.522    0.466    0.396

ADP                0.55     0.55     0.56     0.54
T-Value            1.41     1.57     1.76     1.73
P-Value           0.232    0.177    0.129    0.128

runoff              0.1
T-Value            0.07
P-Value           0.950

S                  5.72     5.12     4.69     4.63
R-Sq              58.37    58.33    58.11    52.28
R-Sq(adj)          6.34    24.99    37.16    38.65
Mallows Cp          6.0      4.0      2.0      0.6
PRESS           2069.93  819.364  306.766  319.632
R-Sq(pred)         0.00     0.00     2.58     0.00
```

Conventional - Passive Sampler Results
Zinc
Results for: conv.XLS

Stepwise Regression: zinc versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.05

Response is zinc on 5 predictors, with N = 12

Step                   1        2
Constant          -366.7   -363.3

age                0.269    0.254
T-Value             3.54     3.19
P-Value            0.012    0.015

raintotal             41
T-Value             1.36
P-Value            0.223

ADP                 2.33     2.37
T-Value             4.21     4.06
P-Value            0.006    0.005

traffic counts        60       73
T-Value             3.89     5.72
P-Value            0.008    0.001

peakhyeta          -1221     -915
T-Value            -2.91    -2.44
P-Value            0.027    0.045

S                   21.8     23.1
R-Sq               91.70    89.15
R-Sq(adj)          84.78    82.95
Mallows Cp           6.0      5.8
PRESS            19116.6  21720.8
R-Sq(pred)         44.52    36.96
```

Copper

Results for: conv.XLS

Stepwise Regression: copper versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.2


Response is copper on 5 predictors, with N = 12


Step                   1        2        3        4        5
Constant          -54.02   -53.33   -52.02   -33.78   -29.67

age                0.025    0.022    0.019
T-Value             0.86     0.80     0.76
P-Value            0.421    0.452    0.469

raintotal              8
T-Value             0.71
P-Value            0.502

ADP                 0.26     0.27     0.27     0.25
T-Value             1.24     1.34     1.44     1.34
P-Value            0.260    0.223    0.189    0.212

traffic counts      14.5     17.1     17.1     17.3     16.7
T-Value             2.47     3.86     4.08     4.22     3.94
P-Value            0.049    0.006    0.004    0.002    0.003

peakhyeta           -117      -56
T-Value            -0.73    -0.43
P-Value            0.490    0.679

S                   8.30     8.00     7.59     7.41     7.70
R-Sq               72.66    70.33    69.54    67.35    60.80
R-Sq(adj)          49.87    53.38    58.12    60.09    56.88
Mallows Cp           6.0      4.5      2.7      1.2      0.6
PRESS            3049.59  3038.88  2008.09  1749.76  785.506
R-Sq(pred)          0.00     0.00     0.00     0.00    48.03
```

TSS

Stepwise Regression: TSS versus age, raintotal, ...

```
Backward elimination.  Alpha-to-Remove: 0.2

Response is TSS on 5 predictors, with N = 12

Step                  1        2        3
Constant         -573.6   -560.3   -565.2

age                0.47     0.43     0.43
T-Value            1.46     1.50     1.57
P-Value           0.195    0.177    0.155

raintotal            80       55
T-Value            0.63     0.54
P-Value           0.551    0.605

ADP                 4.7      4.8      4.8
T-Value            2.02     2.20     2.32
P-Value           0.089    0.064    0.049

traffic counts       62       71       88
T-Value            0.96     1.24     1.93
P-Value           0.376    0.256    0.090

peakhyeta          -669
T-Value           -0.38
P-Value           0.718

S                  91.7     85.9     82.0
R-Sq              57.89    56.88    55.08
R-Sq(adj)         22.80    32.24    38.23
Mallows Cp          6.0      4.1      2.4
PRESS            549627   454268   448404
R-Sq(pred)         0.00     0.00     0.00
```

PFC - Automatic Sampler Results

Zinc

Results for: pfc.XLS

Stepwise Regression: zinc versus age, raintotal, ADP, runoff, traffic

```
Backward elimination.  Alpha-to-Remove: 0.15

Response is zinc on 5 predictors, with N = 17

Step              1        2        3        4
Constant     -18.59   -16.19   -14.68   -13.36

age          0.0036
T-Value        0.65
P-Value       0.532

raintotal      -7.1     -8.2     -7.8
T-Value       -1.10    -1.33    -1.27
P-Value       0.296    0.208    0.226

ADP            0.08     0.11
T-Value        0.69     1.04
P-Value       0.502    0.320

runoff         4.43     4.80     4.63     3.28
T-Value        2.88     3.45     3.34     3.63
P-Value       0.015    0.005    0.005    0.003

traffic         6.9      7.4      7.3      5.3
T-Value        2.33     2.66     2.60     2.24
P-Value       0.040    0.021    0.022    0.042

S              5.01     4.88     4.90     5.00
R-Sq          64.12    62.77    59.42    54.38
R-Sq(adj)     47.82    50.35    50.06    47.87
Mallows Cp      6.0      4.4      3.4      3.0
PRESS       800.909  596.599  597.108  611.963
R-Sq(pred)     0.00    22.37    22.30    20.37
```

Copper

Results for: pfc.XLS

Stepwise Regression: copper versus age, raintotal, ADP, runoff, traffic

```
Backward elimination.  Alpha-to-Remove: 0.15


Response is copper on 5 predictors, with N = 18


Step               1        2        3        4        5
Constant      0.8216   0.8340   1.1145  -0.5243   1.9203

age           0.0019   0.0018   0.0019   0.0023
T-Value         0.91     1.01     1.14     1.39
P-Value        0.380    0.332    0.272    0.184

raintotal       -2.1     -2.1     -2.0
T-Value        -0.89    -0.93    -1.08
P-Value        0.393    0.368    0.299

ADP           -0.004
T-Value        -0.09
P-Value        0.927

runoff          1.45     1.47     1.43     1.07     1.13
T-Value         2.46     2.65     3.13     3.36     3.48
P-Value        0.030    0.020    0.007    0.004    0.003

traffic          0.1      0.1
T-Value         0.12     0.13
P-Value        0.908    0.895

S               1.93     1.85     1.79     1.80     1.85
R-Sq           53.57    53.54    53.47    49.61    43.08
R-Sq(adj)      34.23    39.24    43.50    42.89    39.52
Mallows Cp       6.0      4.0      2.0      1.0      0.7
PRESS        142.766  123.528  95.0116  89.8910  83.1155
R-Sq(pred)      0.00     0.00     1.31     6.63    13.66
```

TSS

Stepwise Regression: TSS versus age, raintotal, ADP, runoff, traffic

```
Backward elimination.  Alpha-to-Remove: 0.2

Response is TSS on 5 predictors, with N = 18

Step               1        2        3        4
Constant     -7.3824  -6.8670  -5.9459   0.6551

age           0.0008
T-Value         0.16
P-Value        0.873

raintotal       -5.8     -6.1
T-Value        -1.02    -1.19
P-Value        0.330    0.257

ADP            0.119    0.126    0.133    0.134
T-Value         1.17     1.44     1.51     1.52
P-Value        0.265    0.174    0.154    0.151

runoff          5.56     5.65     4.54     4.45
T-Value         3.96     4.59     5.64     5.58
P-Value        0.002    0.001    0.000    0.000

traffic          3.4      3.5      2.0
T-Value         1.27     1.45     0.96
P-Value        0.229    0.172    0.353

S               4.59     4.41     4.47     4.46
R-Sq           72.72    72.66    69.70    67.70
R-Sq(adj)      61.35    64.25    63.21    63.40
Mallows Cp       6.0      4.0      3.3      2.2
PRESS        816.175  565.890  524.621  484.671
R-Sq(pred)     11.74    38.81    43.27    47.59
```

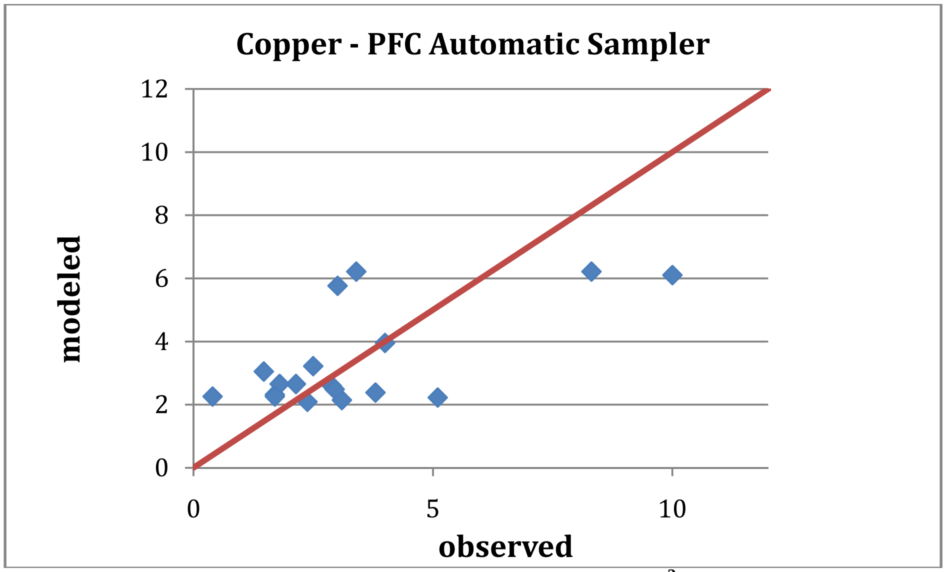


Figure C-1: Modeled vs Observed Data, R^2= 43.06

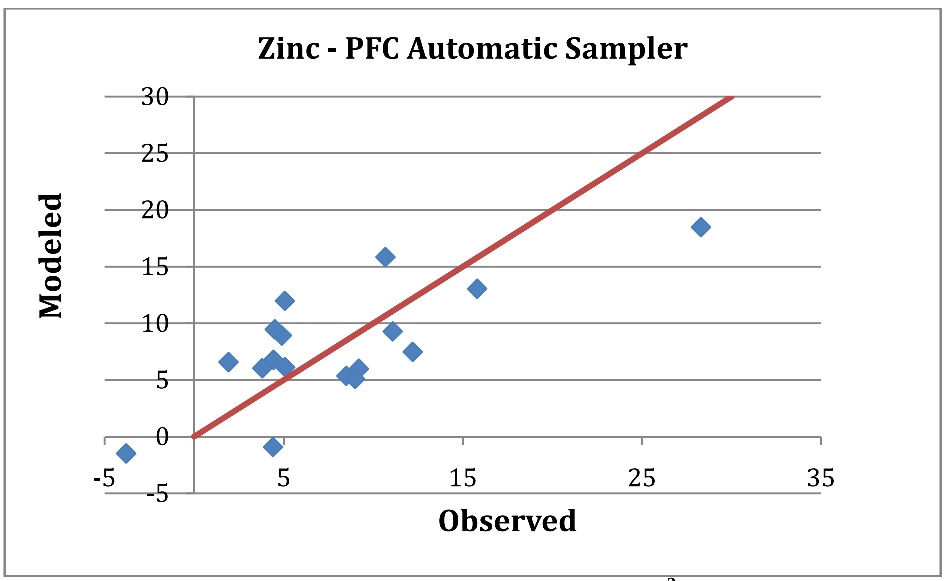


Figure C-2: Modeled vs Observed Data, R^2= 54.80

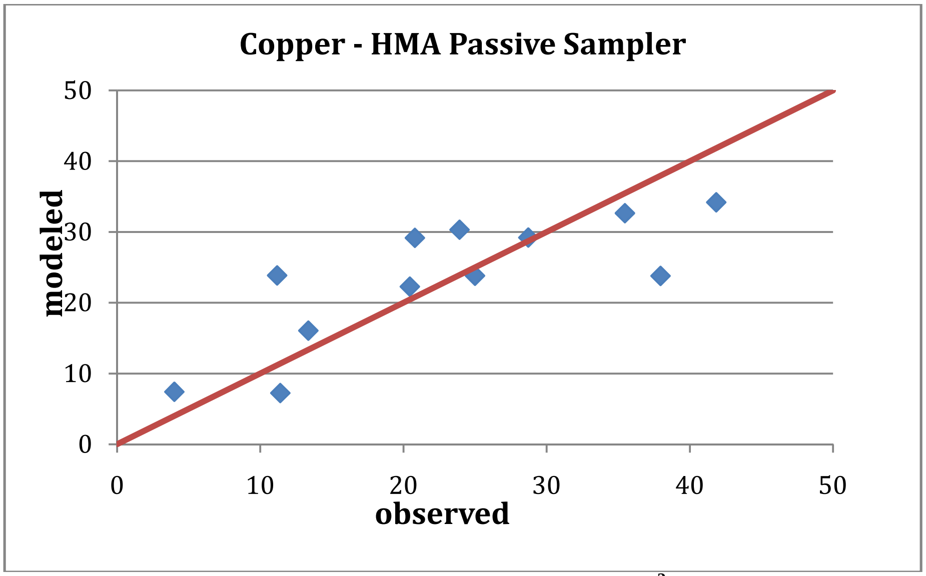


Figure C-3: Modeled vs Observed Data, R^2= 61.84

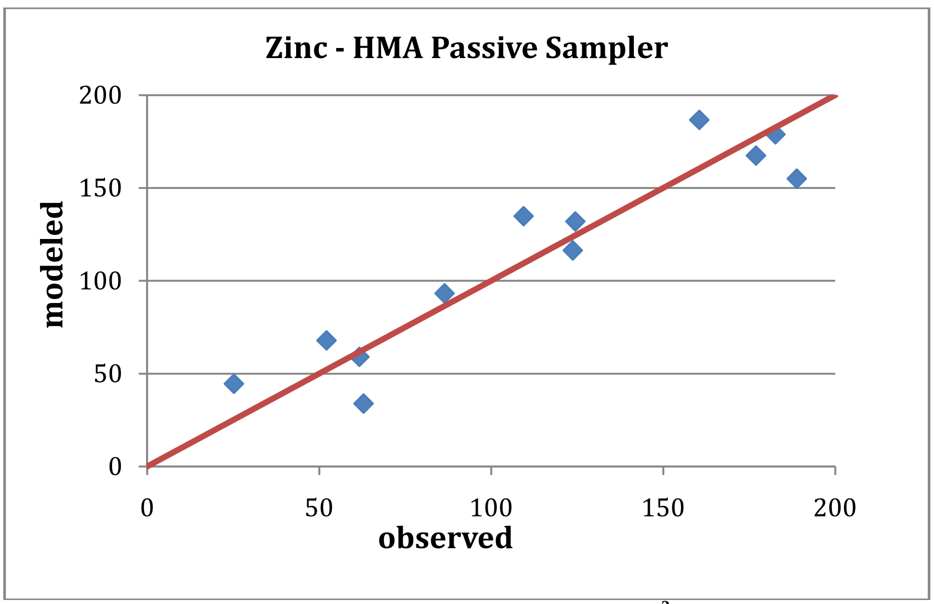


Figure C-4: Modeled vs Observed Data, R^2= 87.88

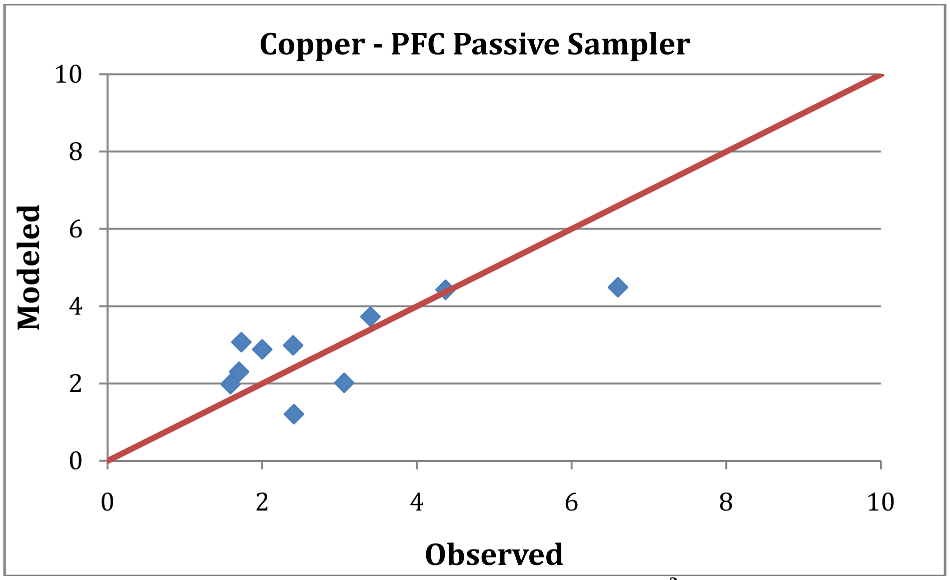


Figure C-5: Modeled vs Observed Data, R^2= 52.08

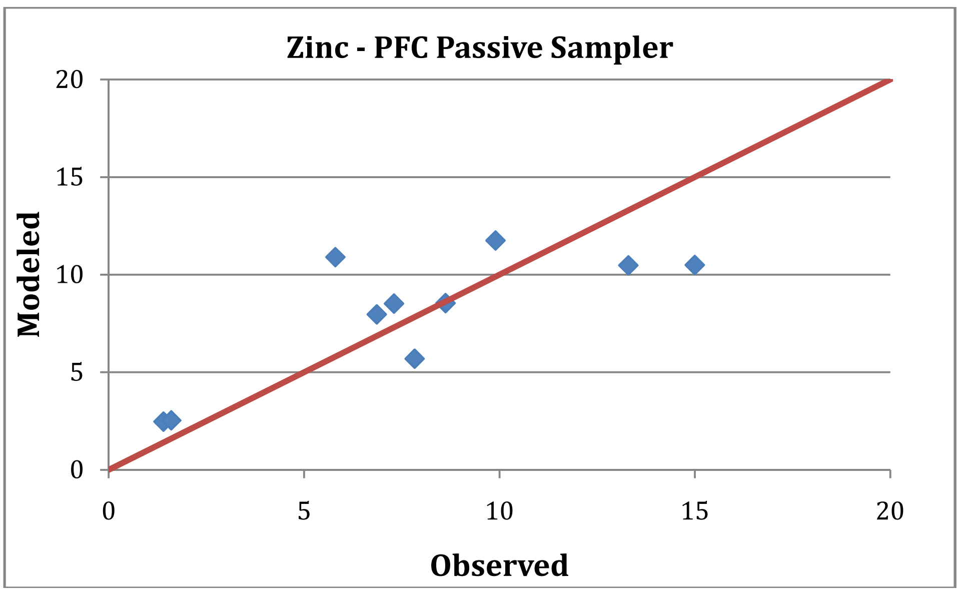
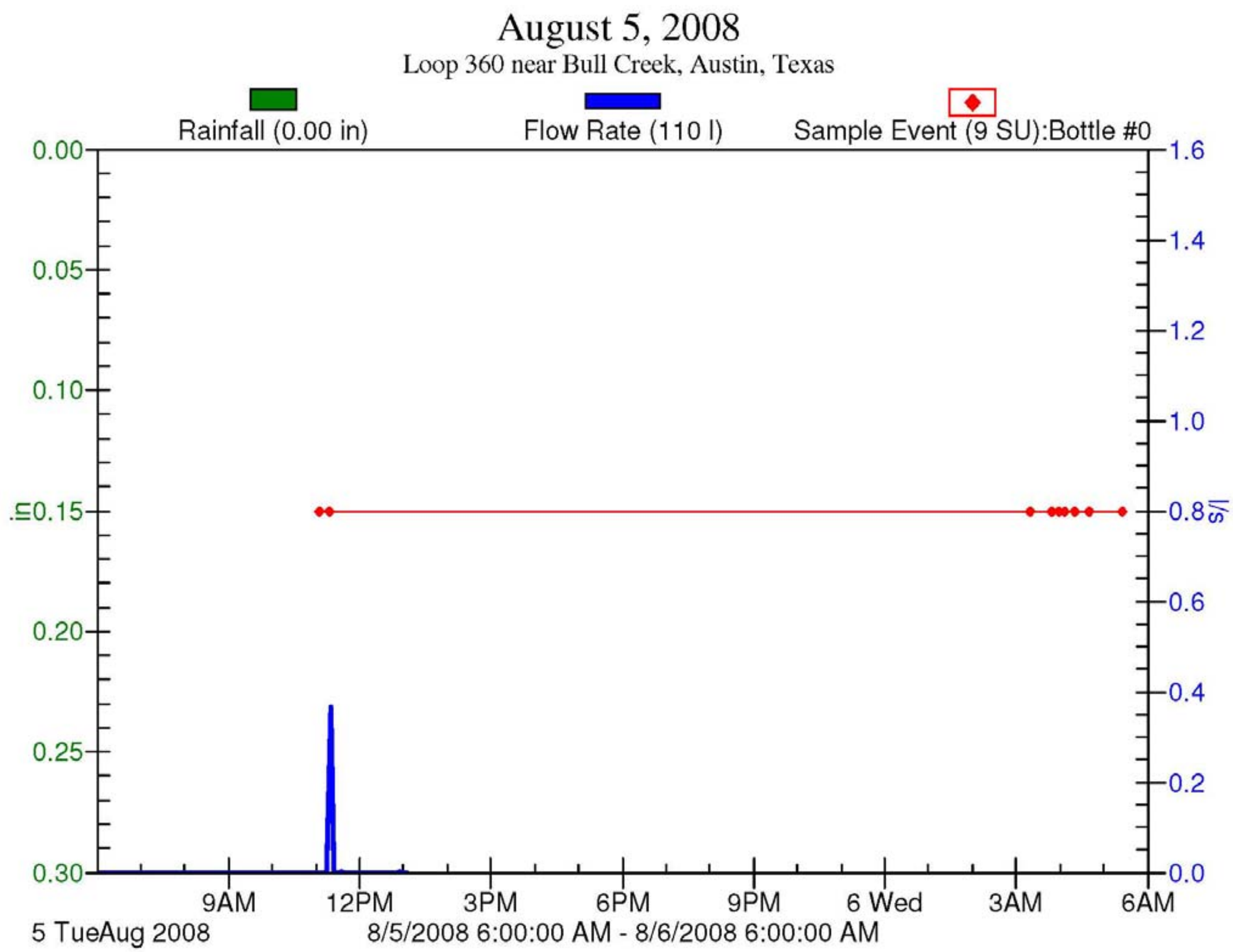


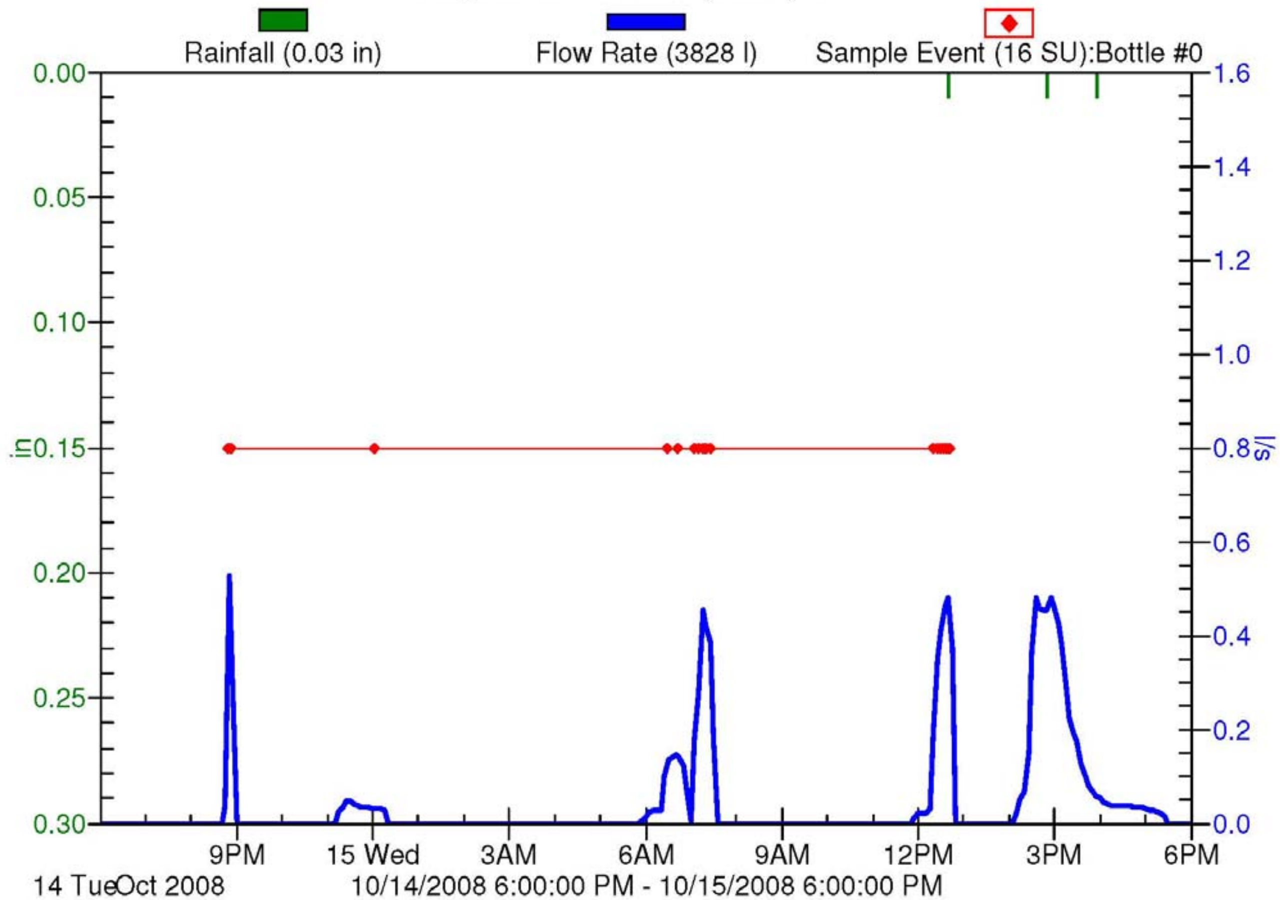
Figure C-6: Modeled vs Observed Data, R^2= 61.18

Appendix D – Hydrographs from Site 1 Sampled Events


August 5, 2008
Loop 360 near Bull Creek, Austin, Texas
Rainfall (0.00 in)
Flow Rate (110 l)
Sample Event (9 SU):Bottle #0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
in
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
l/s
9AM
12PM
3PM
6PM
9PM
6 Wed
3AM
6AM
5 TueAug 2008
8/5/2008 6:00:00 AM - 8/6/2008 6:00:00 AM

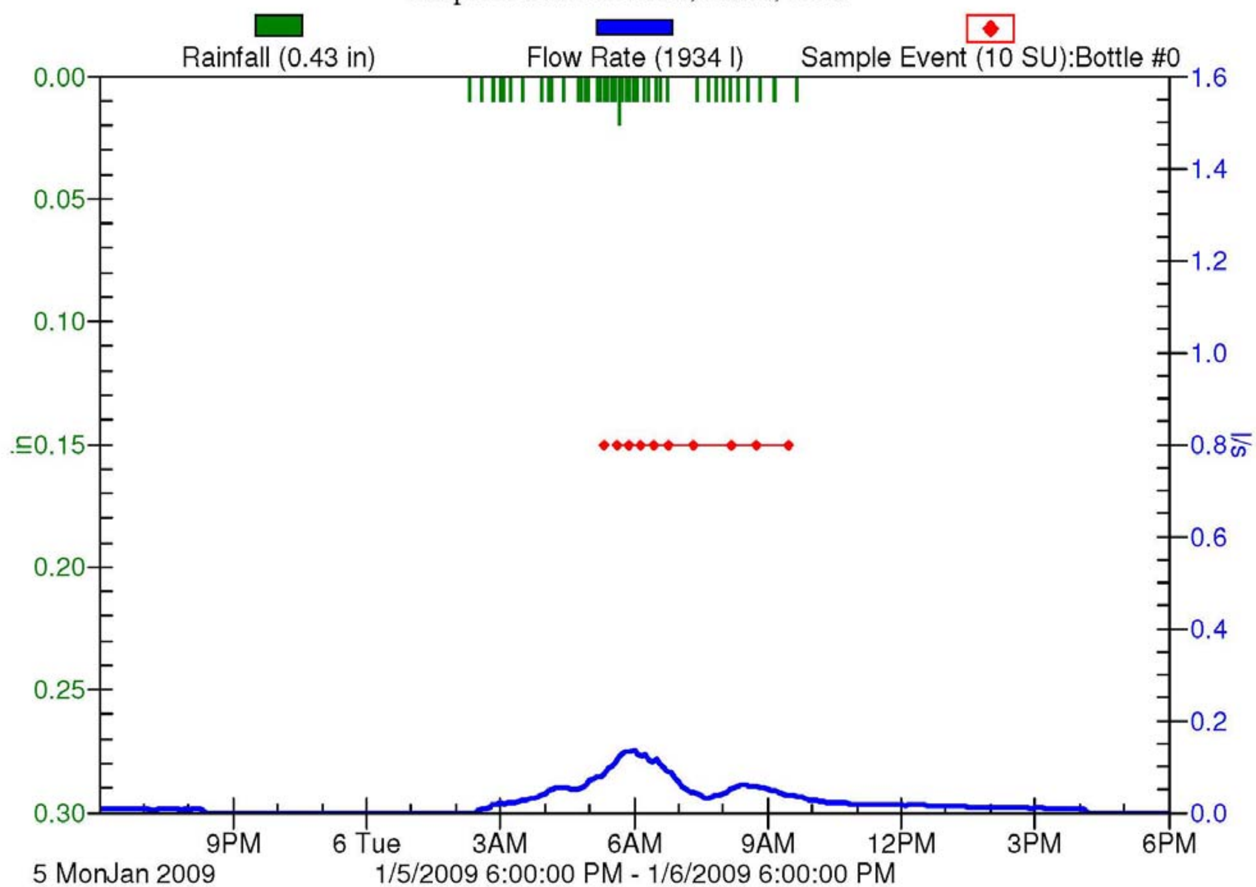
October 14-15, 2008

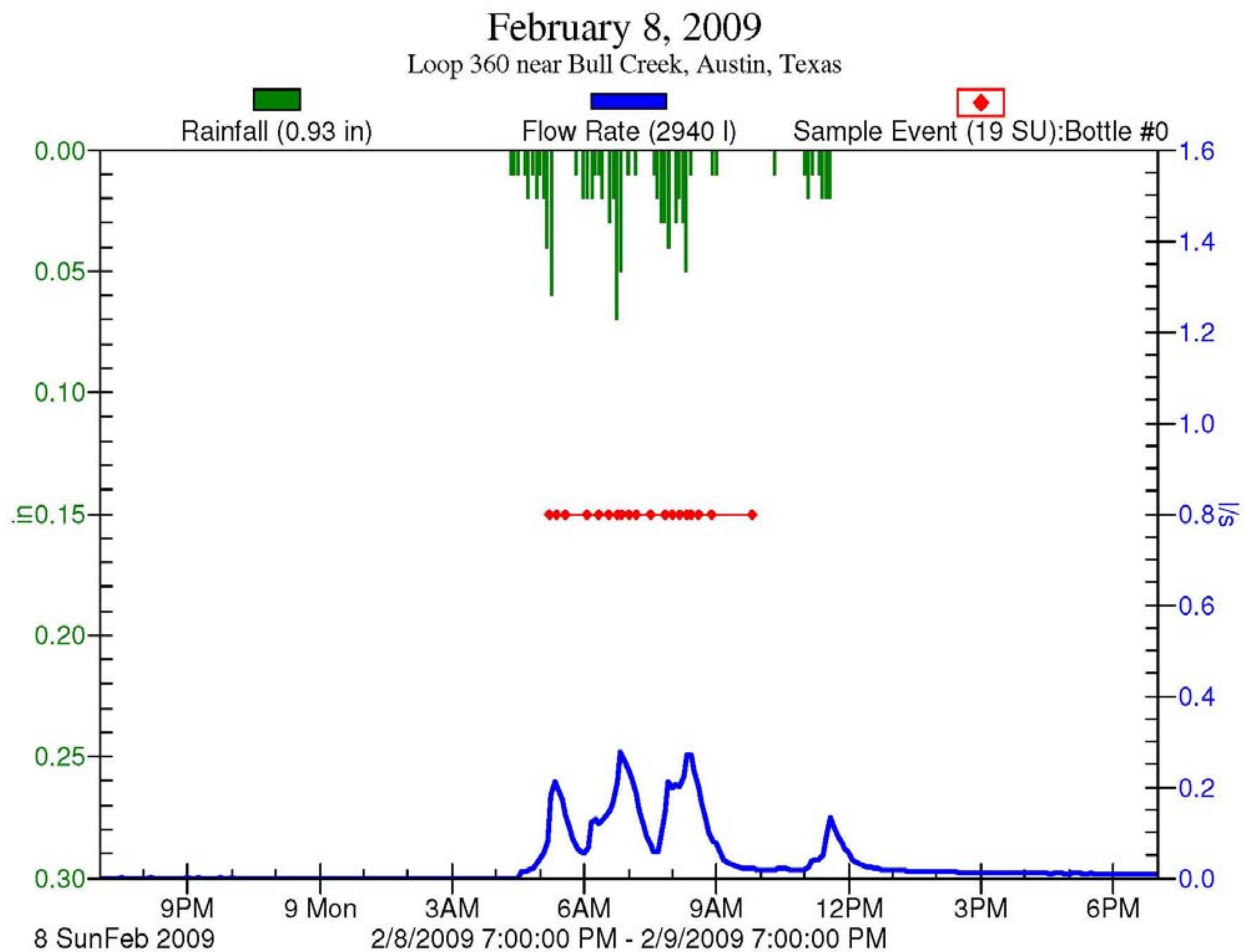
Loop 360 near Bull Creek, Austin, Texas



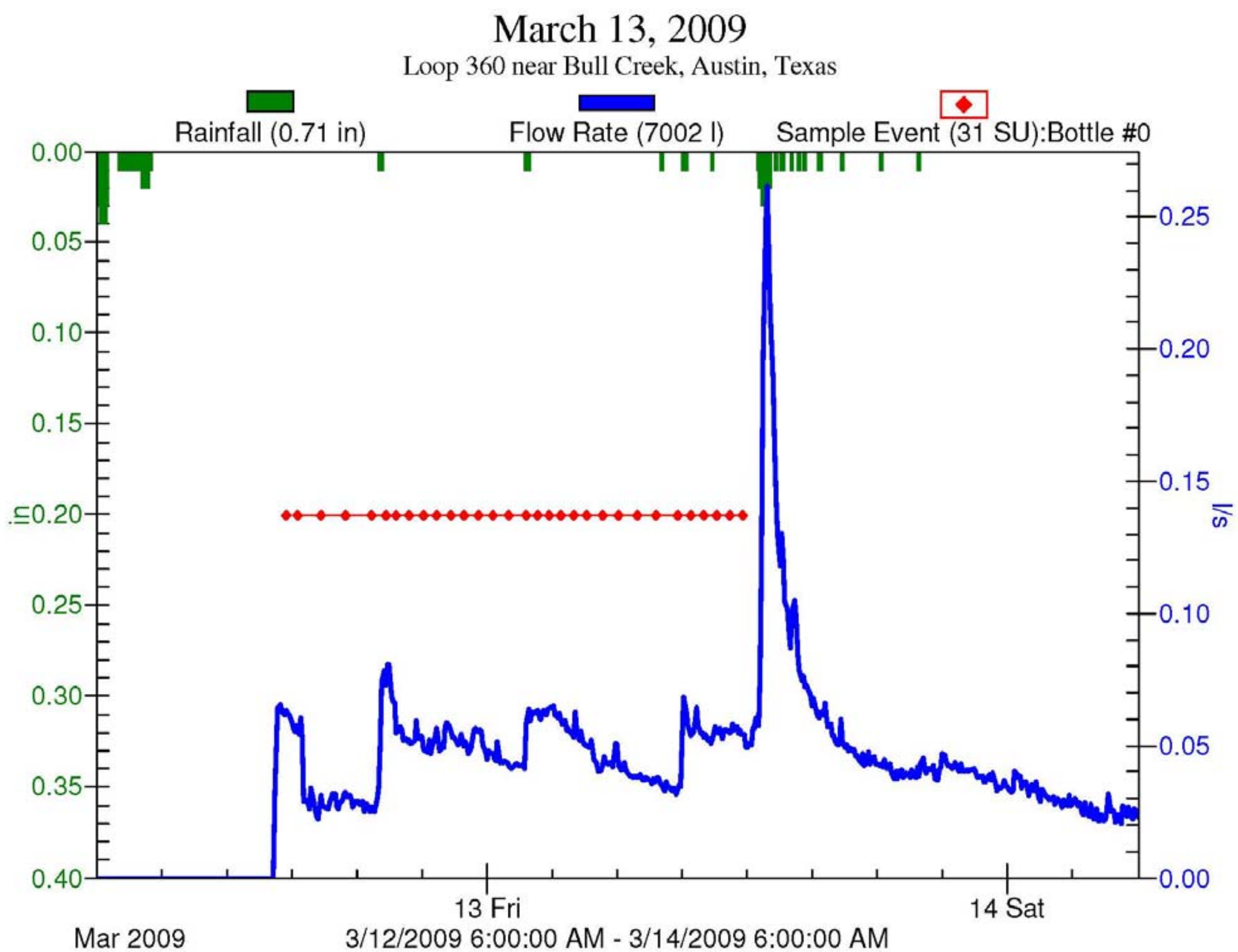
January 5, 2009

Loop 360 near Bull Creek, Austin, Texas

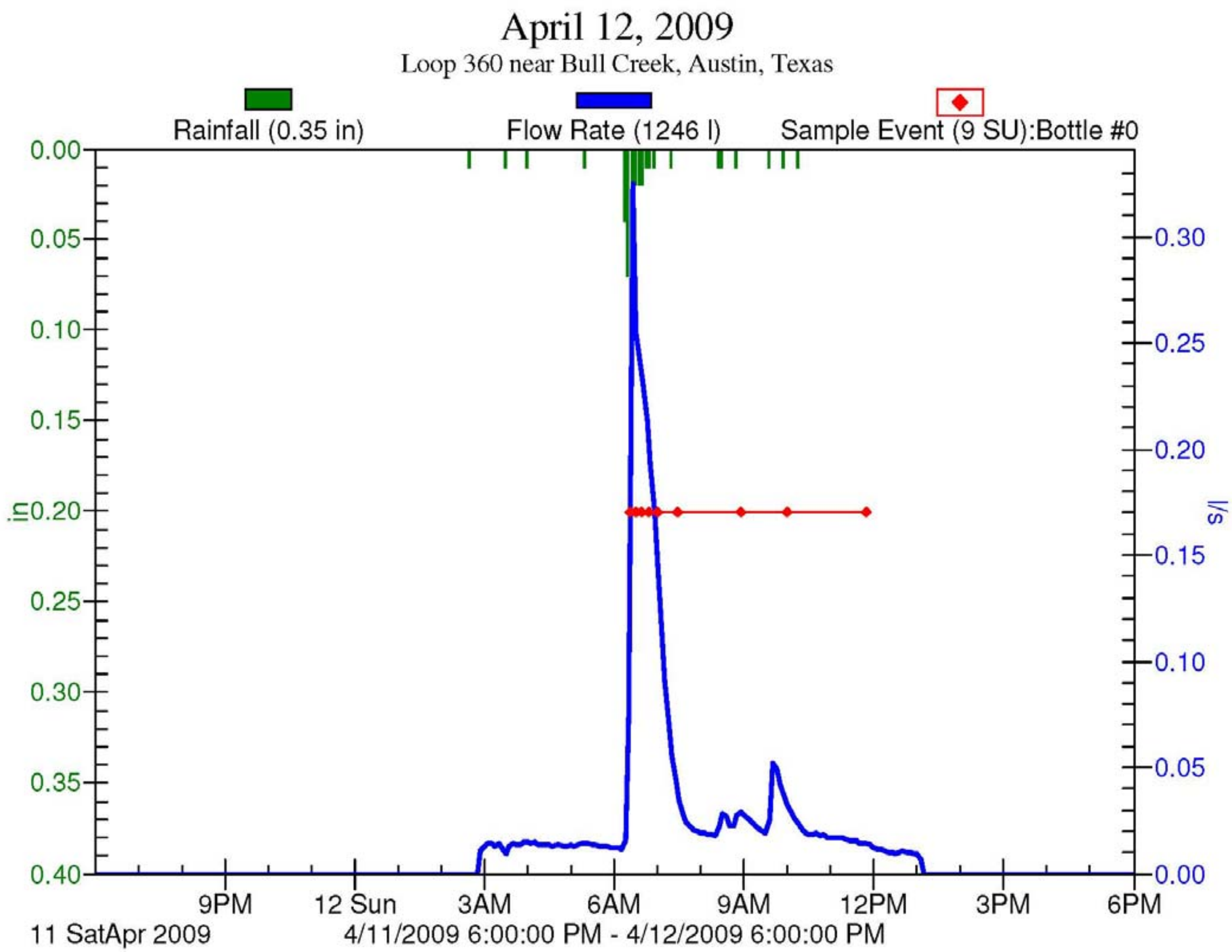


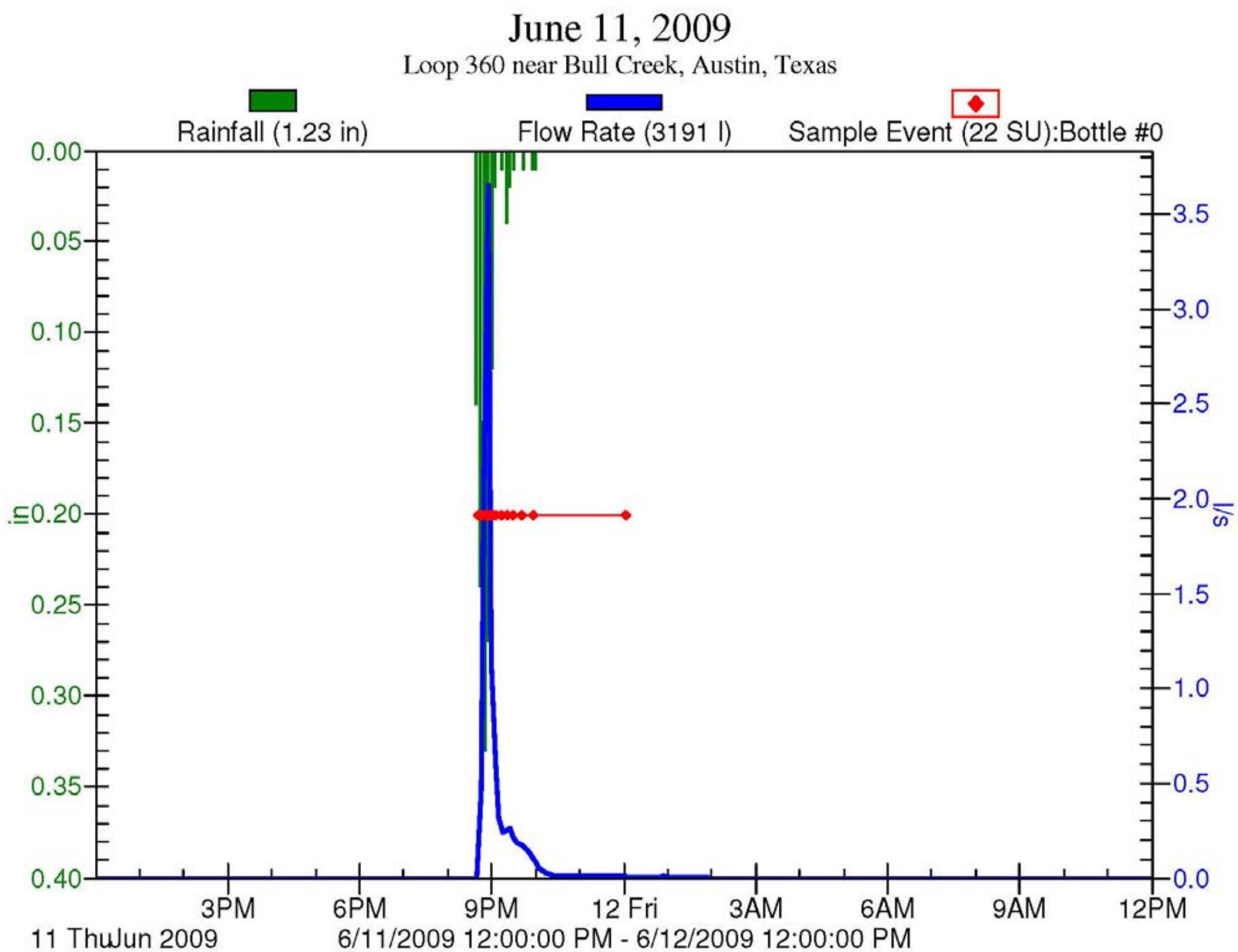


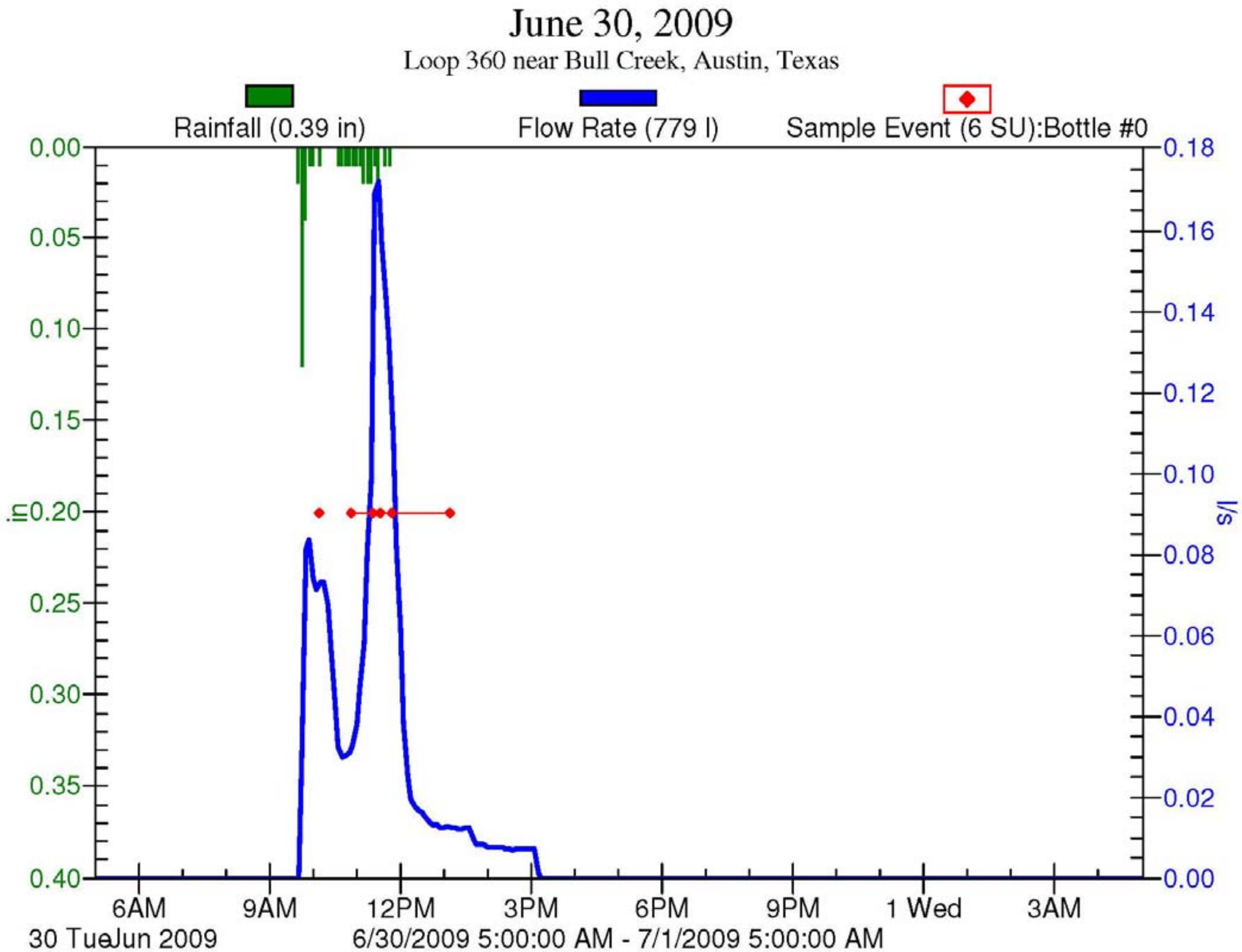
February 8, 2009
Loop 360 near Bull Creek, Austin, Texas
Rainfall (0.93 in)
Flow Rate (2940 l)
Sample Event (19 SU):Bottle #0
0.00
0.05
0.10
0.15
0.20
0.25
0.30
in
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
l/s
9PM
9 Mon
3AM
6AM
9AM
12PM
3PM
6PM
8 SunFeb 2009
2/8/2009 7:00:00 PM - 2/9/2009 7:00:00 PM



March 13, 2009
Loop 360 near Bull Creek, Austin, Texas
Rainfall (0.71 in)
Flow Rate (7002 l)
Sample Event (31 SU):Bottle #0
0.00
0.05
0.10
0.15
in 0.20
0.25
0.30
0.35
0.40
0.25
0.20
0.15
0.10
0.05
0.00
l/s
13 Fri
14 Sat
Mar 2009
3/12/2009 6:00:00 AM - 3/14/2009 6:00:00 AM

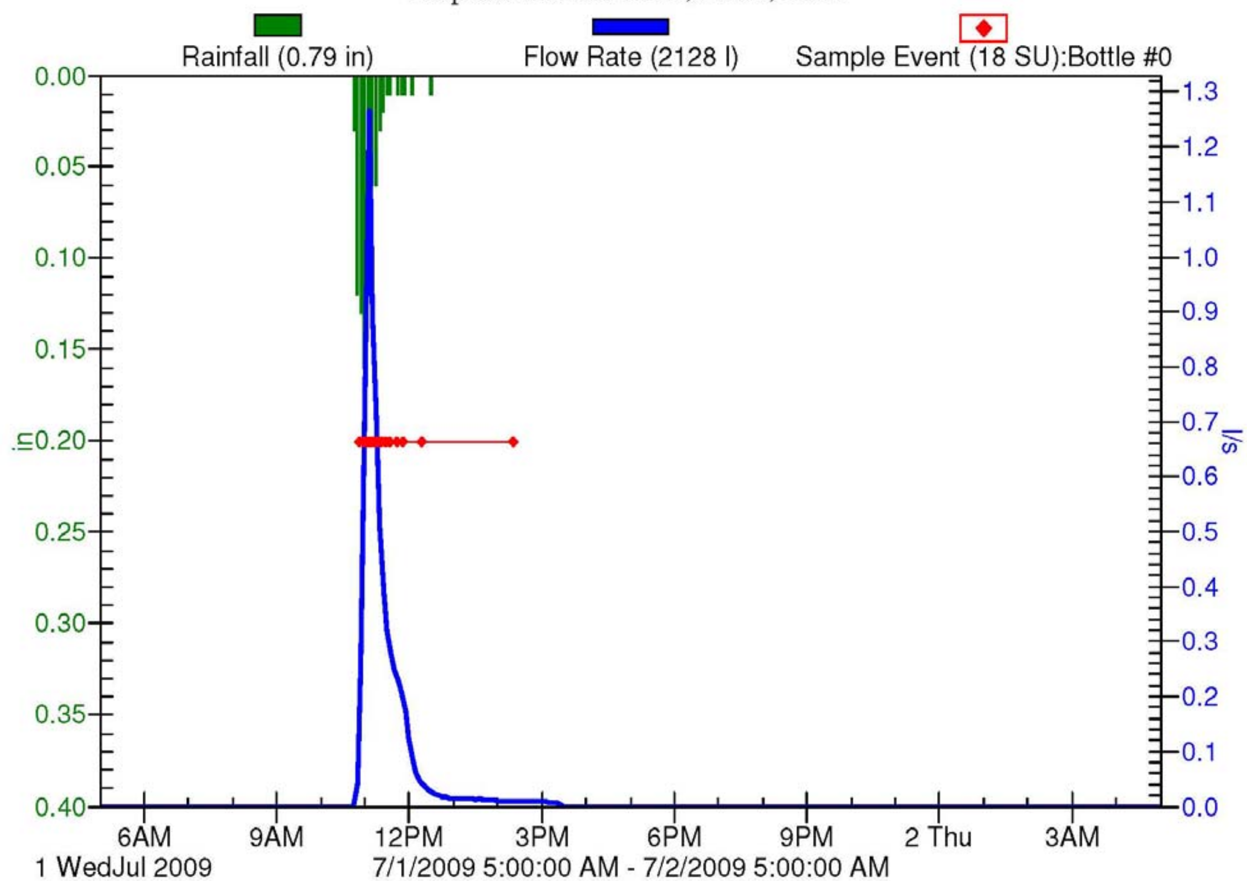

April 12, 2009
Loop 360 near Bull Creek, Austin, Texas
Rainfall (0.35 in)
Flow Rate (1246 l)
Sample Event (9 SU):Bottle #0
in
l/s
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
0.30
0.25
0.20
0.15
0.10
0.05
0.00
9PM
12 Sun
3AM
6AM
9AM
12PM
3PM
6PM
11 SatApr 2009
4/11/2009 6:00:00 PM - 4/12/2009 6:00:00 PM


June 11, 2009
Loop 360 near Bull Creek, Austin, Texas
Rainfall (1.23 in)
Flow Rate (3191 l)
Sample Event (22 SU):Bottle #0
in
l/s
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
3PM
6PM
9PM
12 Fri
3AM
6AM
9AM
12PM
11 ThuJun 2009
6/11/2009 12:00:00 PM - 6/12/2009 12:00:00 PM


June 30, 2009
Loop 360 near Bull Creek, Austin, Texas
Rainfall (0.39 in)
Flow Rate (779 l)
Sample Event (6 SU):Bottle #0
in
0.00
0.05
0.10
0.15
0.20
0.25
0.30
0.35
0.40
l/s
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
6AM
9AM
12PM
3PM
6PM
9PM
1 Wed
3AM
30 TueJun 2009
6/30/2009 5:00:00 AM - 7/1/2009 5:00:00 AM

July 1, 2009

Loop 360 near Bull Creek, Austin, Texas



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Vita

Patrick Martin Frasier was born in San Antonio, TX to Bruce and Jeanie Frasier on October 19, 1985. He was the fourth generation of his family to be raised in Carrizo Springs and the tenth generation to live in Texas. After graduating valedictorian at Carrizo Springs High School in 2004, Patrick entered the College of Engineering at the University of Texas in Austin. Patrick was very active in the Terry Scholar Foundation and Toastmasters International. He was also a member Tau Beta Pi and Chi Epsilon. After graduating with honors in May 2008, Patrick entered the Environmental and Water Resources Engineering graduate program. He plans on teaching high school science upon the completion of his degree.

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