Lake Thunderbird Watershed Implementation Project:
Trailwoods Demonstration Site Monitoring

Draft Final Report

Output 5.3.4d
Lake Thunderbird Watershed Implementation Project, Phase II

OCC Task 11-159
FY 2011 §319(h) Project 5 EPA Grant C9-996100-16

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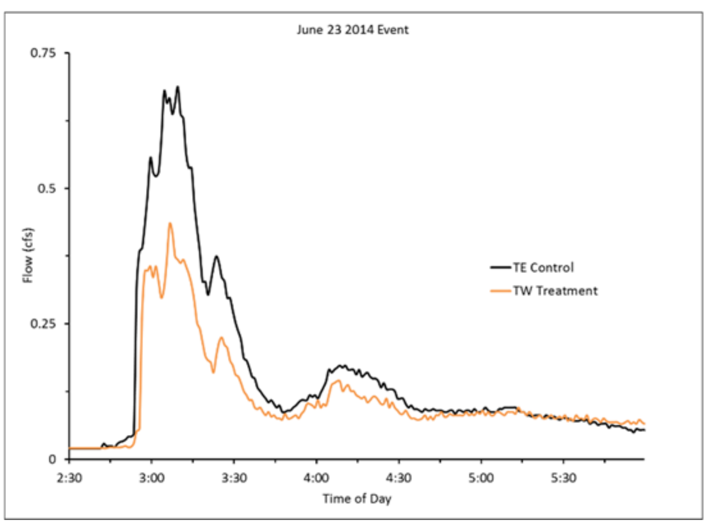
December 2015



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Acknowledgements

The author thanks the U.S. Environmental Protection Agency (EPA) Region VI and the Oklahoma Conservation Commission (OCC) for sponsoring this innovative and important project. Brooks Tramell, Jason Ramming, Greg Kloxin and Judith Wilkins of the OCC Water Quality Division were especially helpful. Additional project partners included Richard McKown, Ideal Homes, Larry Kirkland, CH Guernsey Inc., SMC Engineering, the City of Norman (Public Works and Planning Departments), and the residents of the Trailwoods development. The project was initiated by Reid Coffman, now at Kent State University. Graduate and undergraduate student members of the University of Oklahoma Center for Restoration of Ecosystems and Watersheds (CREW), especially Michael Rice, Noah Berg-Mattson, Brandon Holzbauer-Schweitzer, Jerrett Fowler, Nick Shepherd, Julie LaBar, and Juan Arango Calderon, performed the bulk of the work.

1. Introduction

1.1. Stormwater Impacts

Urban stormwater management has become a major issue for nearly every municipality in the United States. As the natural landscape is urbanized, managing both stormwater quantity (e.g., greater and flashier runoff due to increased impervious surface area) and quality (e.g., elevated pollutant concentrations and subsequent mass loadings) presents challenges. Nearly all water quantity issues created by stormwater are caused by land development and the subsequent loss of water-retention capacity of the soil (Booth and Leavitt 1999). Increased amounts of impervious surface means that a much greater percentage the stormwater runoff is transported directly to adjacent waterways leading to increased peak flows, likelihood of flooding and channel erosion (Booth and Jackson 1997; Liebman et al. 2011; Pappas et al. 2011). Water quality issues have recently become of even greater concern in stormwater management (e.g., USEPA 2012). Depending on land use, stormwater is typically contaminated with elevated concentrations of trace metals, nutrients, bacteria and suspended solids (Duda 1993; Blecken et al. 2012). Solids can be of notable concern because other contaminants attach to solids and are carried into the receiving systems (Wadzuk et al. 2010). Storm event runoff transports these contaminants into receiving waterways. On a watershed scale, the collective contamination of smaller water bodies can lead to major water quality issues in larger bodies of water, oftentimes designated for beneficial uses including drinking water supply. Excess nutrients can lead to cultural eutrophication, creating nuisance algal blooms, fish kills and direct and indirect human health impacts (Wadzuk et al. 2010; Vieux and Associates 2007).

Urban stormwater is a major concern in the Lake Thunderbird watershed of central Oklahoma (Figure 1). The lake and its tributary streams are not supporting all of their designated beneficial uses including Aesthetics, Agriculture, Warm Water Aquatic Community, Primary Body Contact Recreation, Public and Private Water Supply, Fish Consumption, and Industrial and Municipal Process and Cooling Water (OCC 2013). The lake itself is considered a Sensitive Water Supply and, due to elevated turbidity, low dissolved oxygen levels and excessive concentrations of chlorophyll-a (indicative of excess nutrient loading), does not meet its Fish and Wildlife Propagation (Warm Water Aquatic Community) and Public and Private Water Supply beneficial uses. Lake Thunderbird has no point source inputs and excessive nutrient loading in runoff from the watershed, specifically stormwater inputs from rapidly urbanizing areas, is impacting the ability of the lake to supply drinking water and recreation. Lake Thunderbird serves as the primary drinking water source for three communities: Del City, Midwest City and the City of

Norman. Increased urbanization and development within the Lake Thunderbird watershed has been noted to severely impact water quality in the lake (Vieux and Associates 2007; OCC 2013). Nutrient and oxygen-demanding substances loads into Lake Thunderbird have been estimated to include greater than 117,000 kg/yr, 23,000 kg/yr, 236,000 kg/yr and 11,500,000 kg/yr, of total nitrogen (TN), total phosphorus (TP), carbonaceous biochemical oxygen demand (CBOD) and total suspended solids (TSS), respectively (OCC 2013). Lake eutrophication has led also to proliferation of algal species known to cause taste and odor problems, causing concern for both end consumers and water treatment facilities.

Nonpoint sources have been identified as the primary contributors to Lake Thunderbird watershed pollution problems (Vieux and Associates 2007). Specifically, urban stormwater runoff has been shown to increasingly contribute to nutrient and sediment loading. Therefore, addressing urban stormwater quantity and quality is a critical component of lake and watershed management.

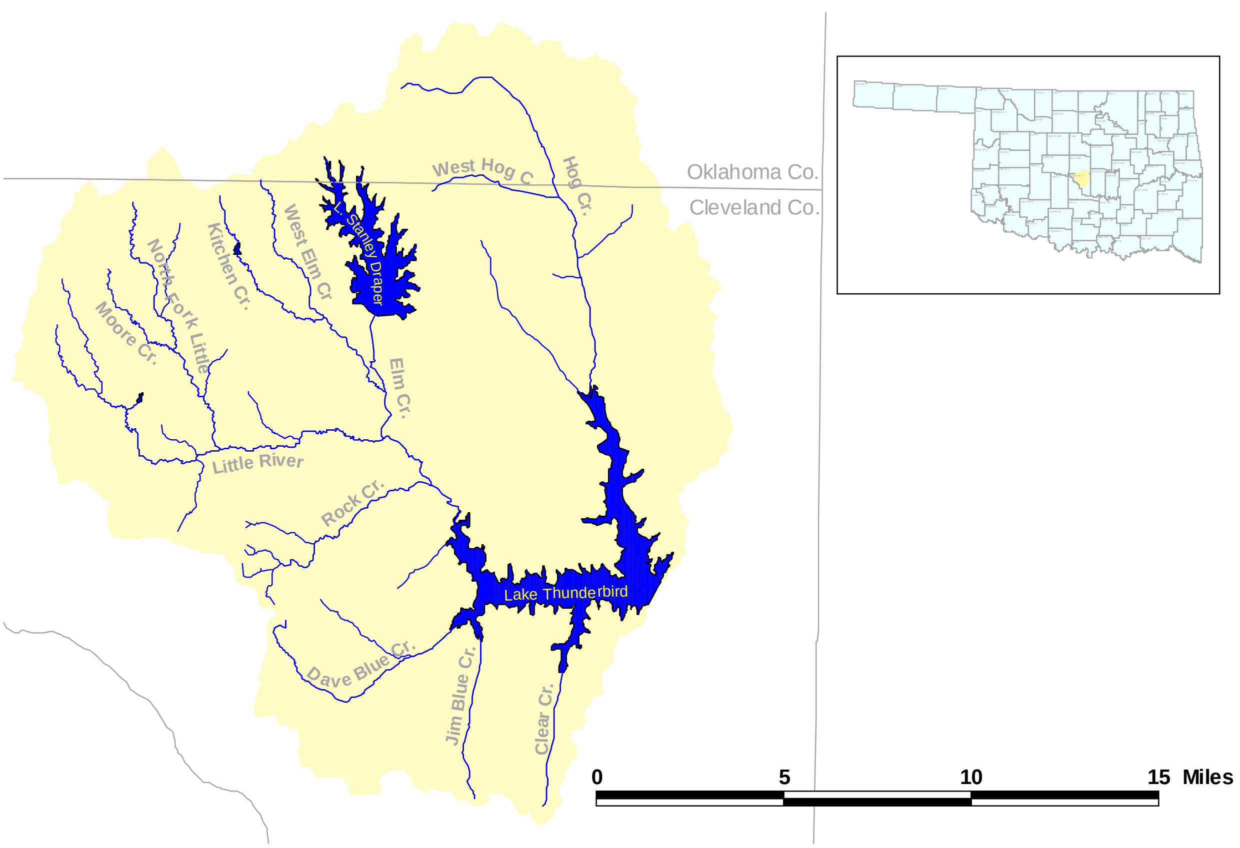


Figure 1. Lake Thunderbird watershed in Cleveland and Oklahoma counties, OK (OCC 2010).

1.2. Traditional Stormwater Management

Traditional urban stormwater management consists of curb and gutter designs to remove water from the land surface as quickly as possible to decrease risks of flooding. These "excess" waters are directed to stormwater detention and retention ponds, designed to collect and store these waters and release them at pre-development rates. These constructed ponds are typically designed and sized for specific storm events based on individual municipal regulations and the use of the Rational method (Harrell and Ranjithan 2003; Hromadka II 1989; Shammaa et al. 2002). The quantity of runoff generated during a given storm event is based on the intensity of the storm, the runoff coefficient of the developed area (based on land use/land cover, soil type, etc.) and the total drainage area (Haestad Methods Engineering 2007). Runoff amounts generated by a specific size storm event can then be calculated. From a practical perspective, runoff from a given area, generally a neighborhood or individual commercial development, is routed into the pond with the intent of matching post-development peak stormwater flows with pre-development conditions.

Historically, detention and retention ponds have been designed with regard to only water quantity concerns. Retention ponds are characterized by outlet structures which retain some amount of water that enters the pond. Only a portion of the water which enters a retention pond during a given storm event flows out of the pond during the same storm event. Provided sufficient precipitation, retention ponds will maintain a permanent water level (USEPA 1999). The freeboard between the permanent water surface level and outlet structure elevation dictates the amount of storage provided by the pond before water flows downstream.

Detention ponds are similar in design to retention ponds except they do not maintain a permanent water level. A detention pond has an outlet structure which allows the pond to drain completely after a given design storm event, albeit at a slower rate than it enters the pond, thus distributing the stormwater flow over a longer period of time and decreasing peak runoff. In general, detention and retention ponds are designed to control peak runoff flows with little to no water quality improvement, although retention ponds may allow for some sedimentation, adsorption, biological uptake and provision of habitat (Walker 1987). Since 1982, some sort of traditional stormwater management, typically retention and detention ponds, have been required for new development in the City of Norman. As is common for most municipalities, current regulations are not adequately flexible to allow for implementation of innovative non-traditional stormwater management options.

1.3. Green Infrastructure/Low Impact Development Best Management Practices

The recognition that urban stormwater runoff detrimentally impacts receiving water bodies has led to increased interest in non-traditional management options. EPA (2015) describes green infrastructure as "an adaptable and multifunctional approach to stormwater management and climate resiliency". It provides many benefits to communities including water quality improvement and conservation, stronger local economies and enhancement of community and infrastructure resiliency. Green infrastructure is a critical tool in the White House Priority Agenda for Enhancing Climate Resilience of America's Natural Resources (CCPR 2014).

The understanding of green infrastructure at the site scale has rapidly evolved over the last several years. The available suite of green infrastructure technologies is often referred to as low impact development (LID) best management practices (BMPs). LID has been described as an innovative stormwater management approach that manages rainfall runoff at the source using distributed decentralized controls (LID Center 2015). The goal is to mimic a given site's pre-development hydrology by implementation of specific BMPs to infiltrate, filter, store, evaporate or detain runoff near the source of generation. EPA (2015) highlights ten LID BMP approaches and/or technologies to address urban stormwater impacts (Table 1). Approaches are often combined and/or used in tandem to address urban stormwater quality and quantity concerns. Because of the innovative nature of green infrastructure applications in an evolving regulatory landscape, LID BMPs are often utilized in coordination with traditional urban stormwater management approaches (e.g., detention or retention basins).

1.4. General Project Description and Tasks

The general approach for the Trailwoods demonstration neighborhood project was to plan, design, construct and monitor LID BMPs to: i) decrease stormwater discharge volumes and improve water quality and ii) serve as a community education vehicle for public officials (Coffman et al. 2009). The revised project work plan identifies several tasks including planning and education, design and construction of the neighborhood, and water quality and quantity monitoring (Coffman et al. 2009). This document summarizes results for Task 5.3.4d: *Monitoring Water Quality and Quantity Evaluation and Assessment: Paired Watersheds* (original Task 5.4.1 in the project work plan).

Table 1. Examples of green infrastructure low impact development best management practices (LID BMPs) from EPA (2015).

Practice	Description	Benefit
Downspout disconnection	Rerouting rooftop drains to collection systems or permeable areas	Enhanced infiltration; especially relevant with combined sewer overflows
Rain gardens and bioswales	Shallow vegetated areas that collect and absorb runoff using plants and soil	Absorption and infiltration; attractive and versatile; also known as bioretention or biofiltration cells
Green roofs	Roofs covered with plants that absorb and use rainwater	Cool and insulate buildings; reduce energy use; cost effective where land values high
Green alleys and streets	Incorporation of a suite of other BMPs in street designs	Soaking and storage; shading and traffic calming
Land conservation	Protection of open space/natural areas within or adjacent to cities	Provision of recreational opportunities; riparian areas, wetlands and steep slopes
Rainwater harvesting	Collection and storage of precipitation for later use	Slow and reduce runoff volume; important in arid regions with limited supply
Planter boxes	Vertical-walled rain gardens in space-limited sites	Appropriate in space-limited sites; provide seating and aesthetics
Permeable pavement	Pervious concrete, porous asphalt, and permeable interlocking pavers	Cost effective where land value high or where icing and flooding problematic
Green parking	Incorporation of a suite of other BMPs in parking lot designs	Collect and absorb runoff; provide shade; reduce heat emissions
Urban tree canopy	Establishment and maintenance of urban trees	Soak up and use rainwater; provide shade; slow traffic

From a monitoring perspective, the Trailwoods demonstration site was designed as a paired watershed study (EPA 1993) to compare a portion of a residential development containing various structural LID BMPs to an adjacent portion using conventionally designed stormwater management practices. The general study design was similar to that used in the Jordan Cove (CT) study (Clausen 2007), however, inclusion of the watershed calibration phase and targeted evaluation of specific practices was not possible. Details regarding the LID BMPs implemented at the Trailwoods demonstration site are summarized in Coffman (2014). In general, four strategies were deployed: i) biological (rain gardens), ii) containment (rain barrels, iii) diversion (downspouts) and iv) capture (porous concrete).

1.5. Task Objectives

The objectives of Task 5.3.4d were twofold:

i. To collect and analyze sufficient water quality and quantity data to compare the performance of LID BMPs to traditional stormwater management techniques by developing representative hydrographs and pollutant concentration/mass loading relationships for an available range of storm events of differing magnitude and duration.
ii. To help build green infrastructure capacity in the Lake Thunderbird watershed through documenting the collective performance of a suite of LID BMPs.

2. Methods

2.1 Watershed Description

The Trailwoods neighborhood demonstration project is located within the Little River basin of the larger Lake Thunderbird watershed in central Oklahoma. The Lake Thunderbird watershed (HUC 111090203010) covers approximately 670 km^2 (259 mi^2) in the Central Great Plans and Cross Timbers ecoregions (Woods et al. 2005) of Oklahoma and Cleveland Counties. Land use is predominately agricultural and residential (Vieux and Associates 2007). The primary tributary to Lake Thunderbird is Little River; other noteworthy tributaries include Hog Creek, Clear Creek, Dave Blue Creek, Jim Blue Creek, Rock Creek, Moore Creek, Kitchen Creek and Elm Creek (Figure 1). Population growth in the watershed has been steady since creation of Lake Thunderbird by the Bureau of Reclamation in 1965. The 1960 population of Cleveland County, where the majority of the watershed is located, was 47,600. In 2014, the estimated county population was nearly 269,908, an increase of almost six-fold. Much of the population growth may be attributed to urban sprawl in the Cities of Norman and Moore, with changes from 33,412 and 1,221 in 1960 to 118,040 and 59,196 in 2014, respectively (U.S. Census 2015).

2.2 Study Site Description

The Trailwoods residential subdivision (N 35^{o}15’2.29”, W 97^{o}27’3.47”, Figure 2) is located in Norman, OK in the upper reaches of the Little River watershed, the primary western inflow to Lake Thunderbird. The project site is zoned R1 (Residential) and bordered by existing and in-development commercial and residential properties. A horseshoe shaped portion of the development was selected for the project, divided into two study watersheds. This paired watershed approach was designed in an attempt to control for other contributing factors (e.g., drainage area, slope, road and driveway cover, soil types, etc.) as to discriminate the effectiveness of LID BMP installations. The control watershed (designated Trail East or TE) included traditional curb and gutter stormwater management. Storm-derived water quality and quantity at the toe of TE provided baseline conditions representative of most residential neighborhoods in central Oklahoma. The treatment watershed (designated Trail West or TW) included four green infrastructure strategies. Specific design information regarding the four strategies are summarized in Table 2. Comparing storm-derived water quality and quantity at the toe of the TW watershed with those of the TE watershed allowed a direct comparison of LID BMP effectiveness. The TE control and TW treatment watersheds were 0.92 hectare (2.28 acres) and 0.93 hectare (2.31 acres) in size, respectively.

Project site selection and planning began in the summer of 2009, with a site master plan created by early 2010. Following City of Norman Public Works Department approval, construction drawings were developed and, by April 2010, preliminary grading and utilities placement began. Roads were paved in October 2010. Home construction began in early 2011 and rain gardens were installed in the treatment watershed as each home was completed. However, home sales slowed dramatically in late 2011, and the last home and rain garden were not completed until October 2013. The final project site included 35 lots, equally divided between the control and treatment watersheds. The treatment watershed included downspout diversions, 18 rain gardens (366 m^2 or 3940 ft^2), 17 rain barrels, and a small section (11 m^2 or 120 ft^2) of porous concrete in the outflow stormwater flume.

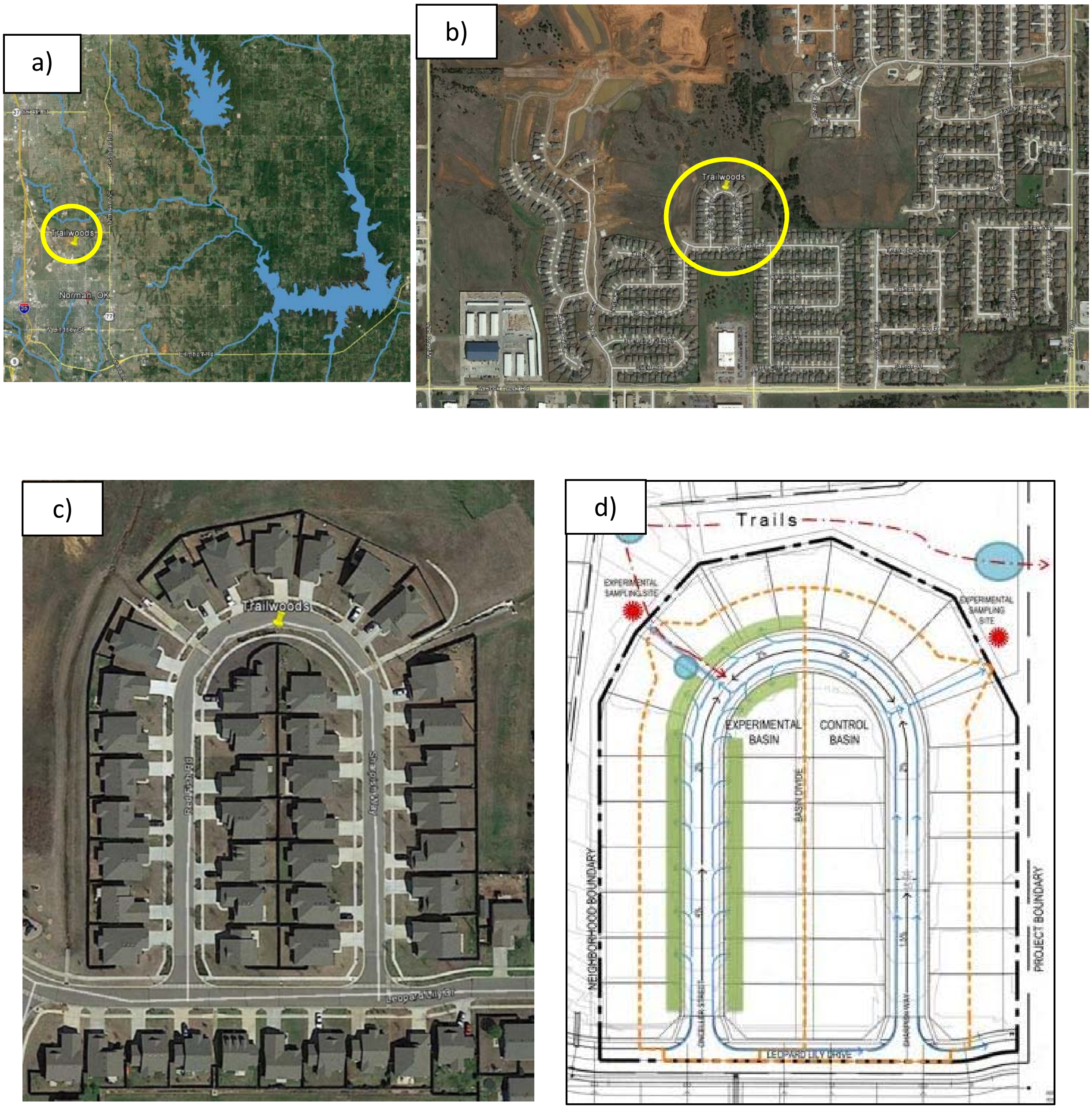


Figure 2. a) Study site location with respect to City of Norman and Lake Thunderbird, b) Trailwoods neighborhood, c) Trailwoods study site (aerial Imagery from Google Earth 2015) and d) diagram showing TE control watershed ("Control Basin") and TW treatment watershed ("Experimental Basin"), from Coffman (2014).

Table 2. Description of LID BMP strategies installed in the TW treatment watershed. Details are available in Coffman (2014).

Strategy	Description
Rain gardens	• Curbside between road and sidewalk • Each 24 m^2 (256 ft^2) • Depth 0.46-61 m (1.5-2 ft) • Coarse engineered substrate of 70% expanded clay, 20% sand, 10% compost • Planted mix of native and exotic vegetation
Rain barrels	• Front corner of each house • 189 L (50 g) capacity
Downspout diversion	• Diverted into grass swales and rain gardens
Porous concrete	• Head of stormwater flume • 11 m2 (120 ft2) • 0.21 m (0.67 ft) concrete over 0.91 m (3 ft) aggregate

2.3 Sampling Design and Methods

Stormwater runoff generated in each watershed was directed to concrete stormwater flumes designed for the Q_{100} storm event (Table 3). The TE control watershed stormwater flume was approximately 43 m (140 ft) long by 1.3 m (4.25 ft) wide; the TW treatment watershed stormwater flume was approximately 18 m (60 ft) long by 1.2 m (4 ft) wide. At the downstream end of each stormwater flume (the toe of each watershed), prefabricated Fiberglas reinforced polyester (FRP), 18" x 45^o trapezoidal test flumes (Plasti-Fab Inc.) were installed (Figure 3). These test flumes were designed to accommodate the Q_2 to Q_{100} storm events and facilitate water quality sampling and water quantity (e.g., storm hydrograph) determinations. Ports in the test flumes were connected to automatic samplers which recorded flume water levels and facilitated water sample collection based upon pre-installed programs.

Automatic flow-activated samplers (Isco model 6712 with Isco model 730 bubbler modules) were used for the hydrologic monitoring portion of the experiment. Each autosampler was housed inside a pre-fabricated gun safe (Figure 4) near the watershed outflow with appropriate connections to the trapezoidal test flume in order to monitor discharge rates and trigger sample collection. The bubbler module measured water levels in the test flume and these data were recorded by the autosampler. Data were downloaded once a sampling event was completed. These water level data were then entered into the appropriate trapezoidal flume equation

Table 3. Calculated design flows for storms of appropriate recurrence intervals.

Design storm	TE control watershed design flow (cfs)	TW treatment watershed design flow (cfs)
Q2	7.38	6.40
Q5	8.84	7.49
Q10	10.07	8.53
Q25	11.67	9.89
Q50	13.27	11.24
Q100	14.74	12.49

Figure 3. Installed trapezoidal test flume at downstream end of concrete stormwater flume showing downstream concrete pad. Note sediment deposition in flume from newly finished lots.

(Equation 1) to calculate flow in cubic feet per second (cfs), where H = head or depth of water (in feet) in the trapezoidal test flume. Flows were then plotted versus time to develop storm hydrographs for each of the studied watersheds.

$$Q\ (\text{cfs}) = 2.853[(H+0.13558)^{2.497}] \qquad \text{Equation 1}$$

When water levels within the trapezoidal test flume reached 0.15 ft depth, the autosampler activated a sampling regime. The samplers would rinse and purge the sample lines three times before beginning sample collection. Two sampling regimes were used in this study. The first or "first flush" regime, used for storm events between September 2013 and April 2015, collected a

Figure 4. Trapezoidal test flume and gun safe (note buried connections between the two) and autosampler inside gun safe.

single 3.5-L sample as soon as a water level depth of 0.15 ft was reached and maintained in the test flume. The second or “storm composite” regime, used for storm events between May and September 2015, began collection of 20-mL samples after the first 50 ft^3 of stormwater runoff passed through the flume and continued collection of 20-mL increments for each 50 ft^3 of stormwater runoff to generate a storm-event composite sample.

Collected samples were gathered as soon as possible after a given storm event and always within 24 hours. The autosamplers utilized 5-L Nalgene sample bottles. Collected volumes were then divided into representative vessels for subsequent analyses in the laboratories of the University of Oklahoma Center for Restoration of Ecosystems and Watersheds (CREW) under an EPA-approved Quality Assurance Project Plan (QAPP; FY 2008 §319(h), EPA Grant # C9-996100-14, Project 10, Output 10.3.2a; OCC 2012)

Samples for analyses of total nitrogen, ammonia-nitrogen, nitrate-nitrogen, total phosphorus and dissolved reactive phosphorus were collected in clean 250-mL HDPE bottles with zero-headspace. No preservatives were used as sample analyses were completed immediately upon return to the laboratory. All nutrient analyses were completed via ion chromatographic or spectrophotometric techniques. Individual clean 1-L HDPE bottles with zero headspace were used for total suspended solids (TSS) and carbonaceous biochemical oxygen demand (CBOD) samples. Again, no preservatives were used as sample analyses were completed immediately upon return to the laboratory. TSS was determined gravimetrically and CBOD was estimated via standard five-day incubations. Samples for total metals (Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn) analyses were collected in clean 250-mL HDPE bottles and were preserved with approximately 2 mL of trace metal grade-nitric acid. Samples for total metals analyses were first hot acid microwave digested and subsequently analyzed via simultaneous axial inductively coupled plasma - optical emission spectroscopy. All sample analyses were completed within designated hold times following CREW Standard Operating Procedures (SOPs) and the approved methods found in Table 3.

Table 3. Water quality analytes and methods for this study.

Analyte	Method
Total nitrogen	Hach TNT 10071
Ammonia-nitrogen	EPA 350.3
Nitrate-nitrogen	EPA 300
Total phosphorus	EPA 365.3
Dissolved reactive phosphorus	EPA 300
Total suspended solids	EPA 160.2
Carbonaceous biochemical oxygen demand	EPA 5210b
Total metals	EPA 3015 (digestion) and EPA 6010

In addition to samples collected for laboratory analyses, field physical parameter data were collected following CREW SOPs. If stormwater runoff was still flowing through the test flumes upon arrival, measurements of pH, dissolved oxygen, temperature, specific conductance and total dissolved solids were obtained directly. If adequate stormwater runoff was not available and the automatic samplers had already completed sample collection, measurements were obtained from the collected samples.

2.4 Quality Assurance and Statistical Analyses

All quality assurance and quality control protocols outlined in the approved QAPP and associated CREW SOPs were followed. Field blanks and duplicates were collected along with laboratory blanks, duplicates, and matrix spikes (known additions) and represented at least 1/3 of all analyses completed. Quality assurance checks included calculation of relative percentage deviation for all duplicate analyses and percent recoveries for matrix spikes. Requirements for precision, accuracy, representativeness, comparability and completeness, as outlined in the QAPP, were followed.

In terms of statistical analyses, descriptive statistical metrics (mean, median, standard deviation, standard error) were calculated for all measured parameters. Box plots and other appropriate figures were generated to help visually discriminate sample differences. Student's t-tests were used, when appropriate, to compare means. Analysis of variance (ANOVA) was used to determine significance of relationships between paired observations, assuming normal distribution of the regression residuals, equal variances and independence. If necessary, data were log-transformed to approach normality using the Wilks-Shapiro statistic. F-tests were used to evaluate equality of variance and residual plots examined for independence of errors. Analysis of covariance (ANCOVA) was used to determine any significant effects of the treatment and bivariate plots of paired observations were generated.

3. Results and Discussion

Despite the initial delays caused by slow home sales, a regional lack of precipitation for a substantial portion of the original study period and periodic malfunctions of the autosamplers, a total of 35 storm events (Table 4) were captured from September 28, 2013 through September 20, 2015. For the first flush sampling regime from September 2013 through April 2015, 25 events were captured but, due to autosampler malfunctions, hydrographs were generated for only 21 events, including five when runoff samples were not collected but only 19 for both watersheds. In addition, valid runoff samples were collected for only 19 events, including four when hydrographs were not generated. Therefore, due to these problems, only 15 events were captured for the first flush sampling regime for which both valid hydrographs and water quality samples were generated. For the storm composite sampling regime, 10 events were captured between May and September 2015, and valid hydrographs and water quality samples were generated for all events.

3.1 Precipitation Data

Storm event rainfall data generated on the study site showed median and mean event precipitation amounts of 0.94 and 0.66 inches (Table 5). Overall, event total rainfall amounts compared well with daily data from the Oklahoma Mesonet Norman Station (OCS 2015) located 2.17 km (1.35 miles) southwest of the study site. On a few occasions, event totals exceeded daily totals measured at this location, demonstrating the spatial and temporal variability of some storms. Individual storm event magnitudes ranged from 0.04 to 3.99 inches.

Table 4. Rainfall data for all storm events sampled in this study.

Storm event date	Daily rainfall (inches)	Maximum five-minute rainfall rate (inches/hour)	Previous day daily rainfall (inches)	Event total rainfall (inches)
First flush sampling regime				
September 28, 2013	1.39	2.64	0	---
October 14, 2013	0.72	0.6	0	---
October 31, 2013	0.28	0.84	0.26	0.31
November 25, 2013	0.07	0.12	0	0.18
December 12, 2013	0.03	0.12	0.07	0.04
March 15, 2014	1.10	0.48	0	---
April 27, 2014	0.06	0.60	0	0.06
May 27, 2014	0.29	0.24	0.09	0.38
June 06, 2014	0.50	1.08	0	0.50
June 07, 2014	0.21	0.48	0.50	1.19
June 12, 2014	1.47	1.68	0	---
June 19, 2014	0.35	0.84	0	0.33
June 23, 2014	0.58	1.92	0	0.58
July 09, 2014	0.68	0.72	0	0.68
July 30, 2014	1.39	0.72	0	1.39
August 09, 2014	0.76	1.80	0	0.76
August 18, 2014	0.51	1.80	0	0.51
September 06, 2014	0.62	0.84	0.18	0.66
October 5, 2014	0.24	1.56	0	---
October 10, 2014	1.43	2.16	0	1.43
October 12, 2014	0.61	1.32	0.03	1.01
November 04, 2014	1.30	0.72	0.02	1.32
November 22, 2014	2.12	1.68	0	---
March 25, 2015	0.47	2.76	0	0.47
April 13, 2015	1.52	2.16	0	1.52
Storm composite sampling regime				
May 22, 2015	0.68	0.48	0	0.66
May 24, 2015	0.90	0.84	3.38	3.99
June 29, 2015	0.51	2.04	0	0.50
July 03, 2015	2.61	2.64	0.86	3.47
July 07, 2015	1.88	2.04	0.02	1.88
July 20, 2015	0.25	0.96	0	0.76
August 04, 2015	0.50	0.48	0	0.50
August 19, 2015	0.52	0.84	0	0.52
September 08, 2015	0.41	1.56	0	0.34
September 20, 2015	1.32	1.20	0.02	1.32

Table 5. Summary rainfall statistics for storm events sampled in this study.

	Daily rainfall (inches)	Maximum five-minute rainfall rate (inches/hour)	Previous day daily rainfall (inches)	Event total rainfall (inches)
Mean	0.81	1.23	0.16	0.94
Median	0.61	0.96	0.00	0.66
Standard deviation	0.62	0.75	0.59	0.90
Maximum	2.61	2.76	3.38	3.99
Minimum	0.03	0.12	0.00	0.04
Standard error	0.10	0.13	0.10	0.17

According to data provided by the Oklahoma Mesonet Norman Station (OCS 2015), measureable precipitation (≥ 0.01 inches) occurred on 27% of the days during the 734-day study period (representing 198 individual days) between the first and last sampling events. Many of these events were too small to generate hydrographs and/or trigger the autosamplers and were therefore were not considered further. For example, 32%, 45% and 74% of these small precipitation events were for rainfall amounts < 0.05, 0.1 and 0.5 inches, respectively. Of the days with measureable precipitation, 51 days (26%) had rainfall totals ≥ 0.5 inches, and only 24 days (12%) had rainfall totals ≥ 1 inch. For days that included sampling events, daily rainfall averaged 0.81 ± 0.10 inches. Maximum and minimum daily rainfall amounts on sampling event days were 2.61 and 0.03 inches at the Norman Mesonet Station, respectively.

The quality of stormwater runoff depends greatly on antecedent conditions, including time from last rainfall. A given storm of adequate magnitude and duration essentially washes contaminants from the land surface, thus decreasing the likelihood of elevated contaminant concentrations in a subsequent runoff event. For the 35 sampled storm events, 24 events occurred on dates with zero rainfall in the prior 24 hours (Table 4). Of the remaining 11 sampling events, previous day 24-hour rainfall totals were ≥ one inch for a single event, ≥ 0.5 inches for three events, ≥ 0.1 inches for five events and ≥ 0.05 inches for seven events.

The period of study essentially includes the 2014 and 2015 water years (October 1, 2013 - September 30, 2015). Monthly rainfall totals for this period indicate a seasonally wet summer and fall in water year 2014, and an exceedingly wet spring and summer in water year 2015 (Figure 5 and Table 6). The long-term annual average precipitation for Norman is 34.67 inches. Total rainfall amounts for water years 2014 and 2015 were 21.63 and 56.32 inches, respectively (Figure 6). Therefore, the two water years sampled as part of this study represented 62% and 161% of annual average rainfall. The historic climate record (1895-2015) for central Oklahoma indicates that annual (calendar year) precipitation amounts vary from less than 20 inches to greater than

56 inches per year (OCS 2015). Therefore, the differences seen in this study are not unexpected, yet they do represent nearly historic extremes.

Seasonal convective storms may have a substantial influence on stormwater runoff in the climate of the central Great Plains. These large events may contribute a substantial portion of annual precipitation. For example, in November 2013, the greatest 24-hour rainfall total amount represented 72% of the monthly total and 8% of the annual water year precipitation. Likewise in September 2015, the greatest 24-hour rainfall total amount represented 67% of the monthly total and 2% of the annual water year precipitation. In both "dry" and "wet" years, these large events may contribute a substantial portion of annual precipitation and play a considerable role in the generation of stormwater runoff.

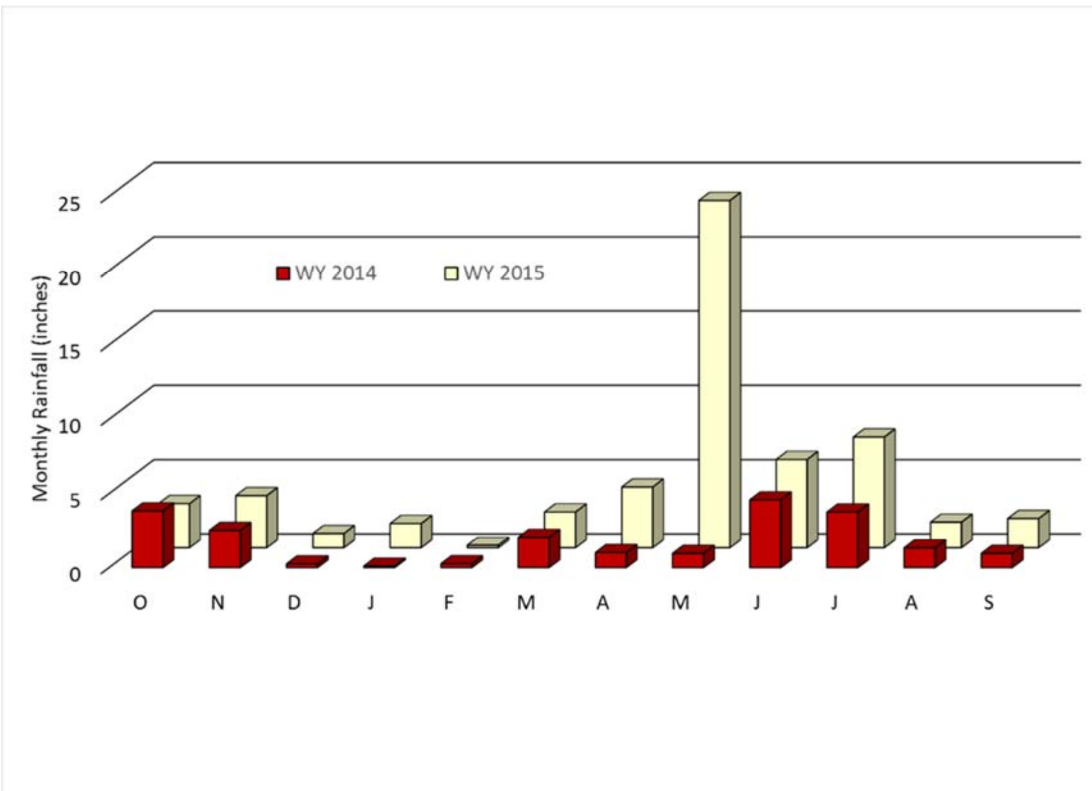


Figure 5. Monthly rainfall totals for water years 2014 and 2015 in Norman, OK.

Table 6. Monthly rainfall statistics for the study period from the Mesonet Norman Station.

	Monthly rainfall (inches)	# days with rain ≥ 0.01 inches	# days with rain ≥ 0.10 inches	Greatest 24 hour total (inches)
Water Year 2014				
October	3.84	10	9	0.81
November	2.52	10	4	1.82
December	0.25	7	0	0.08
January	0.10	3	0	0.05
February	0.26	5	1	0.16
March	2.05	6	5	1.10
April	1.01	10	4	0.30
May	0.96	9	3	0.29
June	4.58	9	7	1.47
July	3.76	6	5	1.39
August	1.34	5	2	0.76
September	0.96	4	3	0.62
Total	21.63	84	43	---
Water Year 2015				
October	2.98	9	6	1.43
November	3.52	6	2	2.12
December	0.97	12	3	0.34
January	1.64	6	4	0.69
February	0.17	5	0	0.05
March	2.42	12	7	0.51
April	4.10	14	7	1.52
May	23.39	19	15	4.67
June	5.95	7	7	1.67
July	7.46	11	7	2.61
August	1.74	5	4	0.52
September	1.98	6	3	1.32
Total	56.32	112	65	---

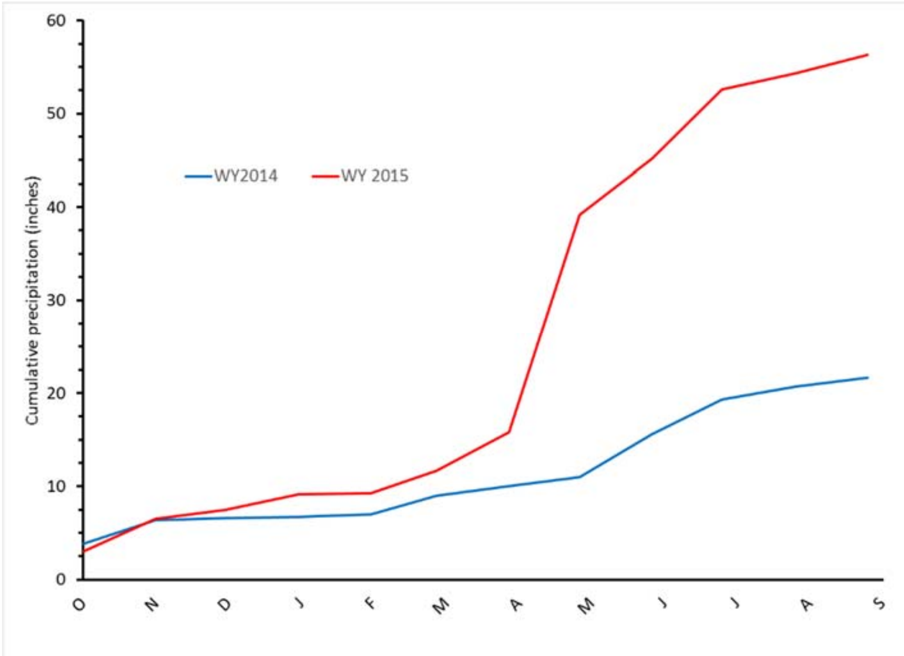


Figure 6. Cumulative precipitation for waters years 2014 and 2015 in Norman, OK.

3.2 Hydrologic Data

3.2.1 Storm Hydrographs

Storm event hydrographs were developed directly from data recorded by the Isco autosamplers. On occasion, one or both of the paired units failed to trigger and record data despite sufficient rainfall and runoff volumes being generated. However, an adequate number of storm events were captured for the purposes of this study (Table 7; Figure 7 through Figure 37).

Construction was completed in October 2013 and fall 2013 hydrographs (October 31 and November 25; Figures 7 and 8) represent site conditions immediately following final grading and sod placement. Both hydrographs show TW treatment watershed total and peak discharge rates below TE control peak discharge rates. The November event shows a delayed, yet steep, rising limb for the TW treatment watershed. The peak discharge rate is lower than the TE control watershed and the falling limb shows a distinct lengthening for a longer duration, presumably as the rain gardens filled and drained slowly. This phenomenon was not apparent for the October event. However, it must also be noted that substantial deposition of accumulated sediment clogged the throats of the trapezoidal test flumes for both of these events. Hydrograph generation and water sample collection was inhibited by this problem, which continued for several months. The last lot completed was adjacent to the TW treatment test flume, exacerbating this problem.

Table 7. Event rainfall and resulting total and peak discharge rates for the study watersheds.

		TE Control		TW Treatment	
Event	Total Rainfall (in)	Total Q (cfs)	Peak Q (cfs)	Total Q (cfs)	Peak Q (cfs)
10/31/2013	0.31	85.6409	1.5272	62.9486	0.8914
11/25/2013	0.18	59.8824	0.2624	53.8059	0.2474
12/12/2013	0.04	43.5035	0.0788	55.409	0.1184
4/27/2014	0.06	31.4769	0.2053	32.5531	0.2009
5/27/2014	0.38	59.0566	0.2474	56.976	0.2053
6/6/2014	0.50	51.7957	0.7789	54.6313	0.5299
6/7/2014	1.19	119.3255	0.7789	120.7808	0.4968
6/19/2014	0.33	72.6465	2.7028	70.3556	1.5916
6/23/2014	0.58	62.7352	0.6875	68.5241	0.4344
7/9/2014	0.68	73.8914	0.7059	55.2436	0.4483
7/30/2014	1.39	120.8084	0.6487	126.1858	0.4795
8/9/2014	0.76	222.2883	10.3833	147.4025	6.4759
8/18/2014	0.51	117.9406	3.6988	88.9058	1.7466
9/6/2014	0.66	63.5352	0.6967	72.3183	0.5299
10/10/2014	1.43	146.0369	2.7514	118.7422	1.4787
10/12/2014	1.01	130.1532	1.2414	118.2211	0.7371
11/4/2014	1.32	130.5171	0.5834	111.6625	0.4117
3/25/2015	0.47	95.6677	4.2729	72.8253	1.961
4/13/2015	1.52	181.0536	2.2518	120.9975	1.0362
5/22/2015	0.66	76.5710	0.6665	42.7670	0.2360
5/24/2015	3.99	716.2800	9.9258	411.2800	4.2096
6/29/2015	0.50	37.6810	0.6665	55.8380	0.4554
7/3/2015	3.47	622.9700	9.2627	335.4100	5.1270
7/7/2015	1.88	91.8210	1.7466	76.9970	0.8020
7/21/2015	0.76	152.2500	1.2544	191.8300	0.7789
8/4/2015	0.50	41.7590	0.3623	45.1440	0.2250
8/19/2015	0.52	50.4500	0.6665	92.3040	0.5724
9/8/2015	0.34	36.5280	0.8808	27.2730	0.7371
9/20/2015	1.32	72.889	0.7277	79.771	0.6113
Mean	0.94	129.90	2.09	102.31	1.16
Median	0.66	76.57	0.78	72.83	0.57
Std. Dev.	0.90	156.95	2.88	84.34	1.53
Maximum	3.99	716.28	10.38	411.28	6.48
Minimum	0.04	31.48	0.08	27.27	0.12
Std. Error	0.17	29.14	0.53	15.66	0.28

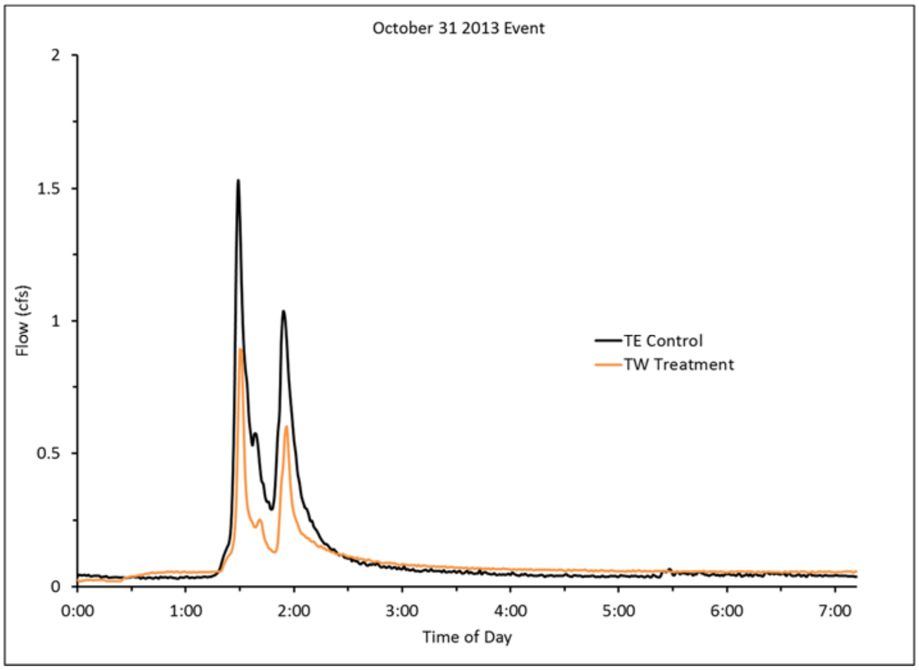


Figure 7. TE control and TW treatment watershed hydrographs for October 31, 2013 storm event of 0.31 inches.

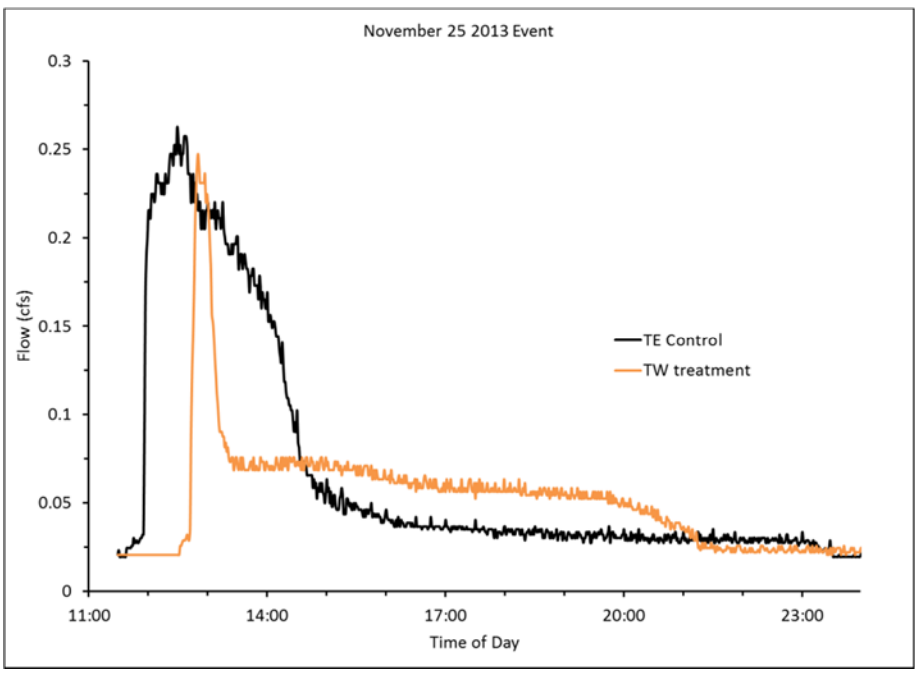


Figure 8. TE control and TW treatment watershed hydrographs for November 25, 2013 storm event of 0.18 inches.

The December event (Figure 9) was not so much a storm event as a “melt event”, especially on the TW treatment side of the study site. Accumulated ice clogged both the concrete stormwater flume and trapezoidal test flume. Ice also blocked flow into the porous concrete as it accumulated at a pedestrian bridge upstream of this section. The rapidly rising limb of the hydrograph represents the breaking of this “dam” and the release of a considerable volume of accumulated waters. The spikiness of both hydrographs likely represents ice flows, blockages and releases in both concrete stormwater and trapezoidal test flumes. Determination of base flow conditions were also compromised for this event, again due to ice accumulations. In any case, total and peak discharge rates were found to be anomalously greater (by 27% and 50%, respectively) for the TW treatment watershed compared to the TE control watershed for this winter event.

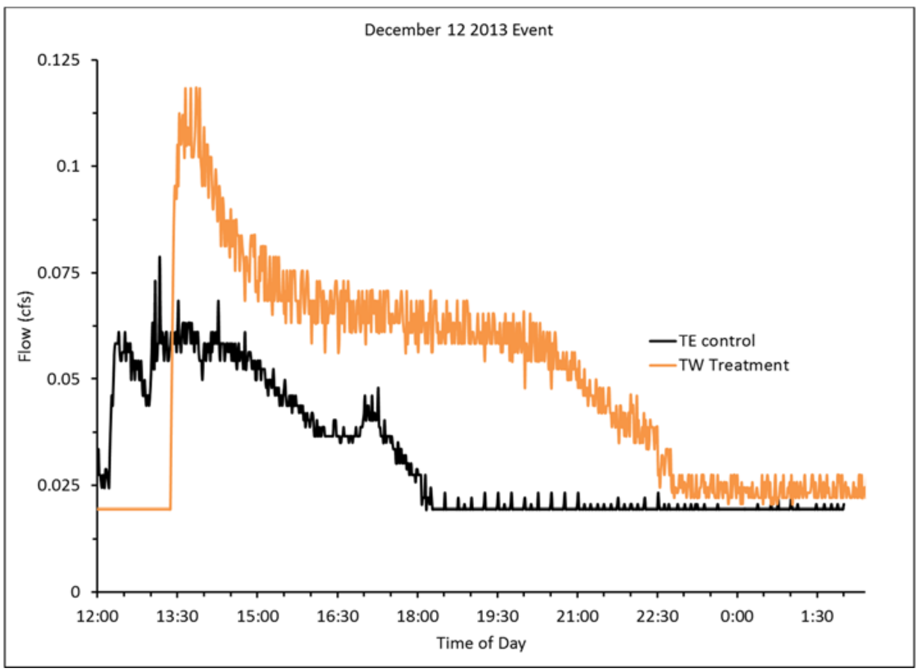


Figure 9. TE control and TW treatment watershed hydrographs for December 12, 2013 ice melt storm event of 0.04 inches. It is likely that the measured precipitation amount was compromised by icing. The peaks of the hydrographs represent melting and release of accumulated runoff waters rather than true storm-event driven runoff values.

Hydrographs for the spring 2014 events (one each in March, April and May and five in June) show similar total discharge rates for the TE control and TW treatment watersheds, when both autosamplers recorded data. Several of these storms consisted of multiple rain events and/or considerable changes in rates of precipitation and subsequent runoff, thus producing multi-peaked hydrographs (Figure 10 through Figure 17).

Total rainfall amounts ranged from 0.06 to 1.19 inches for these events. Overall total discharge rates were very similar for the paired watersheds, but typically greater for the TW treatment watershed than the TE control watershed (by 3.4% for April, 5.5% for June 6, 1.2% for June 7 and 9.2% for June 23). TW treatment watershed total discharge rates were lower by 3.5% for May and 3.1% for June 19. Peak discharge rates, however, were lower for the TW treatment watershed for all events for which data are available for both watersheds, by an average of 27.5%, ranging from 2.1% to over 41%. The storage provided by the rain barrels, rain gardens and short section of porous concrete inhibited rapid runoff, decreasing peak discharge rates and slowly releasing stormwater over a longer period of time (as evidenced by the lack of difference in the total storm discharge rates).

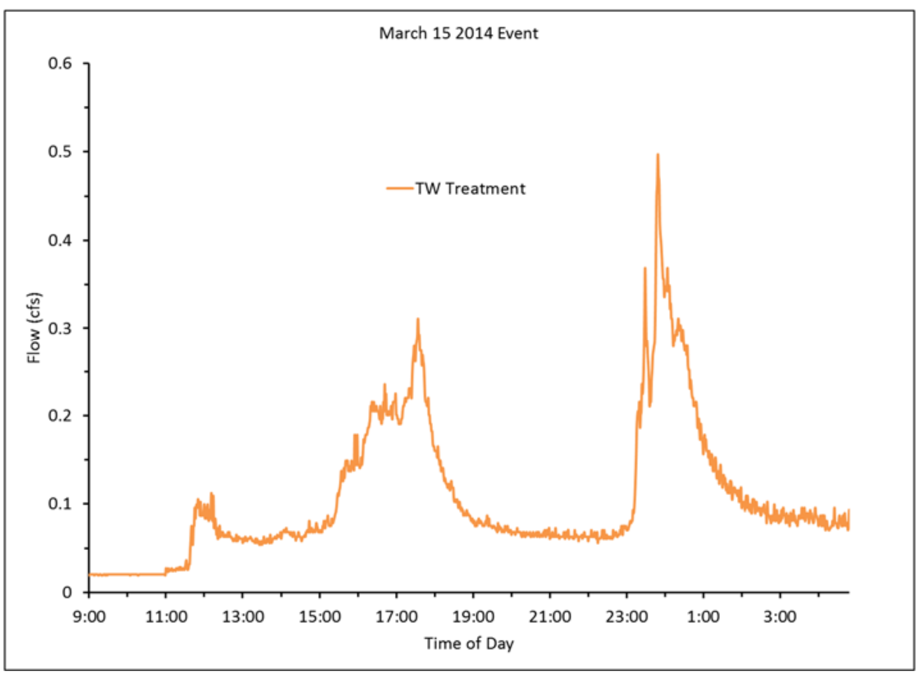


Figure 10. TW treatment watershed hydrograph for March 15, 2014 storm event of 1.29 inches. The TE control autosampler failed to collect hydrographic data or storm water quality samples for this event.

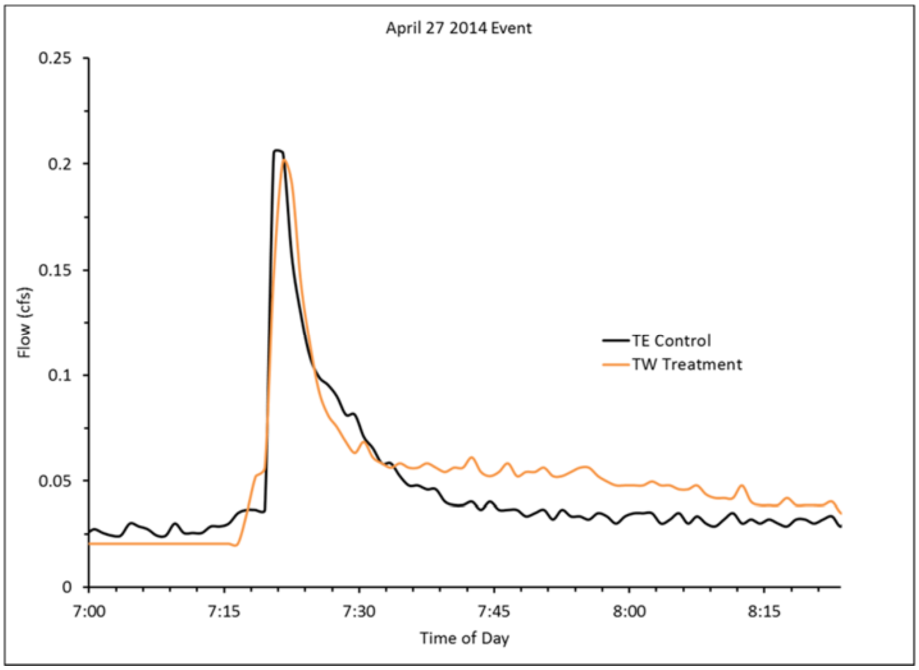


Figure 11. TE control and TW treatment watershed hydrographs for April 27, 2014 storm event of 0.06 inches.

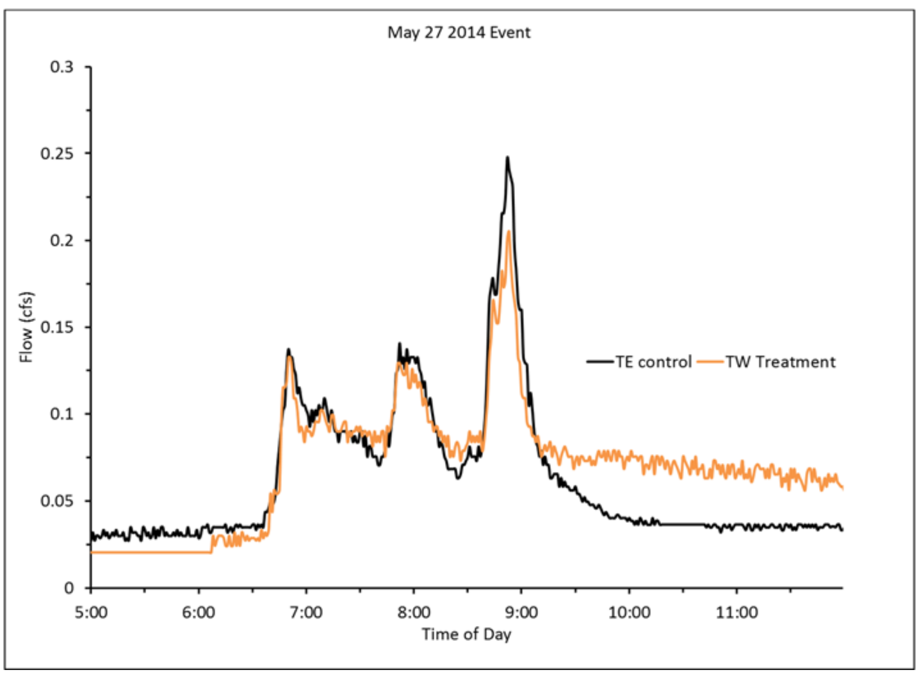


Figure 12. TE control and TW treatment watershed hydrographs for May 27, 2014 storm event of 0.38 inches, showing multiple peaks for both watersheds and both lower peak and delayed release from the TW treatment watershed.

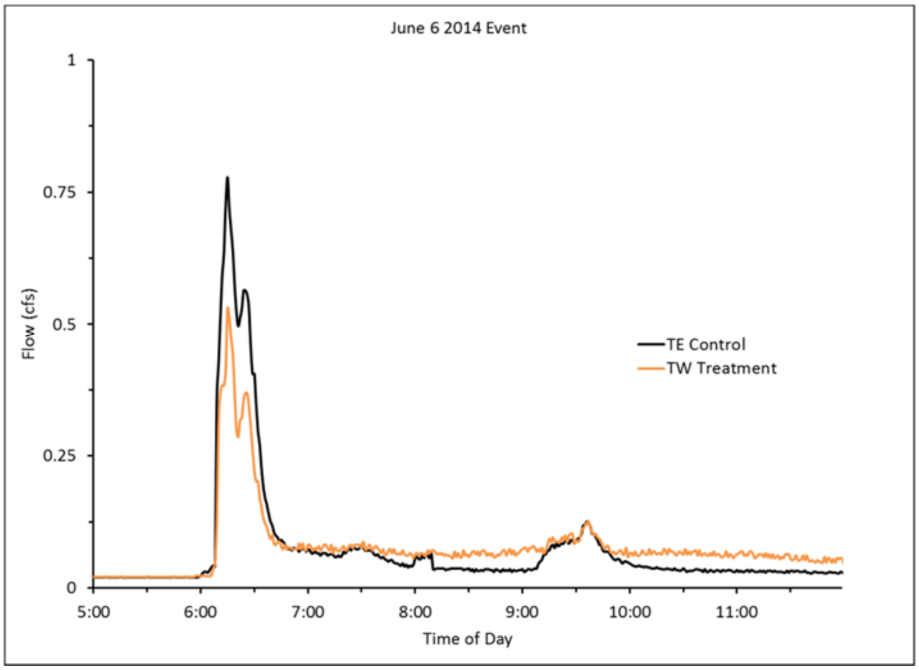


Figure 13. TE control and TW treatment watershed hydrographs for June 6, 2014 storm event of 0.50 inches, showing multiple peaks for both watersheds and both lower peak and delayed release from the TW treatment watershed.

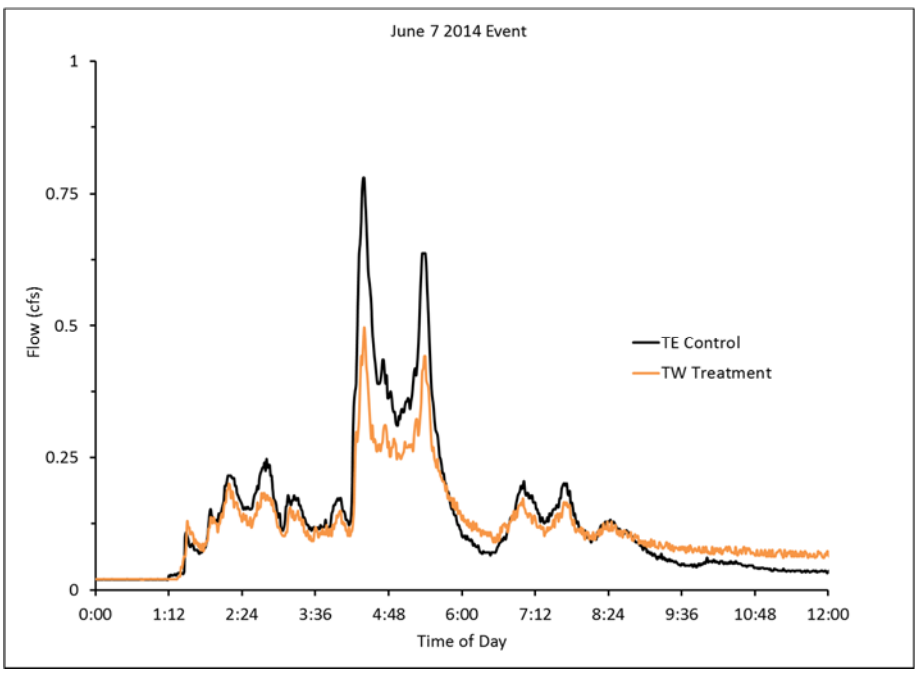


Figure 14. TE control and TW treatment watershed hydrographs for June 7, 2014 storm event of 1.19 inches, showing similar results to June 6 event. Despite immediately following a previous event, concerns about lack of precipitation prompted sampling of this event.

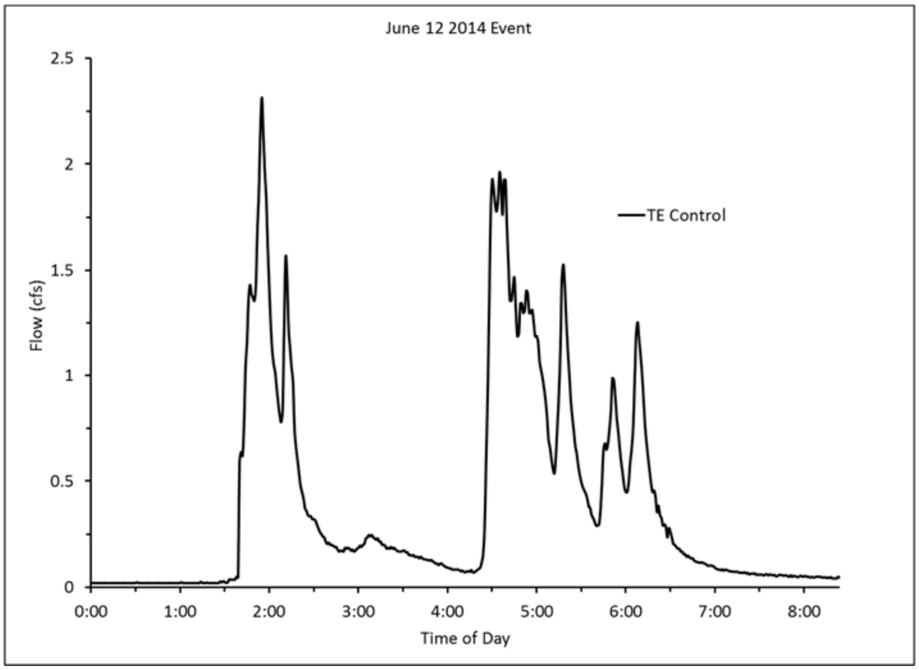


Figure 15. TE treatment watershed hydrograph for June 12, 2014 storm event of 1.47 inches. The TW control autosampler failed to collect hydrographic data or storm water quality samples for this event.

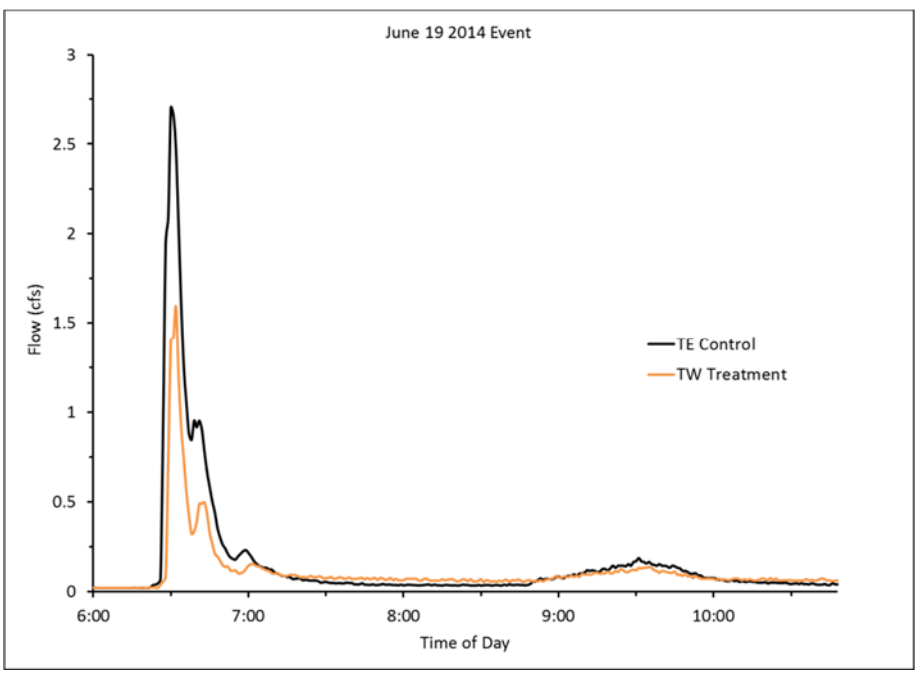


Figure 16. TE control and TW treatment watershed hydrographs for June 19, 2014 storm event of 0.33 inches, showing depressed peak discharge for TW treatment watershed.

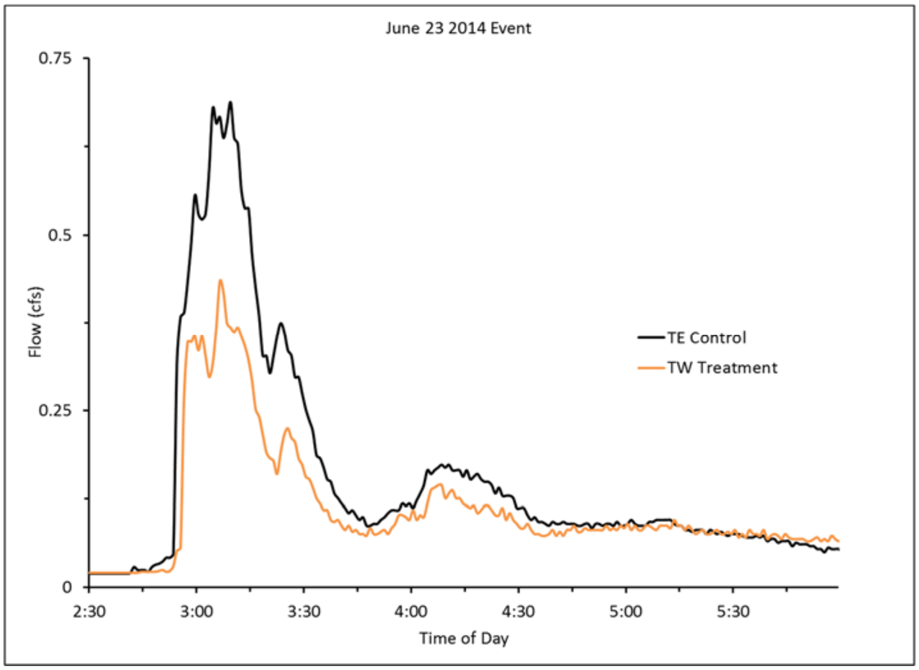


Figure 17. TE control and TW treatment watershed hydrographs for June 23, 2014 storm event of 0.58 inches, showing depressed peak discharge for TW treatment watershed.

Five summer 2014 storm events were sampled, including two in July, two in August and one in September (Figure 18 through Figure 22). Most of these events included classic rapidly evolving and quick moving convective thunderstorms. The July events showed multiple peaks (similar to the spring events), but the later storm events produced characteristic hydrographs with single substantial peaks.

Total rainfall amounts ranged from 0.66 to 1.39 inches for these events. With the exception of the July 30 event, hydrographs for each watershed tracked one another, with the TW treatment watershed demonstrating lower peak discharge rates overall. Total discharge and peak discharge rates for the TW treatment watershed were lower by 13.1% and 35.4%, respectively, including two events when TE control total discharge rates were lower than TW treatment total discharge rates. It appears that by the middle of the first full growing season for the rain gardens and residential lots, the LID BMPs were demonstrating the desired effects on stormwater runoff hydrographs, decreasing both the total and peak discharge for the given events. Total discharge amounts for the TW treatment watershed were 18.65, 74.89 and 29.03 cfs (25.2, 33.7 and 24.6%) lower for three events, and 5.37 and 8.78 cfs (4.4 and 13.8%) higher for the other two. Peak discharges were lower by 0.26, 0.17, 3.91, 1.95 and 0.17 cfs (36.5, 26.1, 37.6, 52.8 and 23.9%).

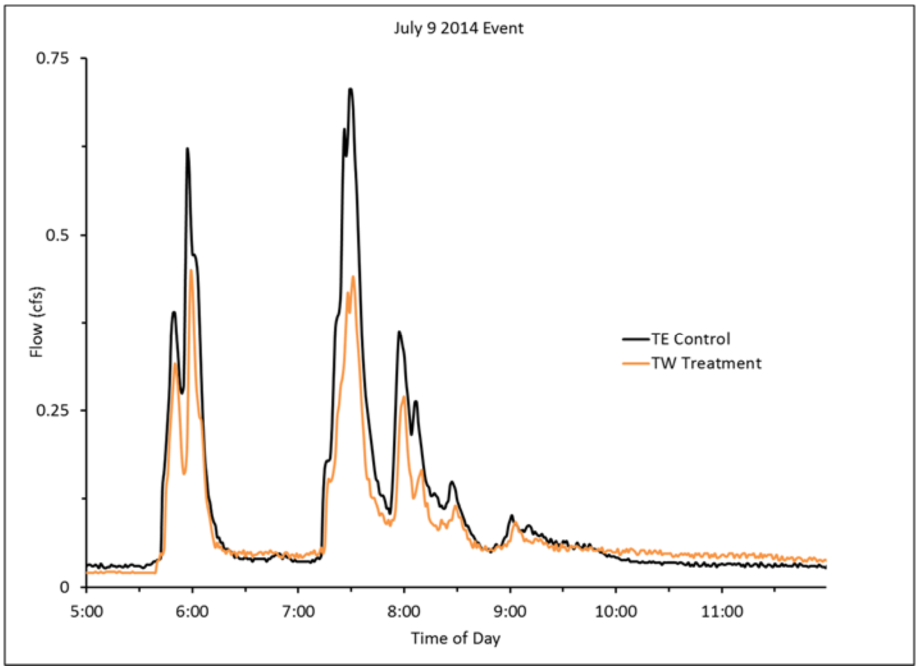


Figure 18. TE control and TW treatment watershed hydrographs for July 9, 2014 storm event of 0.68 inches, showing multiple depressed peak discharge rates for TW treatment watershed.

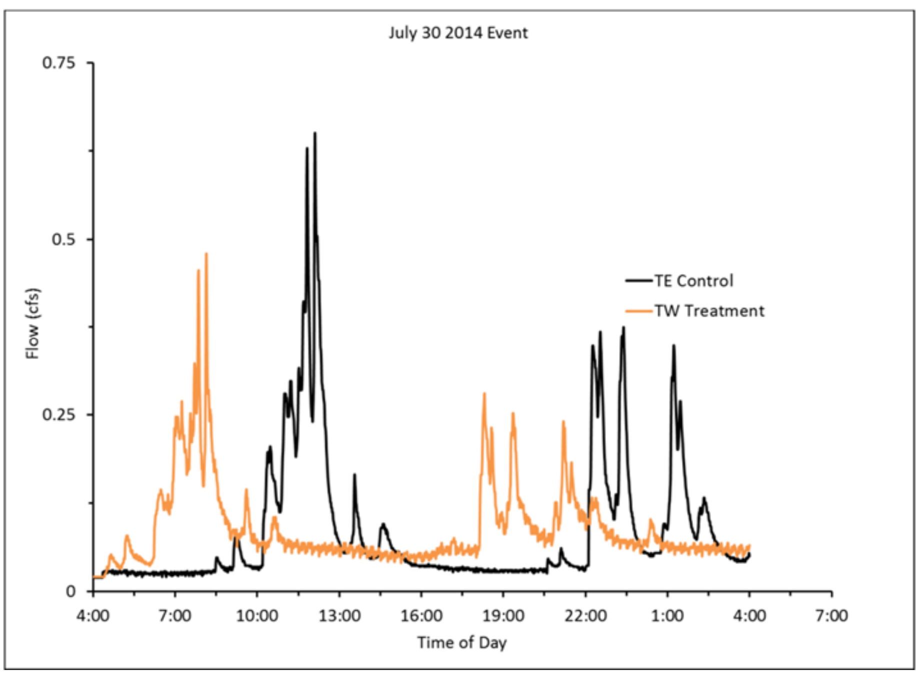


Figure 19. TE control and TW treatment watershed hydrographs for July 30, 2014 storm event of 1.39 inches.

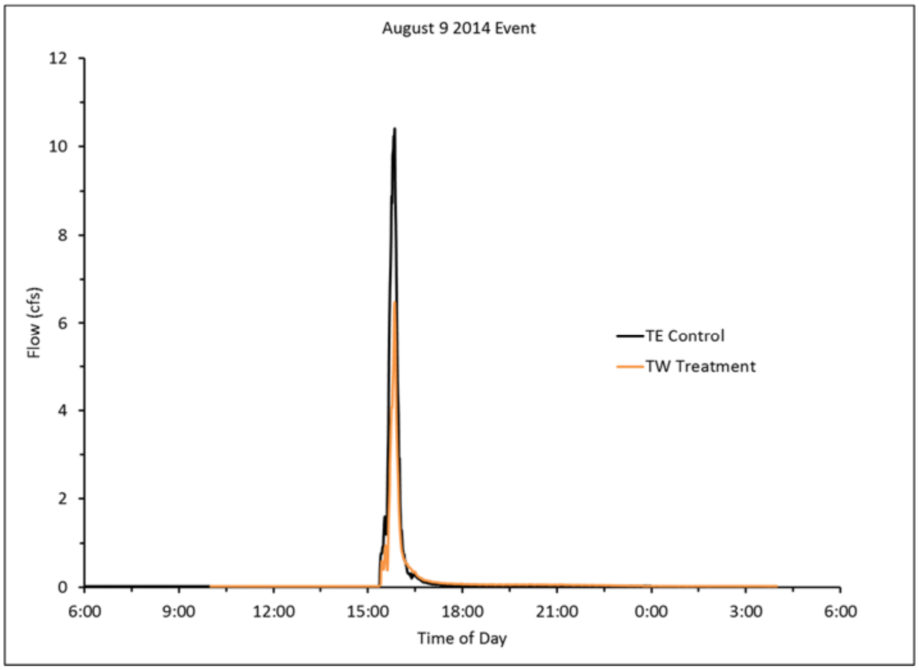


Figure 20. TE control and TW treatment watershed hydrographs for August 9, 2014 storm event of 0.76 inches, showing classic summer thunderstorm peak and dampening of peak in the TW treatment watershed.

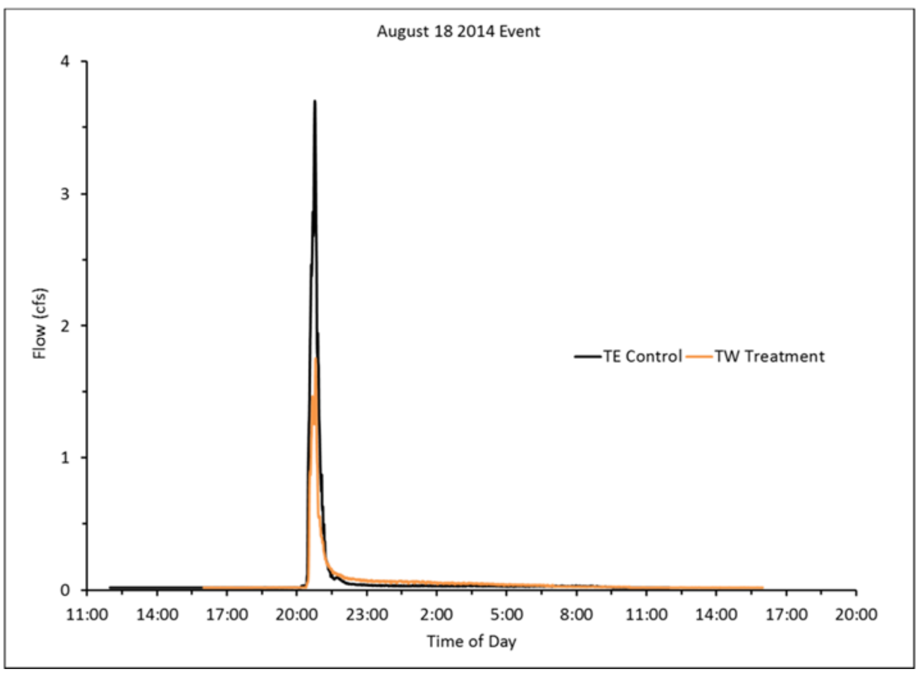


Figure 21. TE control and TW treatment watershed hydrographs for August 18, 2014 storm event of 0.51 inches, showing another classic summer thunderstorm peak and dampening of peak in the TW treatment watershed.

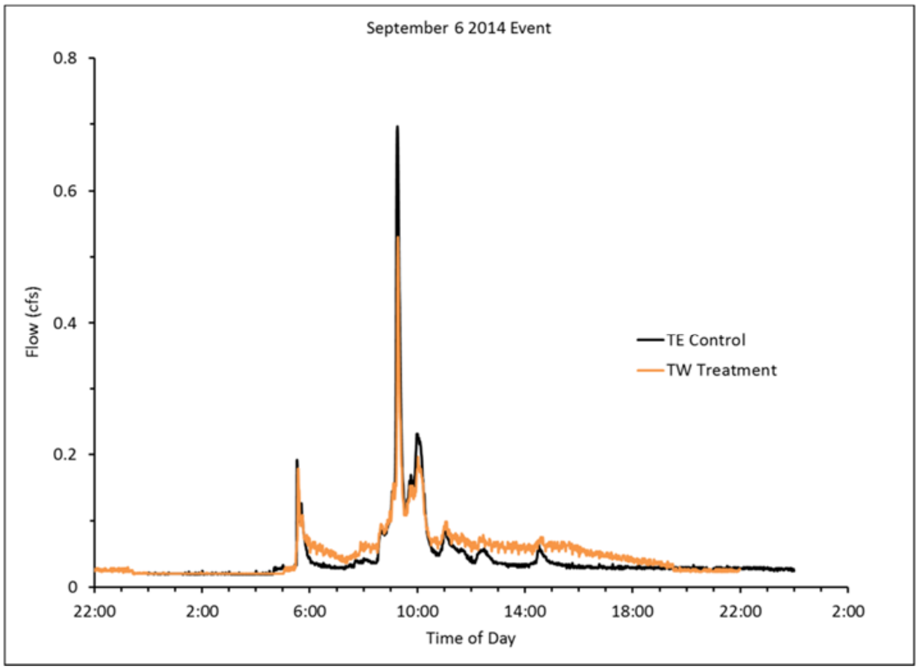


Figure 22. TE control and TW treatment watershed hydrographs for September 6, 2014 storm event of 0.66 inches, showing classic summer thunderstorm peak and dampening of peak in the TW treatment watershed.

Three storm events were sampled in fall 2014, including two in October and one in November (Figure 23 through Figure 25). All three events included multiple peaks (similar to the spring events). Total rainfall amounts ranged from 1.01 to 1.43 inches for these events. Hydrographs for the TE control and TW treatment watersheds tracked one another and the TW treatment watershed demonstrated both lower total storm discharge and lower peak storm discharge rates.

Total discharge rates for the TW treatment watershed were lower by 19.36 ± 7.60 cfs (14.1 ± 4.8%). Peak discharge rates for the TW treatment watershed were lower by 0.65 ± 0.56 cfs (38.8 ± 8.6%). For a single event, peak discharge was lower by as much as 1.27 cfs or 46.3%. Total discharge was lower by as much as 27.29 cfs or 18.7%. For no events were total or peak discharge rates lower in the TE control watershed. The hydrologic performance of the LID BMPs continued to demonstrate the predicted influence on stormwater runoff volumes and rates.

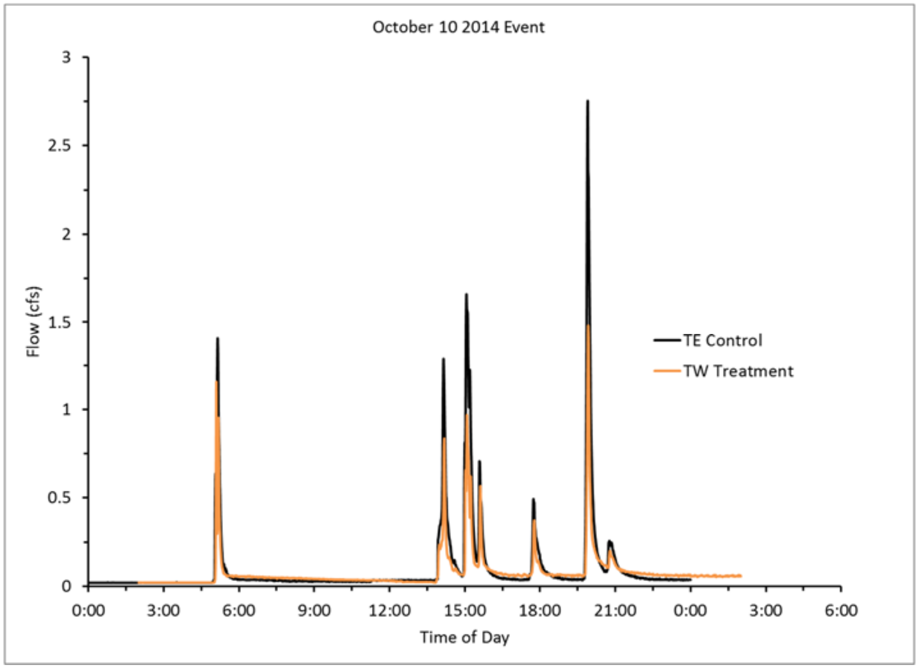


Figure 23. TE control and TW treatment watershed hydrographs for October 10, 2014 storm event of 1.43 inches, showing repeated dampening of peaks in the TW treatment watershed.

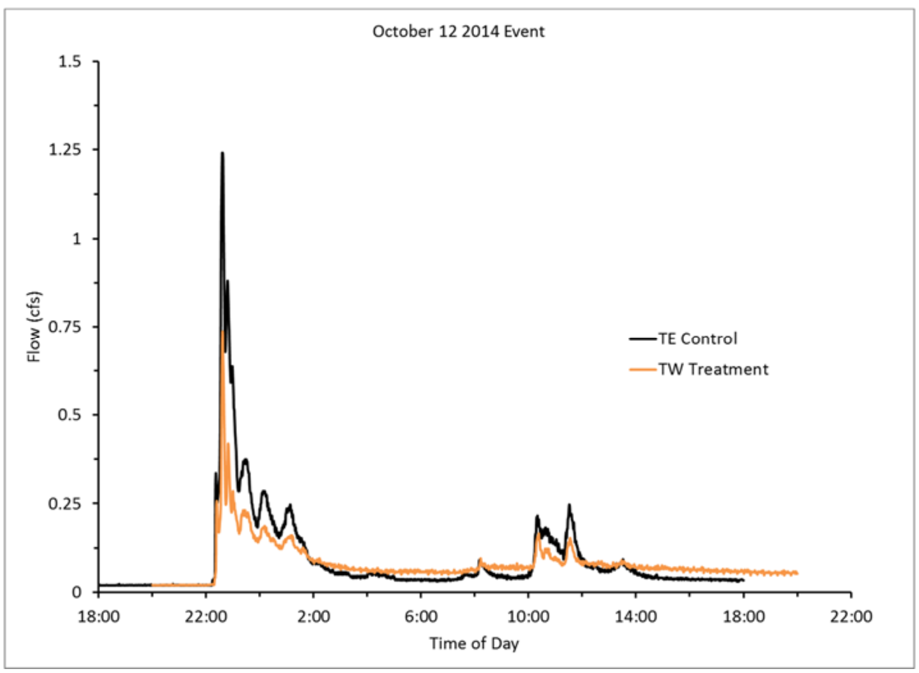


Figure 24. TE control and TW treatment watershed hydrographs for October 12, 2014 storm event of 1.01 inches, again showing repeated dampening of peaks in the TW treatment watershed.

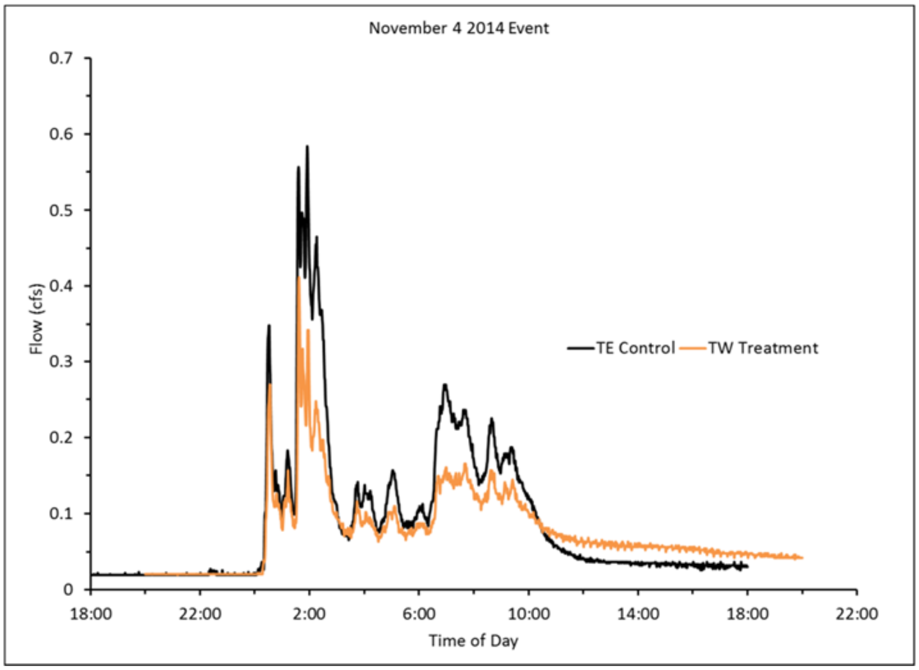


Figure 25. TE control and TW treatment watershed hydrographs for November 4, 2014 storm event of 1.32 inches, again showing repeated dampening of peaks in the TW treatment watershed.

Spring 2015 storms in March, April, May and June produced five events for which data were generated (one each in March and April and June, and two in May). Most events included multiple peaks, ranging in size compared to individual major storm peaks. Rainfall amounts for these events ranged from 0.50 to 3.99 inches, the latter being the largest event sampled in this study (May 24, 2015). It must also be noted that the sampling regime changed during this period. All events through April 13, 2015 were monitored under the first flush sampling regime. Starting with the May 22, 2015 event, data were collected using the storm composite sampling regime.

Hydrographs for the TE control and TW treatment watersheds for these events tracked one another (Figure 26 through Figure 30). Overall, the TW treatment watershed demonstrated both lower total storm discharge and lower peak storm discharge rates. For four of five events, individual storm total discharge and peak discharge rates were lower for the TW treatment watershed. Despite the negative contribution of this one event, total discharge rates for the TW treatment watershed were lower by 81.71 ± 128 cfs (19.1 ± 38.5%). Peak discharge rates for the TW treatment watershed were lower by 1.98 ± 2.24 cfs (52.8 ± 12.9%).

The May 24 event produced total discharge rates of 716 and 411 cfs for the TE control and TW treatment watersheds, 49 and 33 times the calculated Q_{100} design storm flows. Peak discharge rates were 9.93 and 4.21 cfs, for the TE control and TW treatment watersheds. The month of May 2015 was the wettest in Oklahoma history.

For this exceedingly large event, total discharge was lower by 305 cfs or 42.6% in the TW treatment watershed compared to the TE control watershed. Peak discharge for this event was lower by 5.71 cfs or 57.8%. Interestingly, the next storm event on June 29 (0.50 inches) was the only event in this season which showed higher total discharge rates in the TW treatment watershed compared to the TE control watershed (a difference of 18.16 cfs or 48.2%). However, peak discharge rates for this event were lower in the TW treatment watershed by 0.21 cfs or 31.7%. The second growing season for the LID BMPs demonstrated continued performance with regard to stormwater runoff volumes and rates, despite record-breaking rainfall amounts.

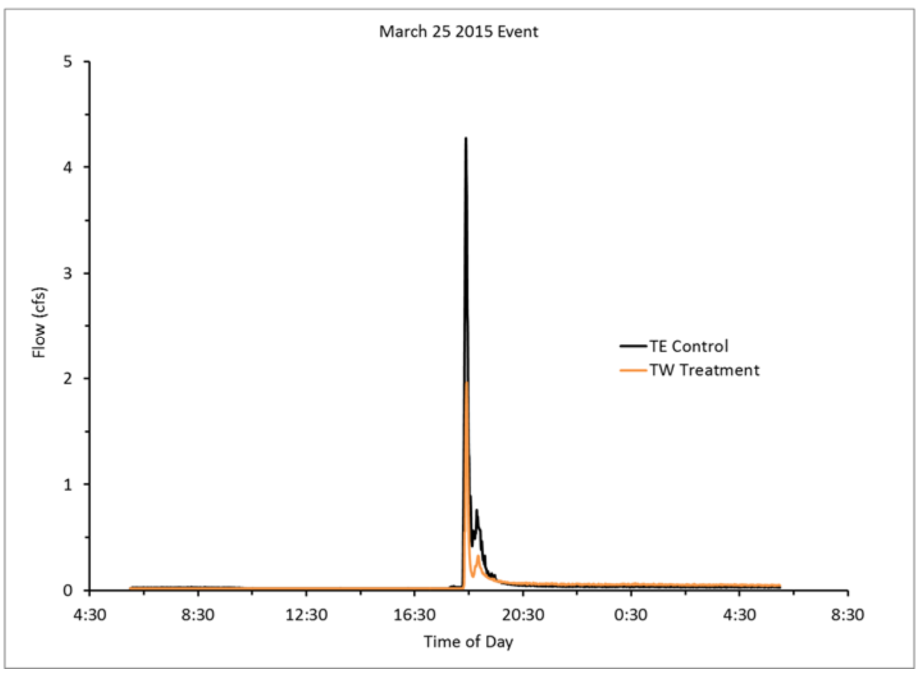


Figure 26. TE control and TW treatment watershed hydrographs for March 25, 2015 storm event of 0.47 inches, showing dampening of peak in the TW treatment watershed.

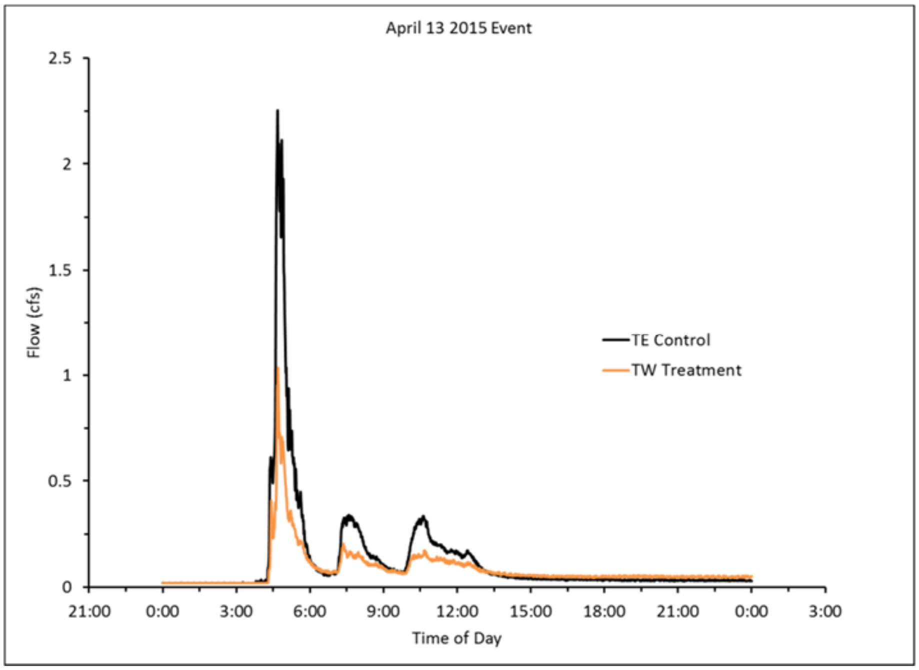


Figure 27. TE control and TW treatment watershed hydrographs for April 13, 2015 storm event of 1.52 inches, showing dampening of peak in the TW treatment watershed.

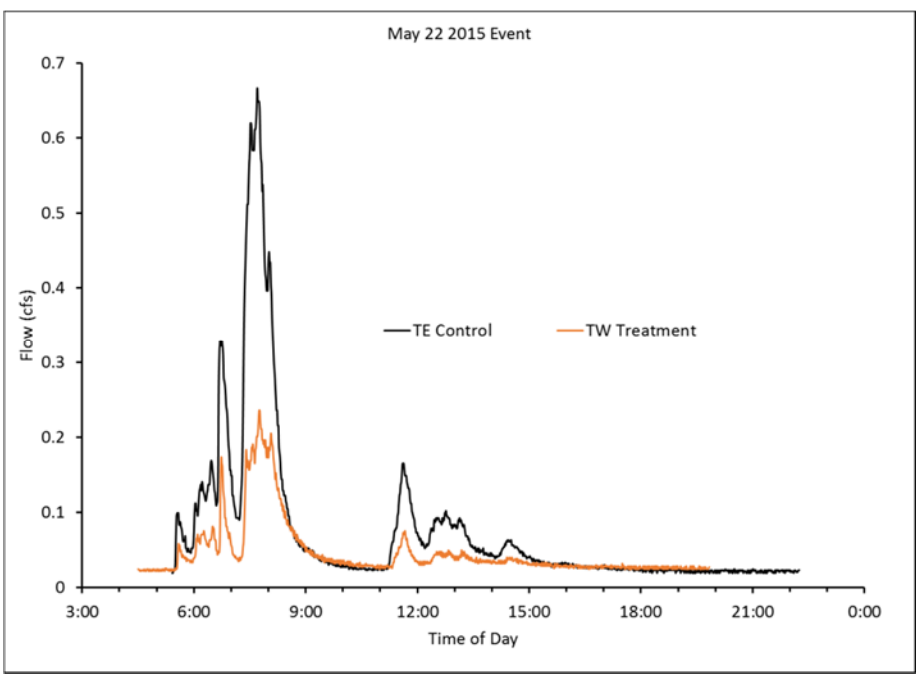


Figure 28. TE control and TW treatment watershed hydrographs for May 22, 2015 storm event of 0.66 inches, showing dampening of multiple peaks in the TW treatment watershed.

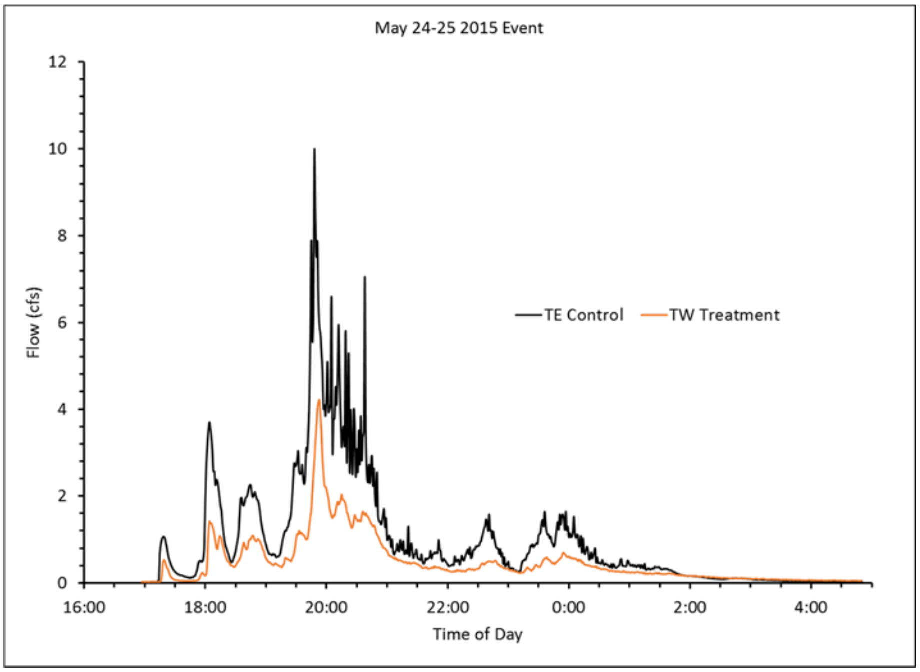


Figure 29. TE control and TW treatment watershed hydrographs for May 24, 2015 storm event of 3.99 inches, showing consistent dampening of peaks in the TW treatment watershed despite the massive rainfall intensity.

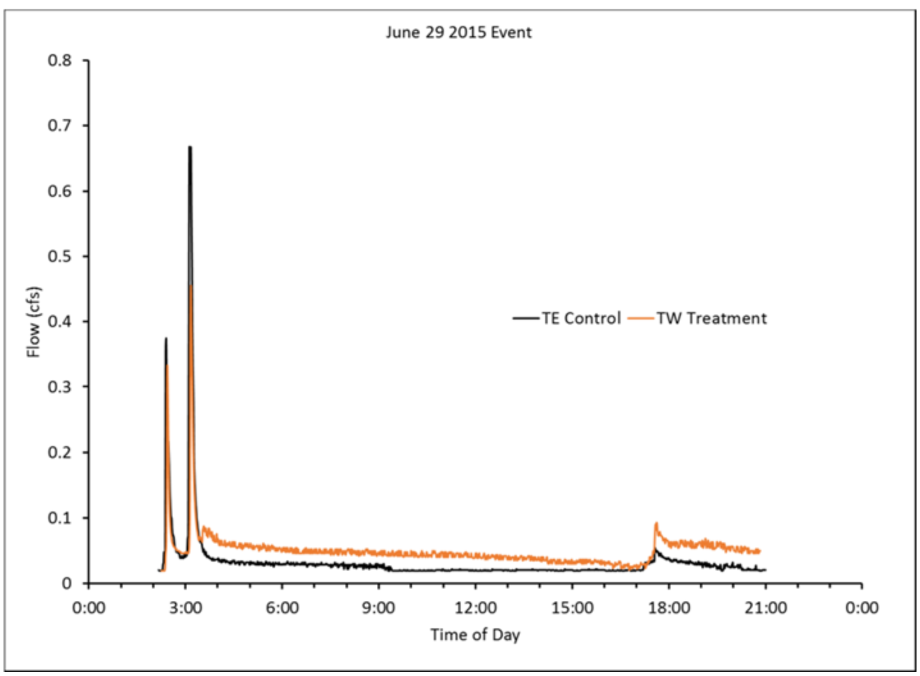


Figure 30. TE control and TW treatment watershed hydrographs for June 29, 2015 storm event of 0.50 inches, showing dampening of peak and delayed release in the TW treatment watershed.

Seven events were monitored in the summer of 2015 (three in July and two each in August and September). Like the summer 2014 events, most of the storms were classic convective thunderstorms, rapidly moving and substantial in intensity of rainfall. Hydrographs for these storms (Figure 31 through Figure 37) demonstrate characteristically steep rising and falling limbs.

Total rainfall amounts ranged from 0.34 to 3.47 inches for these events. Hydrographs for each watershed tracked one another, with the TW treatment watershed generally demonstrating lower peak discharge rates overall. Overall, total discharge and peak discharge rates for the TW treatment watershed were lower by 31.42 cfs (15.4%) and 0.86 cfs (31.6%), respectively, including four of seven events when TE control total discharge rates were lower than TW treatment total discharge rates. On two of these four occasions, the percent difference in the total discharge rate was also lower for the TE control watershed.

The TW treatment watershed lowered total storm event discharge for the large July 3 event (3.47 inches) by 287 cfs (46.2%) and lowered peak discharge by 4.14 cfs (44.7%). It appears that LID BMPs demonstrated considerable resilience to the large events of May and July, substantially decreasing the storm peaks and volumes. However, for the smaller storms in summer 2015 (mean rainfall of 0.78 inches), total discharge was greater in the TW treatment than TE control watersheds.

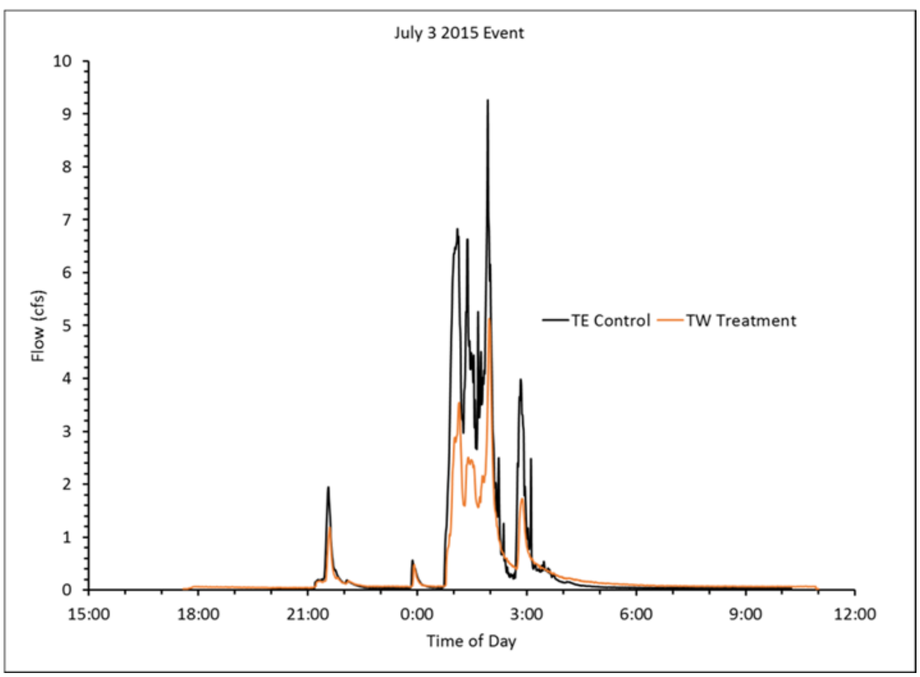


Figure 31. TE control and TW treatment watershed hydrographs for July 3, 2015 storm event of 3.47 inches, showing dampening of multiple peaks in the TW treatment watershed.

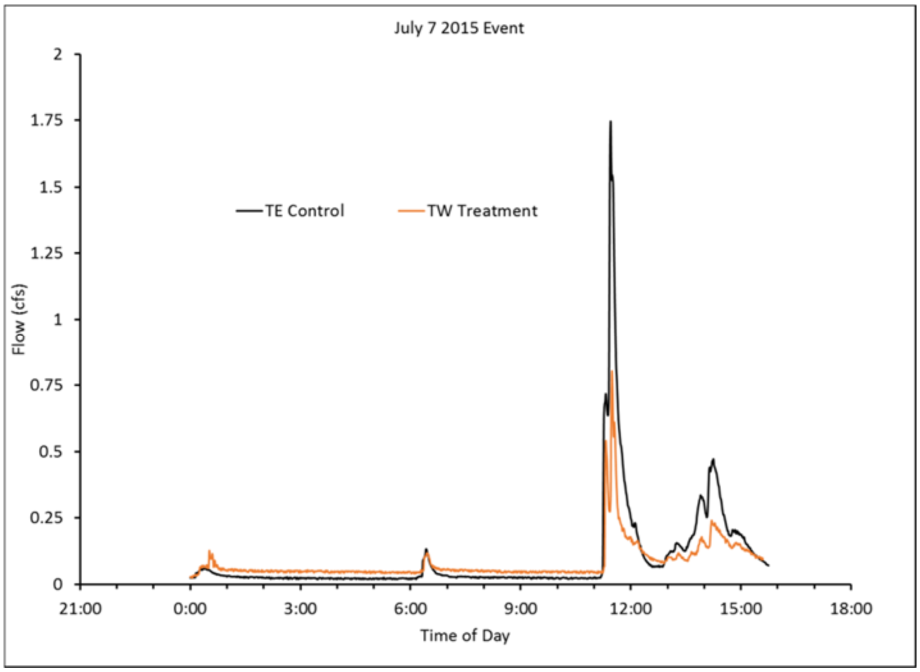


Figure 32. TE control and TW treatment watershed hydrographs for July 7, 2015 storm event of 1.88 inches, showing dampening of large peaks in the TW treatment watershed.

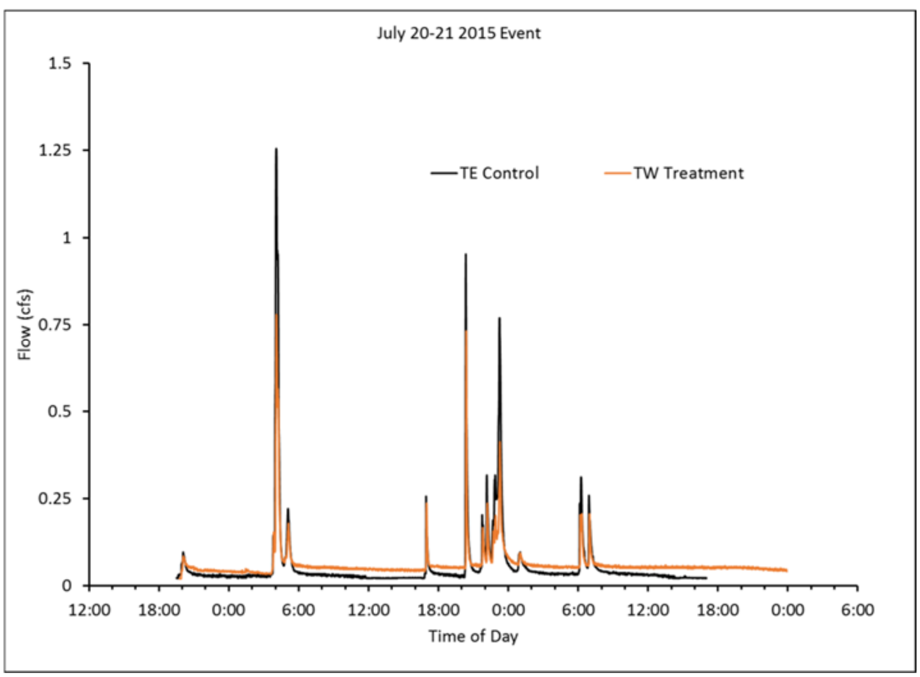


Figure 33. TE control and TW treatment watershed hydrographs for July 20, 2015 storm event of 0.76 inches, demonstrating dampening of peaks but higher base flow conditions in the TW treatment watershed.

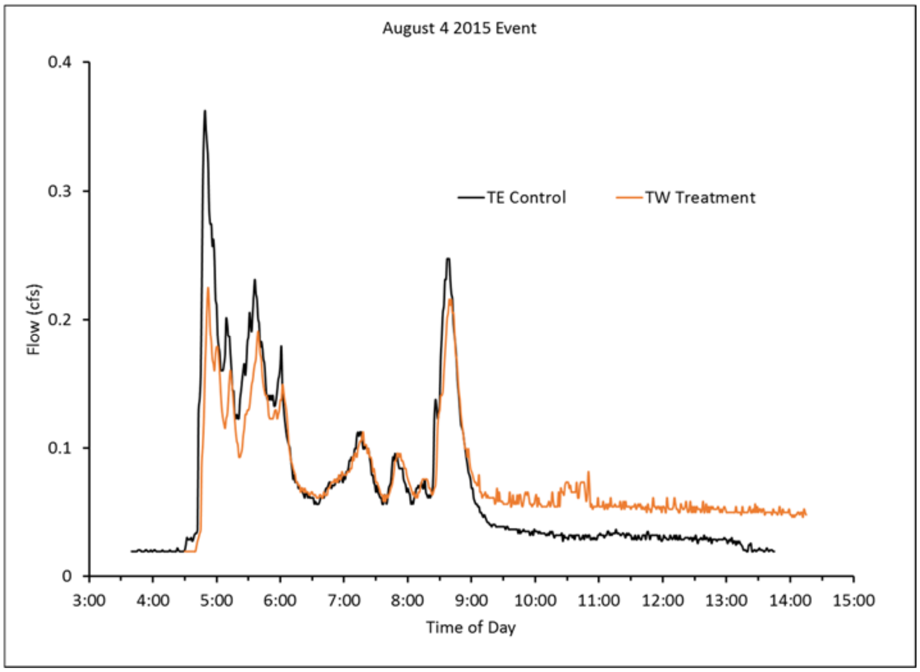


Figure 34. TE control and TW treatment watershed hydrographs for August 4, 2015 storm event of 0.50 inches, demonstrating dampening of large peaks but higher return to base flow conditions in the TW treatment watershed.

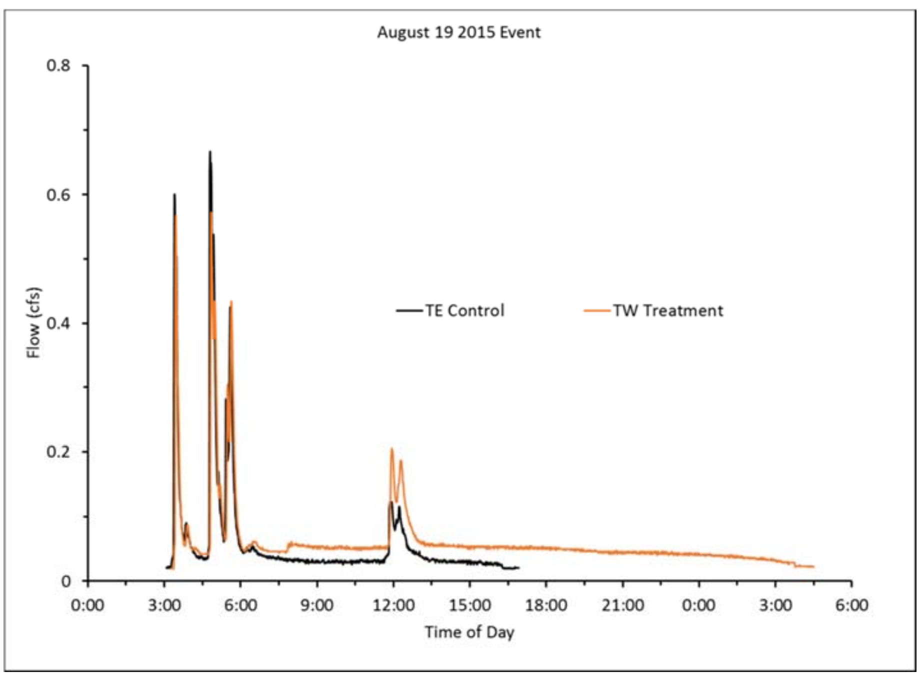


Figure 35. TE control and TW treatment watershed hydrographs for August 19, 2015 storm event of 0.52 inches, demonstrating similar dynamics to previous storms.

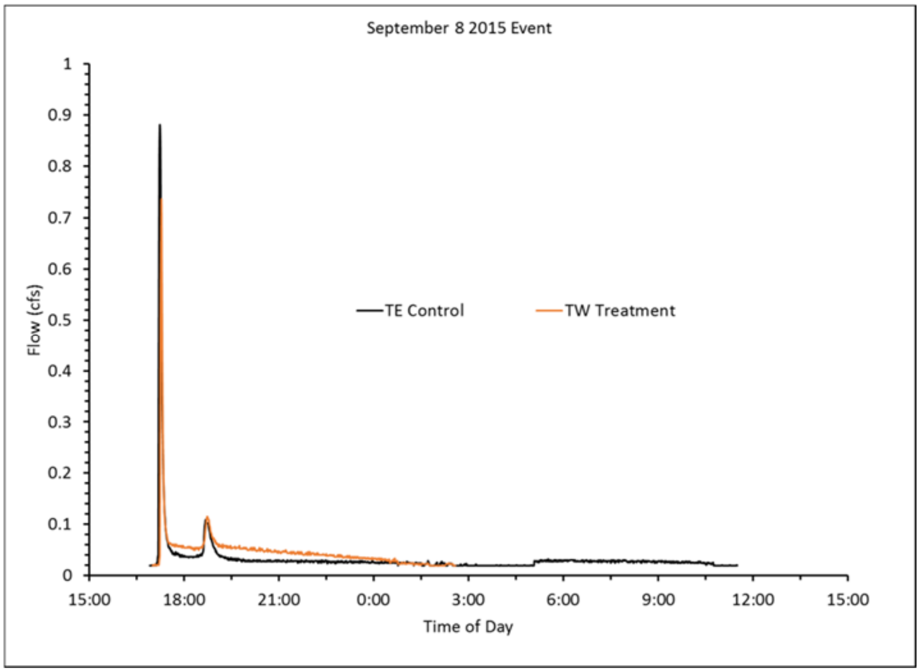


Figure 36. TE control and TW treatment watershed hydrographs for September 8, 2015 storm event of 0.34 inches, demonstrating dampening of large peak.

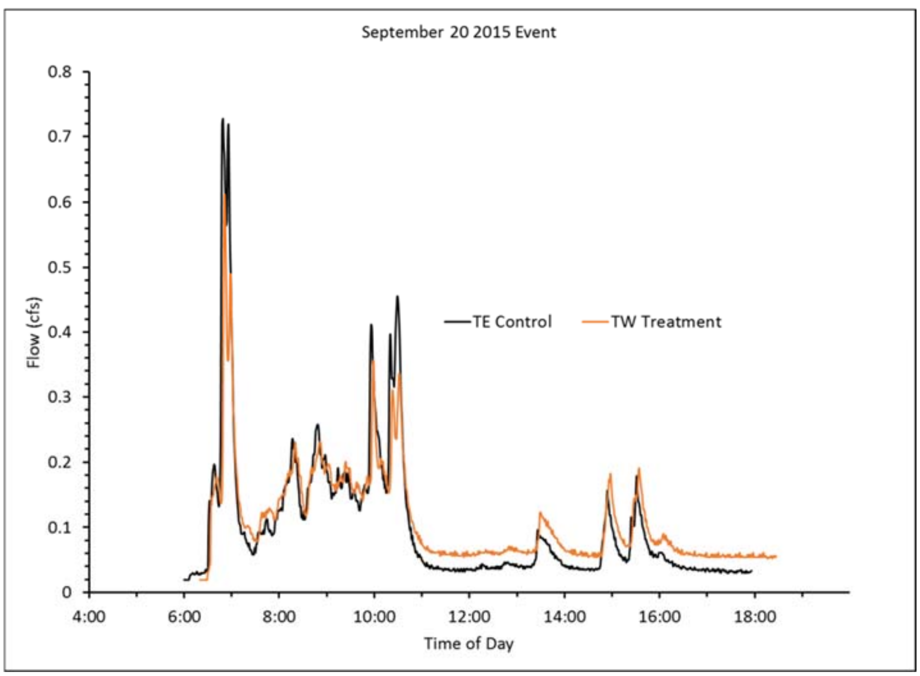


Figure 37. TE control and TW treatment watershed hydrographs for September 20, 2015 storm event of 1.32 inches, demonstrating overall dampening of large peaks but some inconsistency for smaller peaks in the TW treatment watershed.

3.2.2 Relationships Between Precipitation and Volumetric Discharge Rates

A plot of total event precipitation versus event total discharge rate showed strong relationships for both the TE control (r^2 = 0.82) and TW treatment (r^2 = 0.80) watersheds (Figure 38). Larger rainfall events (> 3 inches of rain) typically produced greater event total discharge rates in each watershed. Furthermore, the TW treatment watershed total discharge rates were lower than the TE control discharge rates for these large events, as reflected by the significantly different ($p < 0.10$) slopes of the regression lines. For small events (< 0.50 inches), total discharge rates were similar for each watershed.

A similar analysis comparing total event precipitation versus event peak discharge rates showed weaker relationships for both the TE control (r^2 = 0.43) and TW treatment (r^2 = 0.32) watersheds (Figure 39). As may be expected, large rainfall events (> 3 inches) typically produced greater event peak discharge rates in each watershed. However, some smaller events (< 1 inch), particularly those of substantial rainfall intensity, produced peak discharge rates similar to larger rainfall events. Overall, peak discharge rates were lower for the TW treatment watershed compared to the TE control watershed for all events.

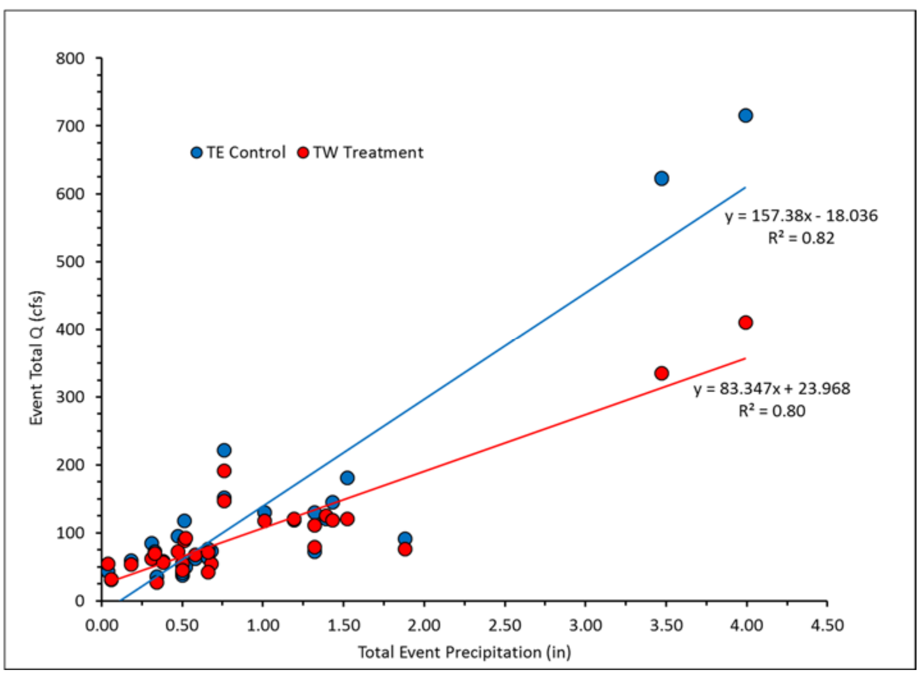


Figure 38. Total event precipitation vs. event total volumetric discharge rates for TE control and TW treatment watersheds.

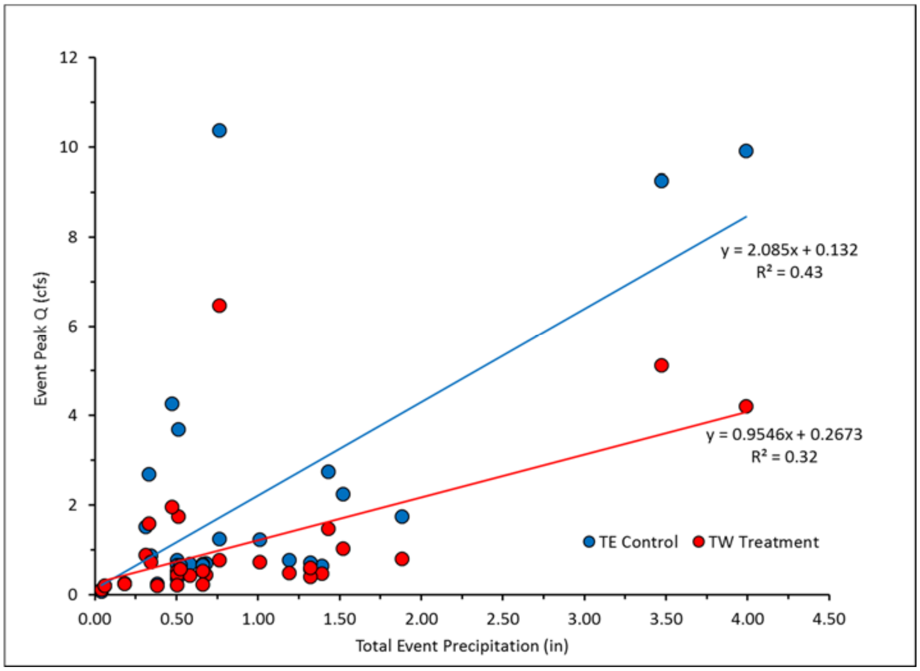


Figure 39. Total event precipitation vs. event peak volumetric discharge rates for TE control and TW treatment watersheds.

3.2.3 Summary of Hydrologic Comparisons

The ability of green infrastructure strategies to decrease total and peak hydrologic discharge values is directly related to their effects on mass loading of stormwater contaminants to receiving waters. Storage and controlled release of stormwater not only allows time for beneficial physical and biogeochemical reactions to occur in LID BMPs, but less water leaving a given site has a direct impact on downstream mass loadings of constituents of concern, absent any water quality improvement.

In this study, comparisons were made between total discharge, peak discharge, runoff depth, runoff ratio and lag times. Total and peak discharge values were generated from each individual storm hydrograph. Runoff depth may be described as the total runoff amount divided by the area of the contributing watershed. It is typically reported in units of inches for a given event, allowing comparison to event precipitation amounts. Runoff ratio is the runoff depth divided by the precipitation for any given event. Lag time refers to the time difference between peak precipitation and peak volumetric discharge rate for any given storm event.

In order to facilitate better comparisons to water quality data, these hydrologic parameters are presented separately herein for each of the two sampling regimes used in this study: first flush and storm composite. As may be expected in any stormwater study, and especially one being conducted in the climate of the central Great Plains, both of the sampling regimes generated hydrologic information demonstrating great variability. Storm events varied in magnitude, duration and intensity, as well as with regard to antecedent conditions (e.g., time since last rainfall). Means comparisons and single factor analyses of variance results are presented to facilitate statistical comparisons. However, as evidenced by the analyses of individual storm hydrographs, the effects of LID BMPs vary by storm event.

Box and whisker plots are utilized to graphically display the data. The center line of the box displays the median value while the top and bottom of the box represent the first and third quartiles, respectively. The upper whisker represents the maximum value and the lower whisker represents the minimum value. Hydrologic data are summarized in Appendix A.

Summary statistics for the first flush sampling regime are presented in Table 8. TE control watershed total and peak discharge rates (104.53 ± 12.16 cfs and 1.84 ± 0.51 cfs, respectively) were greater than TW treatment watershed values (87.16 ± 7.42 cfs and 1.03 ± 0.30 cfs, respectively). Maximum values were also greater for the TE control watershed compared to the TW treatment watershed (TE: 222.63 cfs for total discharge and 10.38 cfs for peak discharge; TW: 147.40 cfs for total discharge and 6.48 cfs for peak discharge). Runoff depths, runoff volumes and lag times differed less dramatically.

Summary statistics for the storm composite sampling regime are presented in Table 9. TE control watershed total and peak discharge rates (189.92 ± 78.63 cfs and 2.62 ± 1.11 cfs, respectively) were greater than TW treatment watershed values (135.86 ± 40.30 cfs and 1.38 ± 0.53 cfs, respectively). Maximum values were also greater for the TE control watershed compared to the TW treatment watershed (TE: 716.28 cfs for total discharge and 9.93 cfs for peak discharge; TW: 411.28 cfs for total discharge and 5.13 cfs for peak discharge). Mean runoff depths were lower for the TW treatment watershed as were lag times.

Figures 40 through 47 compare total discharge rates, peak discharge rates, total discharge differences (in cfs and percent), peak discharge differences (in cfs and percent), runoff depths, runoff ratios and lag times for TE control and TW treatment watersheds in the two sampling regimes.

Table 8. Summary hydrologic statistics for the first flush sampling regime.

	Total Q (cfs)		Peak Q (cfs)	
	TE Control	TW Treatment	TE Control	TW Treatment
Mean	104.53	87.16	1.84	1.03
Median	90.65	72.57	0.78	0.51
Std. dev.	54.37	33.16	2.29	1.36
Maximum	222.63	147.40	10.38	6.48
Minimum	31.48	32.55	0.08	0.12
SE	12.16	7.42	0.51	0.30

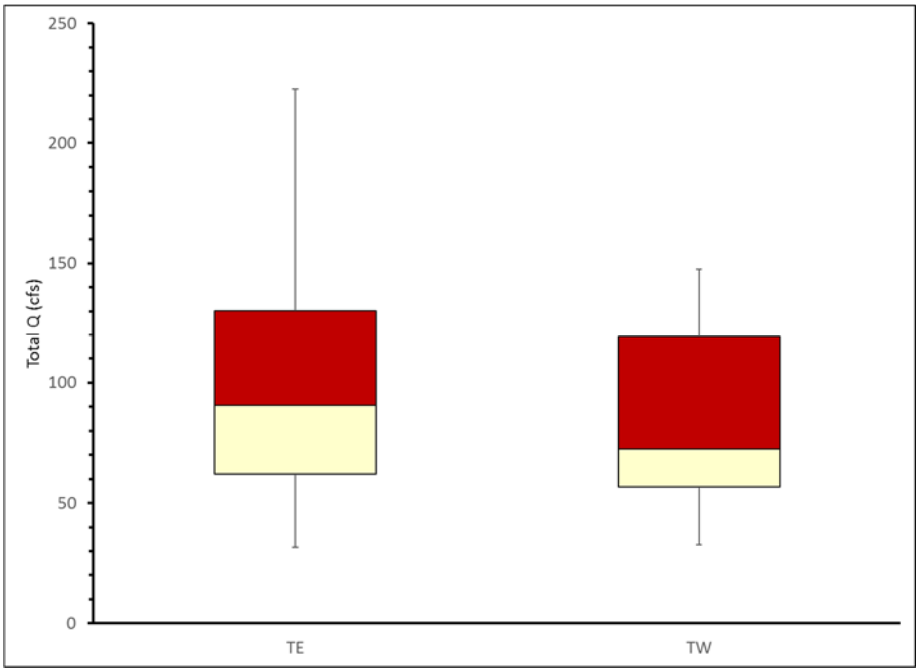
	Runoff Depth (in)		Runoff Ratio		Lag Time (min)	
	TE Control	TW Treatment	TE Control	TW Treatment	TE Control	TW Treatment
Mean	0.0126	0.0104	0.0273	0.0262	1.47	2.00
Median	0.0110	0.0087	0.0169	0.0140	1.00	2.00
Std. dev.	0.0066	0.0040	0.0270	0.0341	7.32	4.13
Maximum	0.0269	0.0176	0.1309	0.1645	20.00	10.00
Minimum	0.0038	0.0039	0.0105	0.0095	-19.00	-11.00
SE	0.0015	0.0009	0.0060	0.0076	1.89	1.07

Table 9. Summary hydrologic statistics for the storm composite sampling regime.

	Total Q (CFS)		Peak Q (CFS)	
	TE Control	TW Treatment	TE Control	TW Treatment
Mean	189.92	135.86	2.62	1.38
Median	74.73	78.38	0.80	0.67
St. dev.	242.96	127.44	3.51	1.67
Maximum	716.28	411.28	9.93	5.13
Minimum	36.53	27.27	0.36	0.23
SE	76.83	40.30	1.11	0.53

	Runoff Depth (in)		Runoff Ratio		Lag Time (min)	
	TE Control	TW Treatment	TE Control	TW Treatment	TE Control	TW Treatment
Mean	0.0229	0.0162	0.0138	0.0129	54.33	15.15
Median	0.0090	0.0093	0.0123	0.0111	8.00	6.00
St. dev.	0.0294	0.0152	0.0062	0.0071	71.26	15.47
Maximum	0.0865	0.0490	0.0242	0.0301	155.00	45.00
Minimum	0.0044	0.0033	0.0059	0.0049	0.00	1.07
SE	0.0093	0.0048	0.0020	0.0022	41.14	5.85

a)



b)

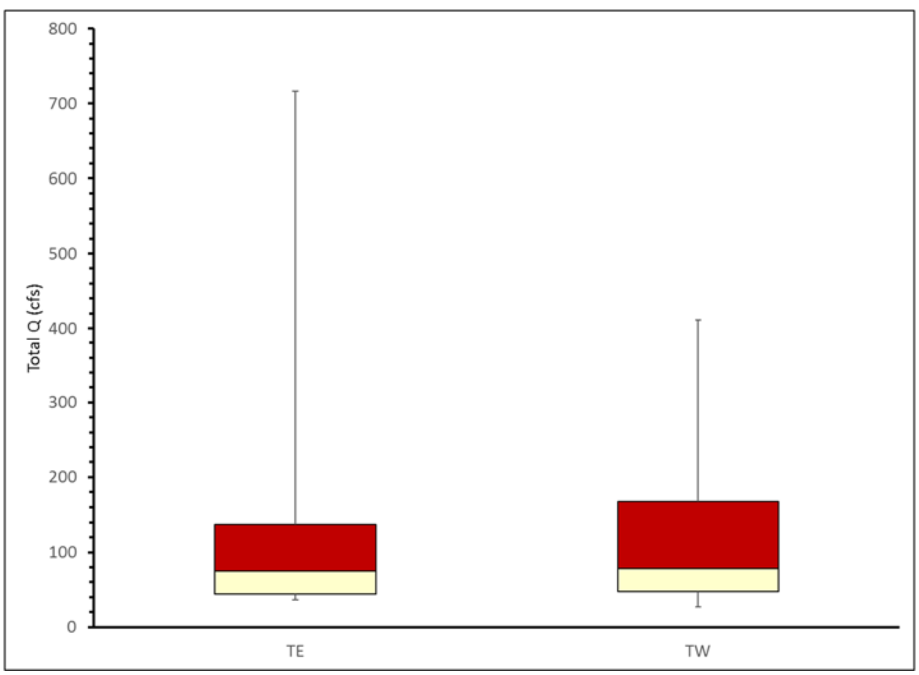
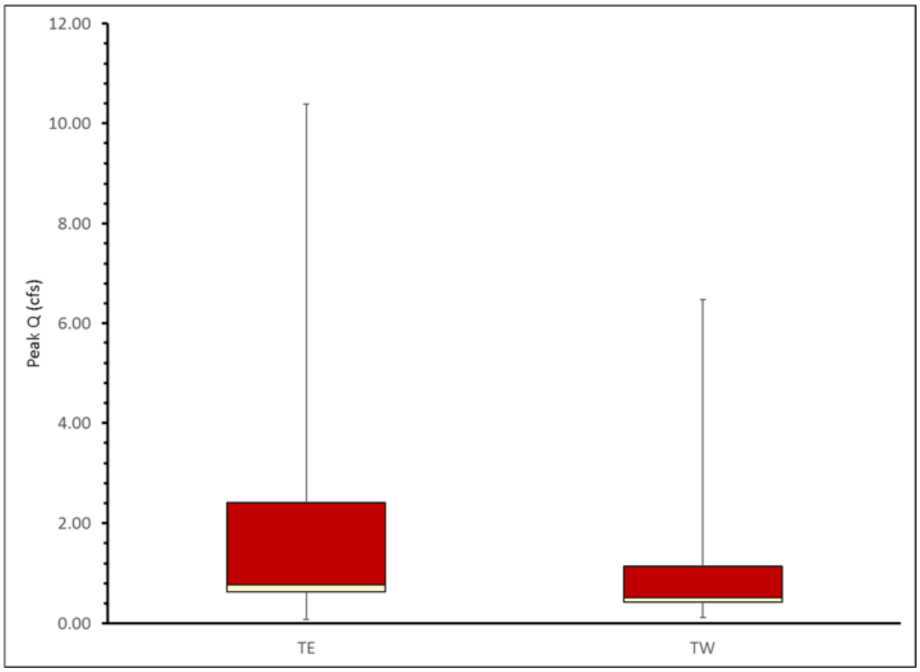


Figure 40. Box and whisker plots of total volumetric discharge rates for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 21) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

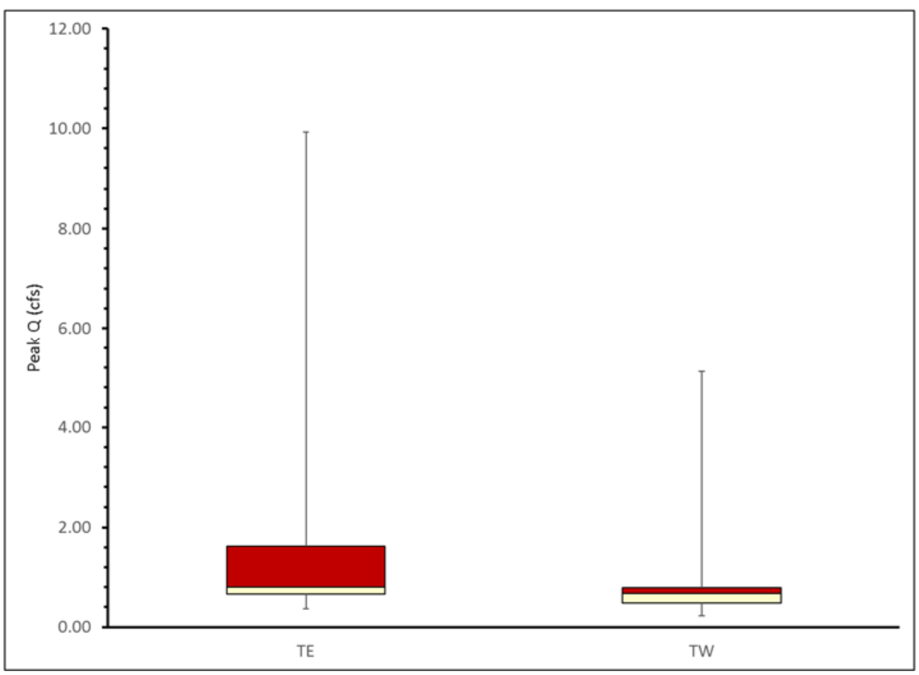
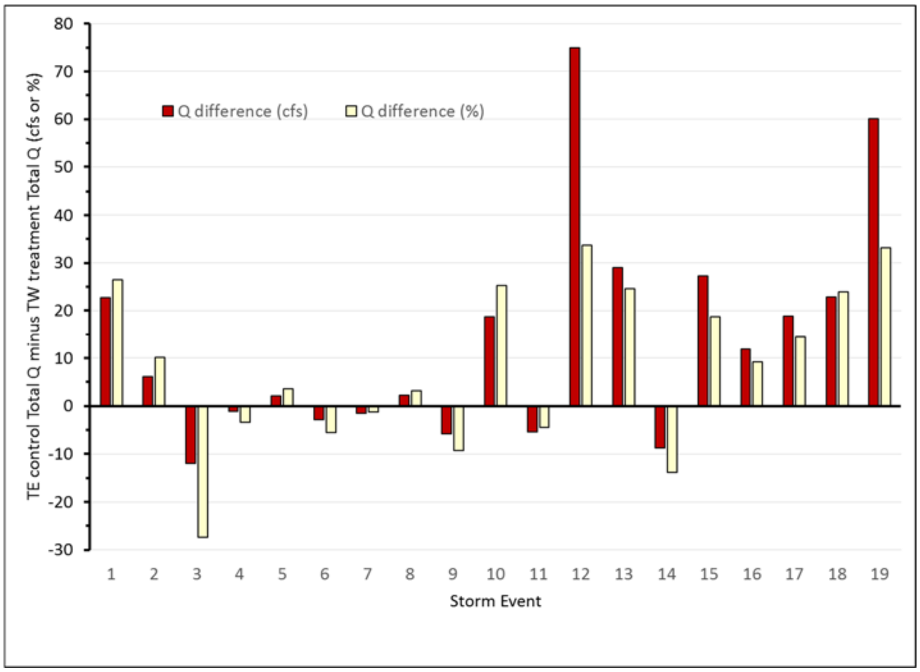


Figure 41. Box and whisker plots of peak volumetric discharge rates for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 21) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

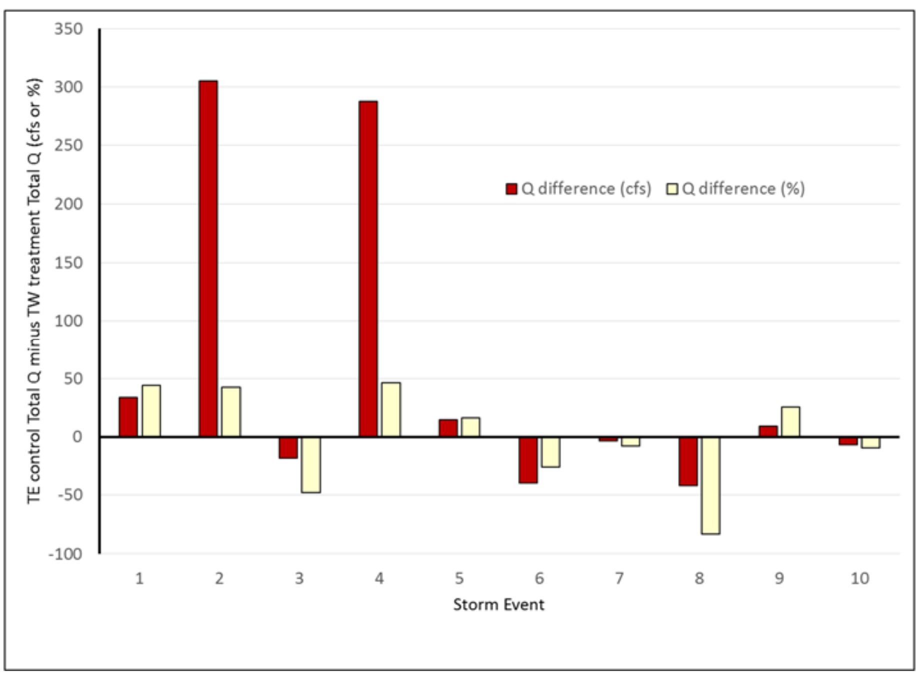
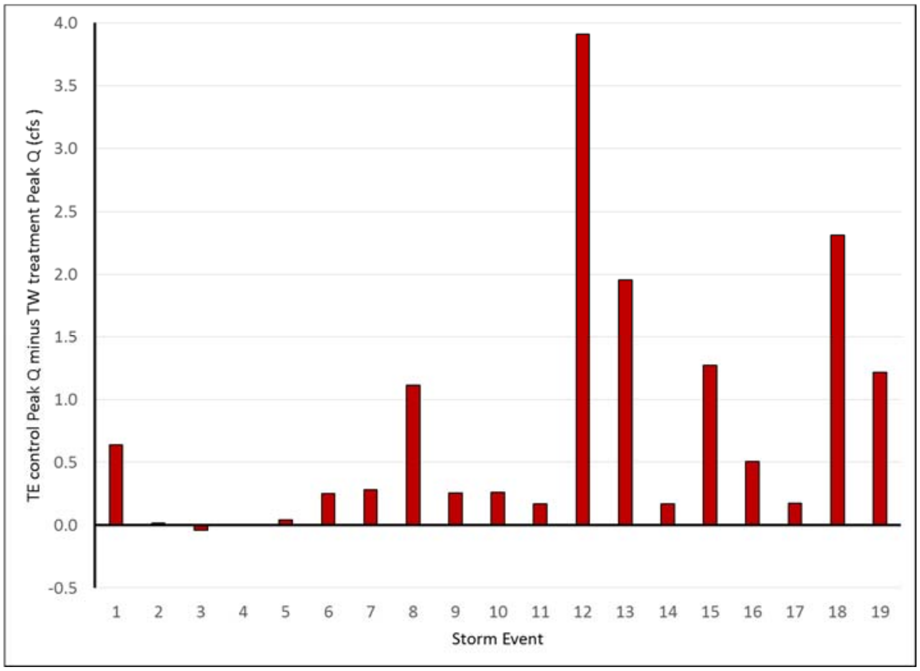


Figure 42. Plots of the difference in total volumetric discharge rates by event for a) the first flush sampling regime (n=19) and b) the storm composite sampling regime (n=10) as both volume (cfs) and percentage.

a)



b)

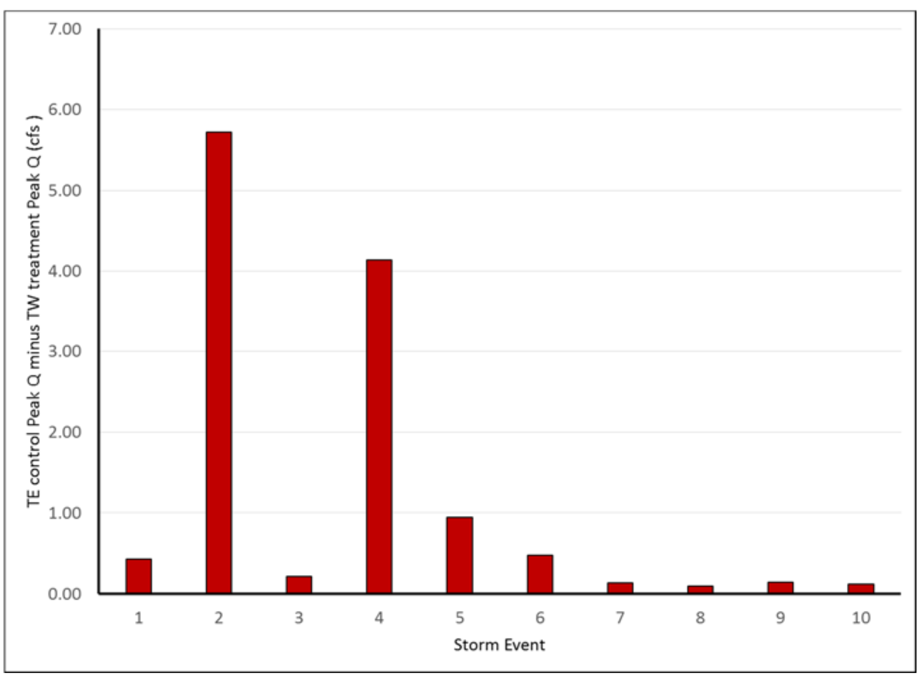
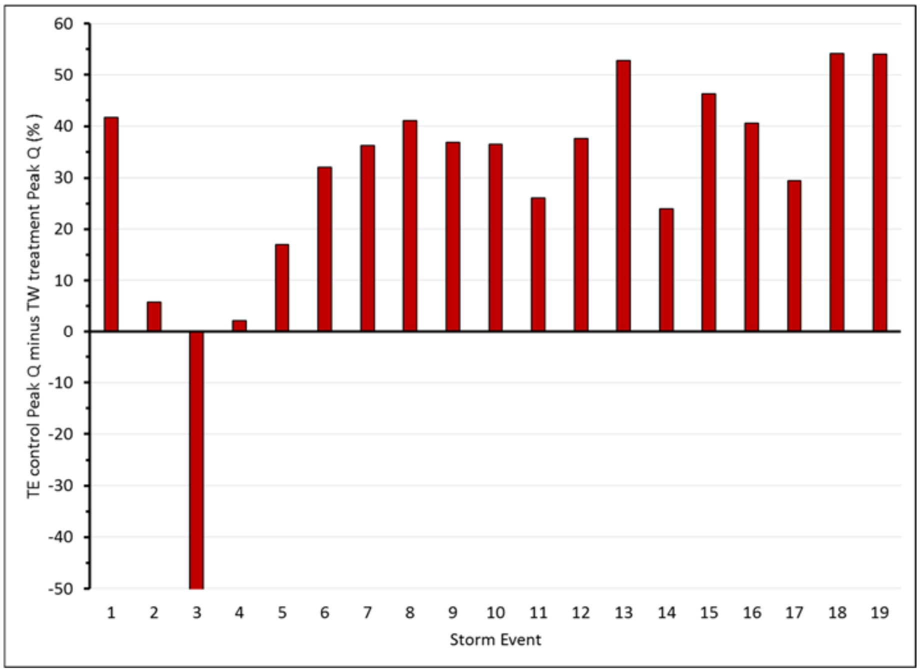


Figure 43. Plots of the difference in peak volumetric discharge rates for a) the first flush sampling regime and b) the storm composite sampling regime as volume (cfs).

a)



b)

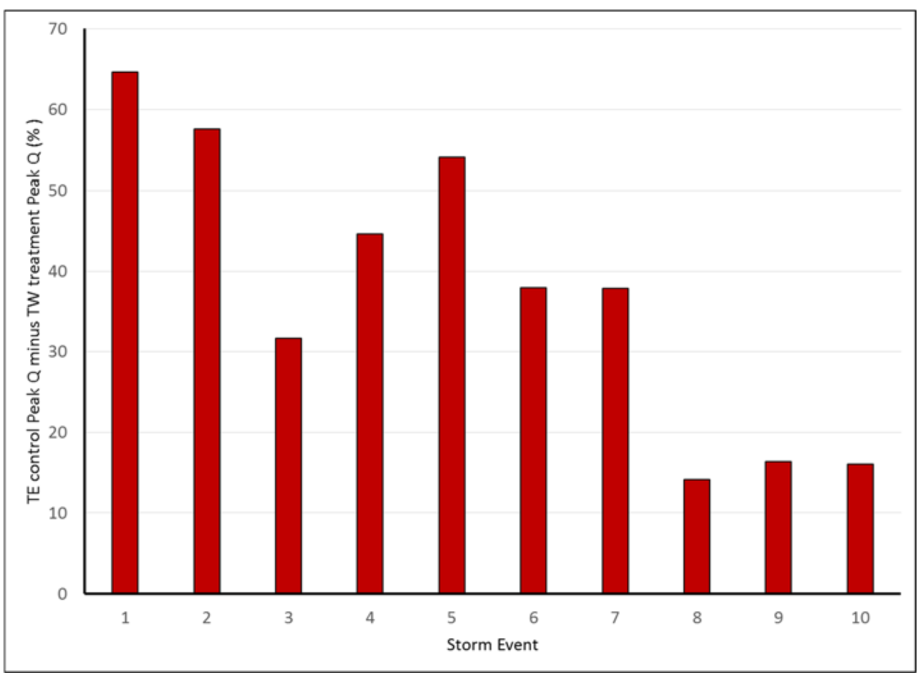
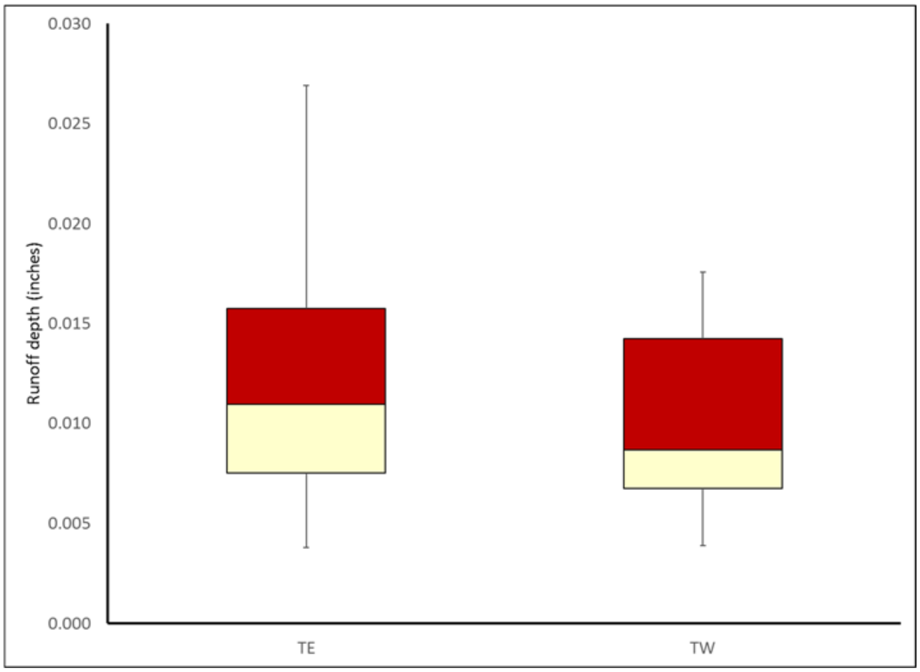


Figure 44. Plots of the difference in peak volumetric discharge rates for a) the first flush sampling regime and b) the storm composite sampling regime as percentage (%).

a)



b)

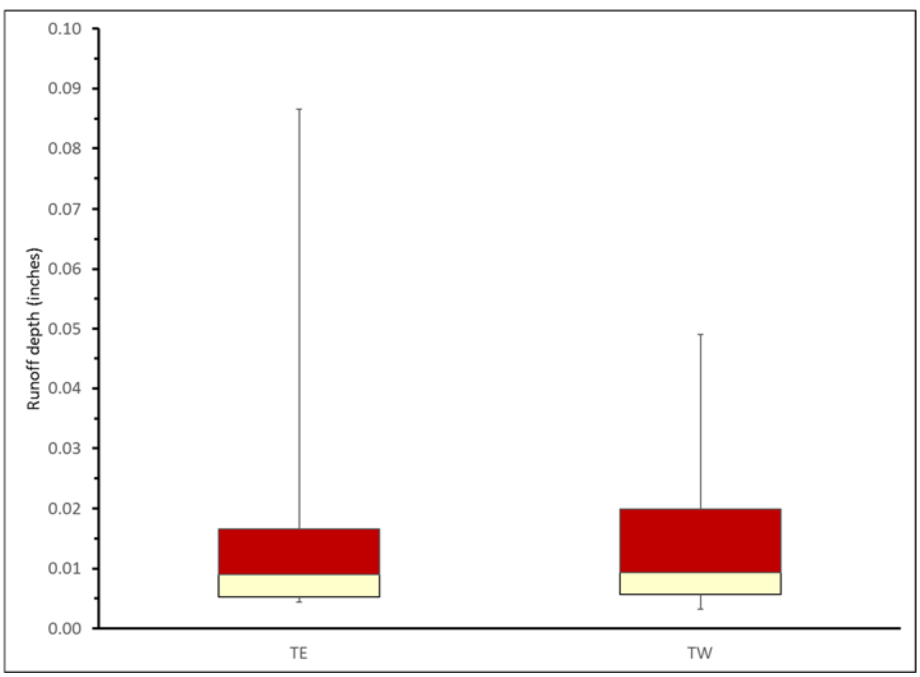
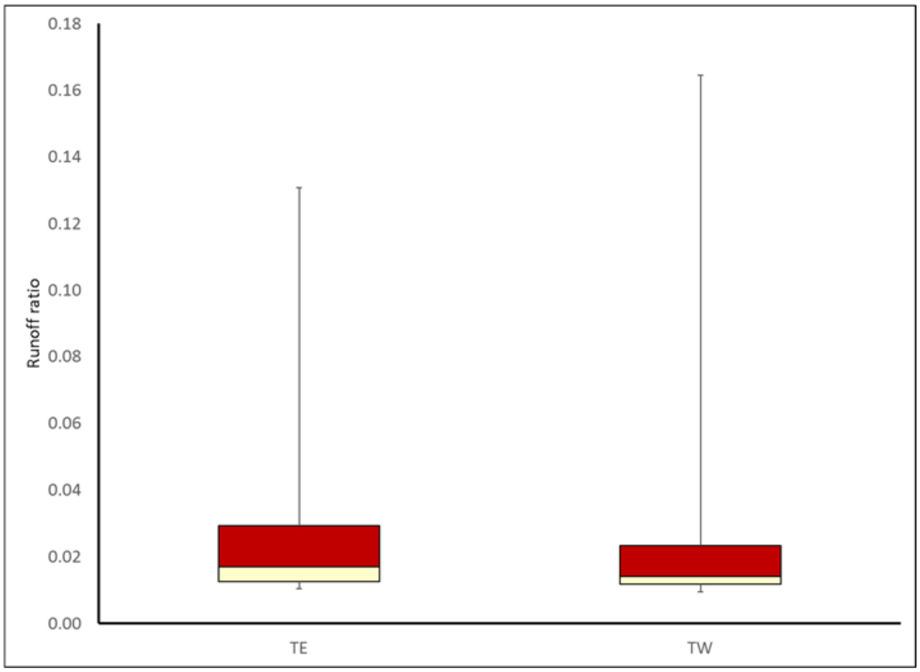


Figure 45. Box and whisker plots of runoff depth for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 21) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

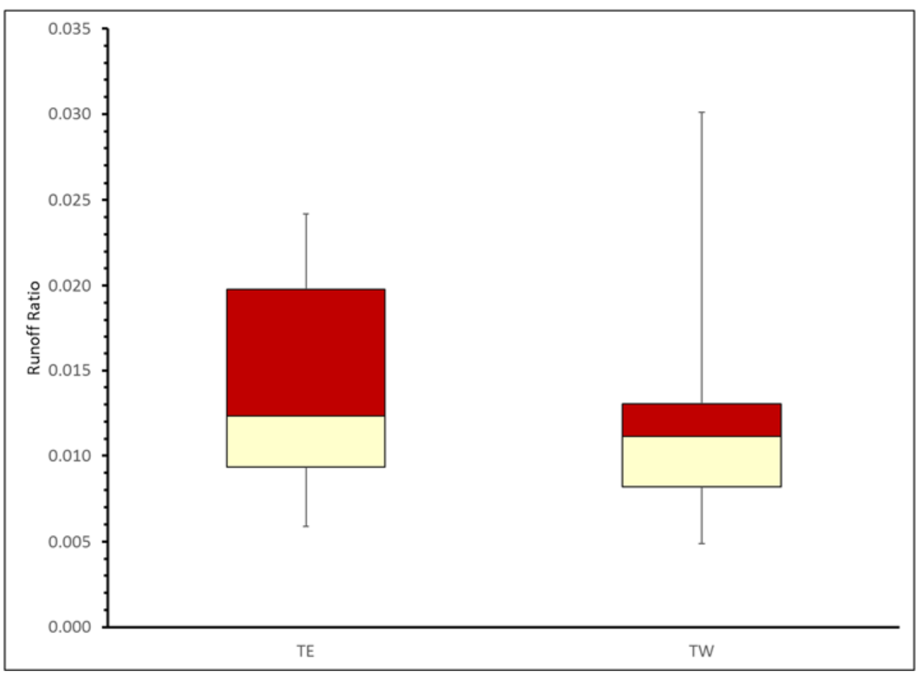
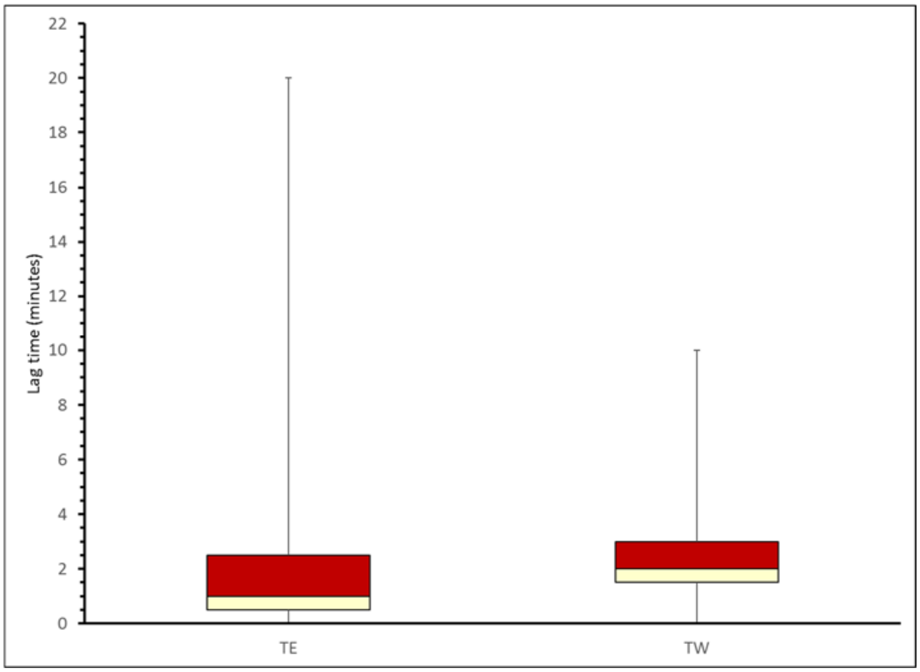


Figure 46. Box and whisker plots of runoff ratio for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 21) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

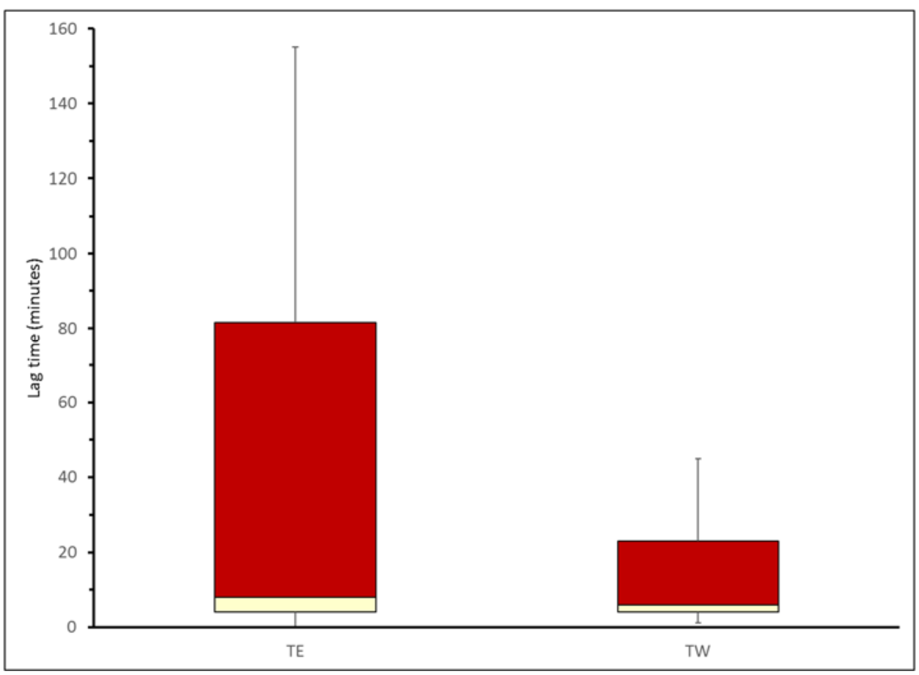


Figure 47. Box and whisker plots of lag times for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 21) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Figure 40 compares TE control and TW treatment watershed event total discharge for both sampling regimes. Simple means comparisons did not demonstrate statistical differences for the first flush ($p = 0.12$) or storm composite ($p = 0.11$) sampling regimes. ANOVA results (Tables 10 and 11) support these conclusions (First flush: $p = 0.24$, $F = 1.41$, F-crit = 2.84; Storm composite: $p = 0.56$, $F = 0.35$, F-crit = 3.01).

Figure 41 compares TE control and TW treatment watershed event peak discharge for both sampling regimes. Simple means comparisons demonstrated statistical differences at the α = 0.10 level for both the first flush ($p = 0.09$) and storm composite ($p = 0.04$) sampling regimes. ANOVA results (Tables 12 and 13) do not support these conclusions (First flush: $p = 0.19$, $F = 1.78$, F-crit = 2.84; Storm composite: $p = 0.35$, $F = 0.92$, F-crit = 3.01).

Figure 42 compares watershed differences in event total discharge values for both sampling regimes. For the first flush sampling regime, seven of 19 events showed TE control watershed total discharge to be less than TW watershed total discharge. Event 3 represents the winter melt event. For the first storm composite regime, four of 7 events showed TE control watershed total discharge to be less than TW watershed total discharge. Figures 43 and 44 present watershed differences in event peak discharge values as volume (cfs) and percentage (%) for both sampling regimes. For the first flush sampling regime, only one (the winter melt event) of 19 events showed TE control watershed peak discharge to be less than TW watershed total discharge. For the storm composite regime, all events showed TW treatment watershed peak discharge to be less than TE control peak discharge.

Figure 45 compares TE control and TW treatment watershed runoff depths for both sampling regimes. Simple means comparisons did not demonstrate statistical differences for the first flush ($p = 0.11$) and storm composite ($p = 0.11$) sampling regimes. ANOVA results (Tables 14 and 15) support these conclusions (First flush: $p = 0.21$, $F = 1.61$, F-crit = 2.84; Storm composite: $p = 0.55$, $F = 0.37$, F-crit = 3.01).

Figure 46 compares TE control and TW treatment watershed runoff ratios for both sampling regimes. Simple means comparisons did not demonstrate statistical differences for the first flush ($p = 0.45$) and storm composite ($p = 0.33$) sampling regimes. ANOVA results (Tables 16 and 17) support these conclusions (First flush: $p = 0.91$, $F = 0.01$, F-crit = 2.84; Storm composite: $p = 0.55$, $F = 0.37$, F-crit = 3.01).

Figure 47 compares TE control and TW treatment watershed lag times for both sampling regimes. Simple means comparisons did not demonstrate statistical differences for the first flush ($p = 0.41$)

and storm composite (p = 0.13) sampling regimes. ANOVA results (Tables 18 and 19) support these conclusions (First flush: p = 0.81, F = 0.06, F-crit = 2.89; Storm composite: p = 0.25, F = 1.53, F-crit = 3.46).

Combining discharge data from both sampling regimes helped to discriminate results. Simple means comparisons demonstrated statistical differences at the $\alpha = 0.05$ level for both the event total discharge (p = 0.03) and event peak discharge (p = 0.0007). ANOVA results (Tables 20 and 21) did not support these conclusions (total discharge: p = 0.41, F = 0.70, F-crit = 2.80; peak discharge: p = 0.13, F = 2.35, F-crit = 2.80).

Table 10. Single factor ANOVA results for total discharge for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	20.00	2090.59	104.53	3111.12
Column 2	20.00	1743.29	87.16	1157.61

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3015.50	1.00	3015.50	1.41	0.24	2.84
Within Groups	81105.71	38.00	2134.36			
Total	84121.20	39.00				

Table 11. Single factor ANOVA results for total discharge for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
Column 1	10.00	1899.20	189.92	65587.03
Column 2	10.00	1358.61	135.86	18045.26

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	14611.61	1.00	14611.61	0.35	0.56	3.01
Within Groups	752690.56	18.00	41816.14			
Total	767302.16	19.00				

Table 12. Single factor ANOVA results for peak discharge for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	20.00	36.82	1.84	5.51
TW	20.00	20.52	1.03	1.94

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.64	1.00	6.64	1.78	0.19	2.84
Within Groups	141.68	38.00	3.73			
Total	148.32	39.00				

Table 13. Single factor ANOVA results for peak discharge for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	10.00	26.16	2.62	13.70
TW	10.00	13.75	1.38	3.10

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.69	1.00	7.69	0.92	0.35	3.01
Within Groups	151.17	18.00	8.40			
Total	158.87	19.00				

Table 14. Single factor ANOVA results for runoff depth for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	20.00	0.25	0.01	0.00
TW	20.00	0.21	0.01	0.00

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1.00	0.00	1.61	0.21	2.84
Within Groups	0.00	38.00	0.00			
Total	0.00	39.00				

Table 15. Single factor ANOVA results for runoff depth for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	10.00	0.23	0.02	0.00
TW	10.00	0.16	0.02	0.00

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1.00	0.00	0.37	0.55	3.01
Within Groups	0.01	18.00	0.00			
Total	0.01	19.00				

Table 16. Single factor ANOVA results for runoff ratio for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	20.00	0.55	0.03	0.00
TW	20.00	0.52	0.03	0.00

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1.00	0.00	0.01	0.91	2.84
Within Groups	0.04	38.00	0.00			
Total	0.04	39.00				

Table 17. Single factor ANOVA results for runoff ratio for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	10.00	0.23	0.02	0.00
TW	10.00	0.16	0.02	0.00

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.00	1.00	0.00	0.37	0.55	3.01
Within Groups	0.01	18.00	0.00			
Total	0.01	19.00				

Table 18. Single factor ANOVA results for lag time for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	15.00	22.00	1.47	57.41
TW	15.00	30.00	2.00	18.29

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.13	1.00	2.13	0.06	0.81	2.89
Within Groups	1059.73	28.00	37.85			
Total	1061.87	29.00				

Table 19. Single factor ANOVA results for lag time for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	3.00	163.00	54.33	7616.33
TW	7.00	106.07	15.15	279.16

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3223.81	1.00	3223.81	1.53	0.25	3.46
Within Groups	16907.64	8.00	2113.46			
Total	20131.45	9.00				

Table 20. Single factor ANOVA results for event total discharge for all sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	29.00	3767.15	129.90	24631.85
TW	29.00	2967.10	102.31	7113.97

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	11035.91	1.00	11035.91	0.70	0.41	2.80
Within Groups	888882.98	56.00	15872.91			
Total	899918.88	57.00				

Table 21. Single factor ANOVA results for event peak discharge for all sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	29.00	60.66	2.09	8.29
Tw	29.00	33.78	1.16	2.33

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.46	1.00	12.46	2.35	0.13	2.80
Within Groups	297.19	56.00	5.31			
Total	309.66	57.00				

3.3 Stormwater Runoff Quality

The full suite of water quality data (physical parameters, nutrients, CBOD, TSS, and metals) were generated for a total of 29 storm events (19 under the first flush sampling regime and 10 under the storm composite sampling regime). Physical parameters are presented herein as a single combined dataset; other stormwater constituents are discussed based upon the specific sampling regime.

3.3.1 Physical Parameters Comparison

Substantial variability in values of pH, specific conductance, total dissolved solids and dissolved oxygen was apparent between individual storm events. Physical parameter data were generated for storm events over a wide range of storm magnitudes (0.04 to 3.99 inches). Furthermore, the collection times of physical parameter data varied temporally within the hydrograph, e.g., data were not collected at a standardized time after onset of precipitation or runoff generation. The difficulty in collecting physical parameter data in an equivalent manner between treatment and control watersheds and between different storm events likely compromised the comparability of the data. However, great variability in these data was expected due to the wide range of contributing storm events. Given these constraints, no significant statistical differences were found between control and treatment watersheds for any of the measured physical parameters ($p > 0.10$, Student's t-tests; Table 22).

Table 22. Summary statistics for physical parameter data for TE control (TE) and TW treatment (TW) watersheds. SD = standard deviation, SE = standard error, p = results of Student's t-tests.

		Mean	Median	Maximum	Minimum	SD	SE	p
pH	TE	7.50	7.59	8.08	6.70	0.42	0.12	0.29
	TW	7.83	7.72	9.33	6.26	0.96	0.29	
SC (μS/cm)	TE	80.25	86	146	2	49.32	14.24	0.10
	TW	138.58	104	435	2	132.36	38.21	
TDS (g/L)	TE	0.052	0.056	0.032	0.095	0.002	0.009	0.10
	TW	0.097	0.067	0.085	0.280	0.001	0.026	
DO (%)	TE	102.55	97.00	133.70	81.00	15.94	4.81	0.27
	TW	120.51	106.25	241.50	76.50	49.57	15.68	
DO (mg/L)	TE	10.48	9.92	14.58	8.35	2.03	0.61	0.26
	TW	12.23	10.63	21.34	7.41	4.55	1.44	
T (^oC)	TE	15.73	16.43	20.98	1.33	3.67	1.06	0.47
	TW	15.83	16.62	20.48	0.45	4.21	1.21	

Mean and median values for pH were circum-neutral, although the TW treatment watershed produced water with pH > 9 for two storm events, while the highest recorded pH value for the TE control watershed was slightly greater than 8. The contribution of alkaline materials in the compost of the rain gardens, perhaps coupled with flow through the porous concrete section, may have contributed to the elevated pH values for waters exiting the TW treatment watershed on specific occasions.

Specific conductance (SC) and total dissolved solids (TDS) values differed between the TE control and TW treatment watersheds, but not significantly. SC values for the TW treatment watershed were greater than those for the TE control watershed for greater than 70% of collected samples. TW treatment watershed mean and median SC values were 151 and 105 μS/cm, respectively, with a standard error of approximately 40 μS/cm. Transport of dissolved mineral and organic materials from the rain garden substrate likely contributed to slightly elevated SC and TDS values. Interestingly, the highest SC value (435 μS/cm on September 28, 2013) was found for the first storm event sampled, shortly after completion of the last rain garden. With the exception of one other event (358 μS/cm on June 12, 2014), no values exceeded 179 μS/cm for the TW treatment watershed. For the TE control watershed, SC values did not exceed 146 μS/cm, and mean and median values were 80 and 86 μS/cm, respectively, with a standard error of 14 μS/cm. TDS values tracked SC values with the TW watershed producing waters with 0.097 ± 0.026 g/L (mean ± standard error) and the TE control watershed producing waters with 0.052 ± 0.009 g/L. Median and maximum TDS values were 0.067 g/L and 0.280 g/L for the TW treatment watershed and 0.056 g/L and 0.095 g/L for the TE control watershed, respectively.

Dissolved oxygen values did not differ between the TW treatment and TE control watersheds. In all cases, discharging waters were greater than 76% saturated with oxygen. For 42% of all samples, dissolved oxygen was supersaturated in the stormwater runoff samples, likely due to turbulent flow of the runoff prior to entering the test flumes. Values as high as 242% (September 28, 2013 for TW treatment watershed) and 134% (November 4, 2014 for TE control watershed) were determined. Likewise, mean dissolved oxygen concentrations were 12.23 ± 1.44 mg/L for the TW treatment watershed (median = 10.63 mg/L) and 10.48 ± 0.61 mg/L for the TE control watershed (median = 9.92 mg/L).

3.3.2 Comparison of Stormwater Constituent Concentration Data

Measured concentration data were generated for 21 constituents for all 29 sampling events (19 events under the first flush sampling regime and 10 events under the storm composite sampling regime). Data were generated for each of the sampling regimes for two bulk constituents (total suspended solids or TSS and carbonaceous biochemical oxygen demand or CBOD), five nutrients (dissolved reactive phosphorus, total phosphorus, nitrate-nitrogen, ammonia-nitrogen and total nitrogen) and 15 metals (Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn). The presentation herein of trace metal data is limited to nine metals with potential toxicity concerns, i.e., Al, As, Cd, Co, Cr, Cu, Ni, Pb and Zn.

3.3.2.1 Total Suspended Solids and Carbonaceous Biochemical Oxygen Demand

Samples for both TSS and CBOD were collected under the first flush sampling regime. The results of these efforts indicated that CBOD values were low enough to not be of concern and these analyses were therefore not completed under the storm composite sampling regime. CBOD results may have been compromised by the delay in retrieval of storm-derived samples (sometimes up to 24 hours after initiation of a sampling event) but in all cases were lower than applicable criteria. Summary statistics for TSS values for the first flush, storm composite and combined sampling regimes are presented in Table 23 along with CBOD values for the first flush regime. CBOD values were not different between the two watersheds (Figure 48) and were never greater than 13 mg/L. Mean, median and maximum TSS concentrations were higher exiting the TE control watershed than the TW treatment watershed, regardless of the sampling regime (Figure 49). However, given the variability in the data, means comparisons did not indicate any significant differences between the TE control and TW treatment watersheds for either TSS or CBOD concentrations.

Table 23. Summary statistics for TSS and CBOD for first flush, storm composite and the combined data set. Std. Dev = standard deviation and Std. error = standard error. Student's t-test p-values are for comparison of the values for the two watersheds for each sampling regime.

	First Flush		Storm Composite		Combined	
	TE	TW	TE	TW	TE	TW
TSS (mg/L)						
Mean	89.66	63.65	69.24	35.54	83.94	54.71
Median	50.98	26.30	44.40	34.40	44.40	30.35
Std. Dev.	156.10	139.99	70.43	28.23	136.34	116.07
Maximum	698.80	565.60	174.00	84.80	698.80	565.60
Minimum	4.10	5.97	1.60	1.20	1.60	1.20
Std. Error	36.79	36.14	26.62	10.67	27.27	24.75
p	0.31		0.13		0.22	
CBOD (mg/L)						
Mean	9.72	10.03	---	---		
Median	9.58	9.95	---	---		
Std. Dev.	2.22	2.10	---	---		
Maximum	12.94	12.69	---	---		
Minimum	4.79	4.51	---	---		
Std. Error	0.64	0.63	---	---		
p	0.37					

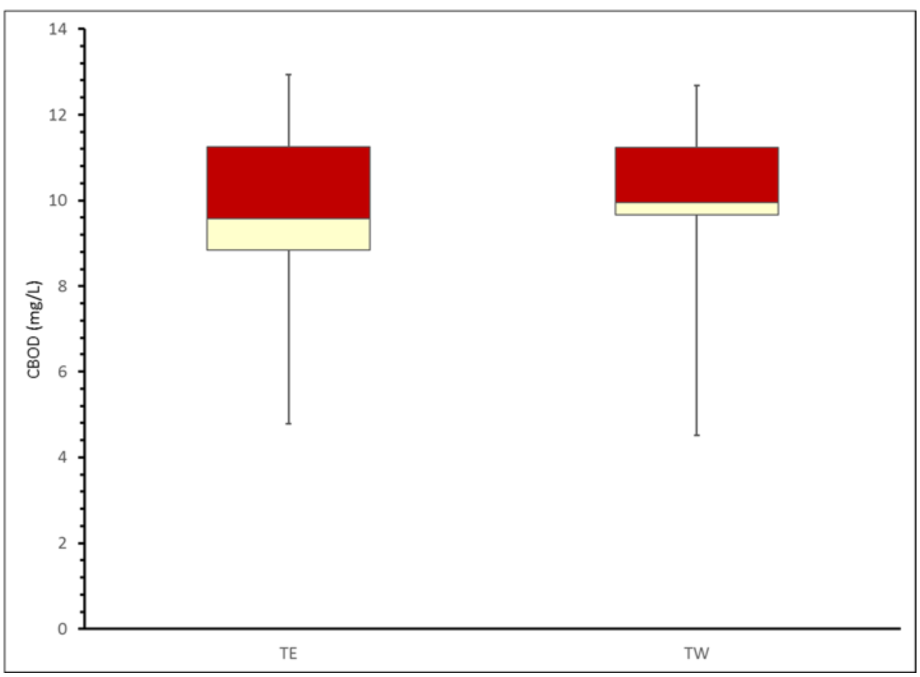
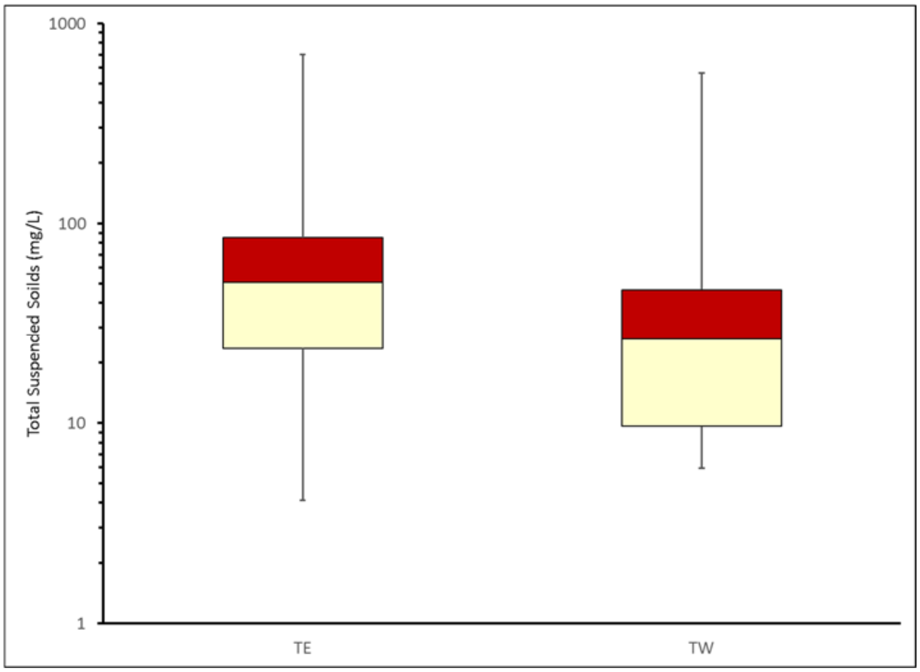


Figure 48. Box and whisker plots of carbonaceous biochemical oxygen demand for the first flush sampling regime.

a)



b)

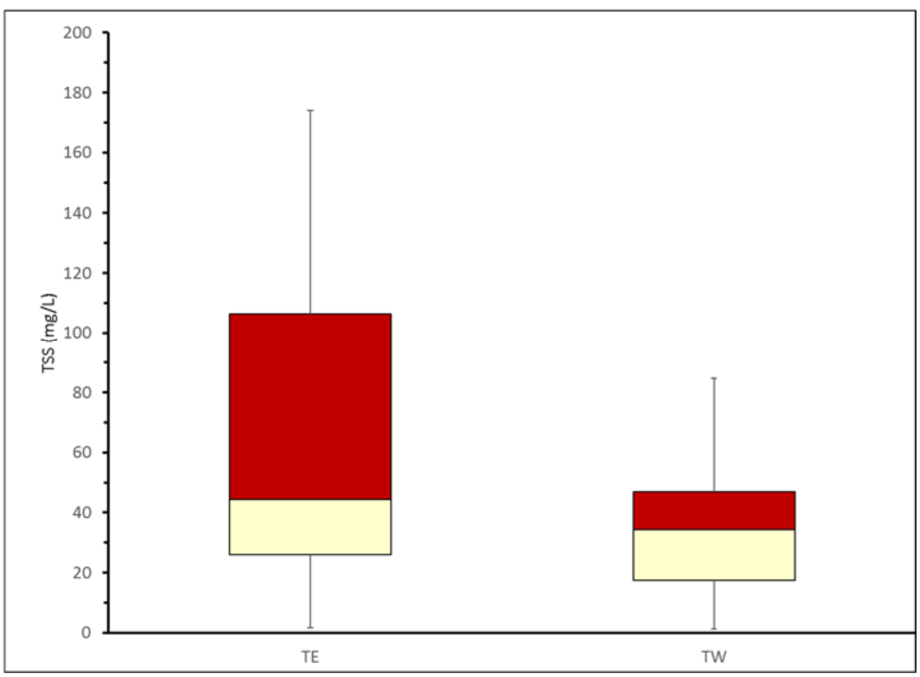


Figure 49. Box and whisker plots of total suspended solids (TSS) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Furthermore, ANOVA results (Tables 24, 25, 26 and 27) support these conclusions for CBOD first flush data and TSS across both sampling regimes and the combined data set. No significant differences were found for CBOD and TSS concentrations between the TE control and TW treatment watersheds.

Table 24. Single factor ANOVA results for CBOD for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	12.00	116.70	9.72	4.94
TW	11.00	110.32	10.03	4.42

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.53	1.00	0.53	0.11	0.74	2.96
Within Groups	98.49	21.00	4.69			
Total	99.02	22.00				

Table 25. Single factor ANOVA results for TSS for first flush sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	18.00	1613.89	89.66	24366.91
TW	15.00	954.72	63.65	19595.95

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	5536.21	1.00	5536.21	0.25	0.62	2.87
Within Groups	688580.70	31.00	22212.28			
Total	694116.91	32.00				

Table 26. Single factor ANOVA results for TSS for storm composite sampling regime events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	7.00	484.71	69.24	4959.97
TW	7.00	248.80	35.54	797.20

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3975.22	1.00	3975.22	1.38	0.26	3.18
Within Groups	34543.01	12.00	2878.58			
Total	38518.23	13.00				

Table 27. Single factor ANOVA results for TSS for all events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	25.00	2098.60	83.94	18587.42
TW	22.00	1203.52	54.71	13471.26

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	10004.00	1.00	10004.00	0.62	0.44	2.82
Within Groups	728994.59	45.00	16199.88			
Total	738998.59	46.00				

3.3.2.2 Nitrogen and Phosphorus Compounds

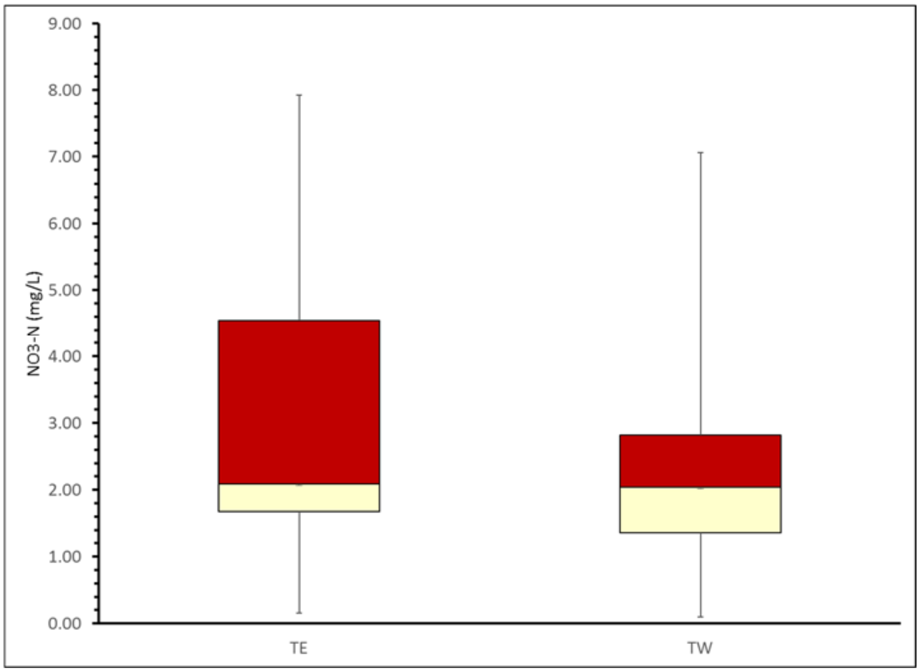
Samples for nitrate-nitrogen (NO_3-N), ammonia-nitrogen (NH_3-N), total nitrogen (TN), dissolved reactive phosphorus (DRP) and total phosphorus (TP) were collected and analyzed under both the first flush and storm composite sampling regimes. Summary statistics for nitrogen compounds for the first flush, storm composite and combined sampling regimes are presented in Table 28. Mean and median NO_3-N, NH_3-N and TN concentrations were higher exiting the TE control watershed than the TW treatment watershed, regardless of the sampling regime (Figures 50, 51 and 52). Maximum NO_3-N concentrations were also higher exiting the TE control watershed than the TW treatment watershed, possibly due to denitrification in the rain garden substrate. Maximum NH_3-N concentrations were found exiting the TW treatment watershed under the storm composite regimes, and maximum TN concentrations were found exiting the TW treatment watershed under the first flush regime. The ranges for NO_3-N, NH_3-N and TN were 0.08 - 7.93 mg/L, 0.05 - 10.40 mg/L and 3.20 - 15.90 mg/L, respectively. However, means comparisons indicated significantly lower concentration in waters exiting the TW treatment watershed compared to the TE control watershed for storm composite NO_3-N (TE: 1.08 ± 0.24 mg/L vs. TW: 0.36 ± 0.10 mg/L, $p = 0.01$), combined data set NO_3-N (TE: 2.48 ± 0.42 mg/L vs. TW: 1.53 ± 0.31 mg/L, $p = 0.04$) and combined data set TN (TE: 7.99 ± 0.76 mg/L vs. TW: 6.62 ± 0.67 mg/L, $p = 0.09$).

Furthermore, ANOVA results (Tables 29, 30 and 31) support these conclusions for NO_3-N concentrations. First flush NO_3-N concentrations were not significantly different ($p = 0.21$, $F = 1.60$, F-crit = 2.86). However, storm composite NO_3-N concentrations were significantly lower for the TW treatment watershed compared to the TE control watershed ($p = 0.01$, $F = 8.24$, F-crit = 3.03). Likewise, NO_3-N concentrations for the combined data set were significantly lower for the TW treatment watershed compared to the TE control watershed ($p = 0.08$, $F = 3.28$, F-crit = 2.80).

Table 28. Summary statistics for nitrogen compounds for first flush, storm composite and the combined data set. Std. Dev = standard deviation and Std. error = standard error. Student's t-test p-values are for comparison of the values for the two watersheds for each sampling regime.

	First flush		Storm composite		Combined	
	TE	TW	TE	TW	TE	TW
NO_3-N (mg/L)						
Mean	3.15	2.26	1.08	0.36	2.48	1.53
Median	2.09	1.94	0.79	0.21	1.78	1.16
Std. Dev.	2.36	1.65	0.71	0.33	2.20	1.60
Maximum	7.93	7.06	2.23	0.99	7.93	7.06
Minimum	0.15	0.10	0.08	0.03	0.08	0.03
Std. Error	0.54	0.41	0.24	0.10	0.42	0.31
p	0.11		0.01		0.04	
NH_3-N (mg/L)						
Mean	4.15	3.54	1.55	1.39	3.15	2.59
Median	3.40	3.20	0.35	0.05	2.75	2.50
Std. Dev.	1.95	1.32	3.17	4.35	2.75	3.17
Maximum	9.00	7.60	10.40	14.50	10.40	14.50
Minimum	2.60	2.50	0.05	0.05	0.05	0.05
Std. Error	0.49	0.35	1.00	1.31	0.54	0.63
p	0.17		0.46		0.25	
TN (mg/L)						
Mean	9.07	7.93	5.83	4.54	7.99	6.62
Median	8.90	7.85	3.70	3.05	6.80	6.75
Std. Dev.	3.47	3.16	4.17	2.89	3.96	3.44
Maximum	15.90	17.20	14.40	9.90	15.90	17.20
Minimum	3.60	3.80	3.20	2.20	3.20	2.20
Std. Error	0.82	0.79	1.39	0.91	0.76	0.67
p	0.16		0.22		0.09	

a)



b)

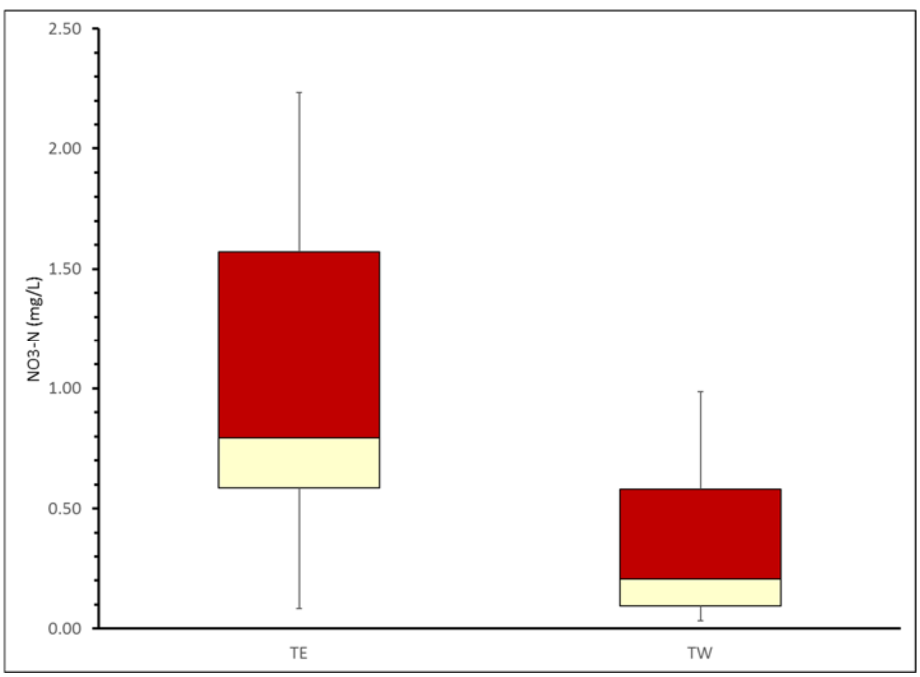
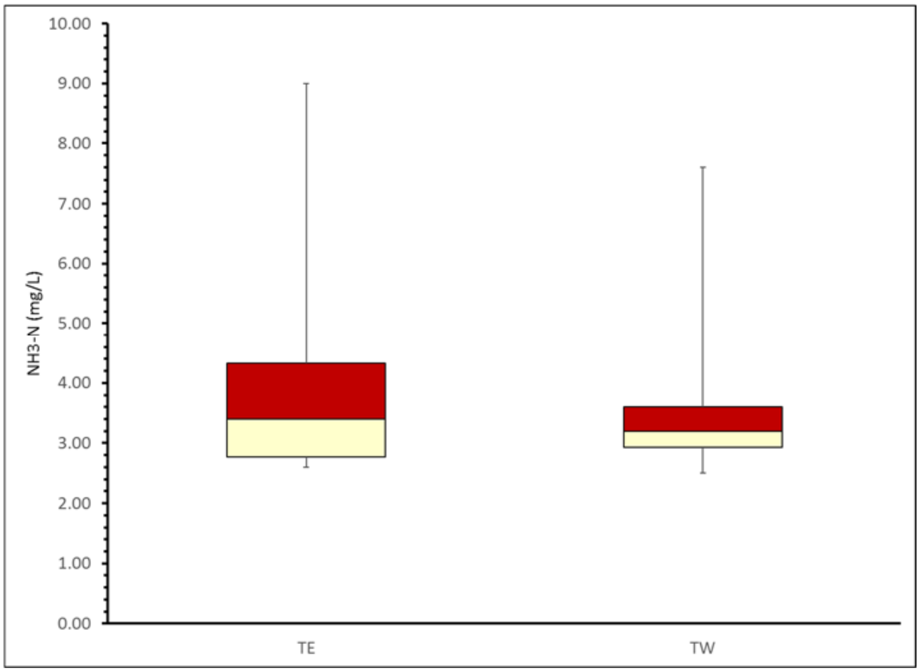


Figure 50. Box and whisker plots of nitrate-nitrogen (NO_3-N) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

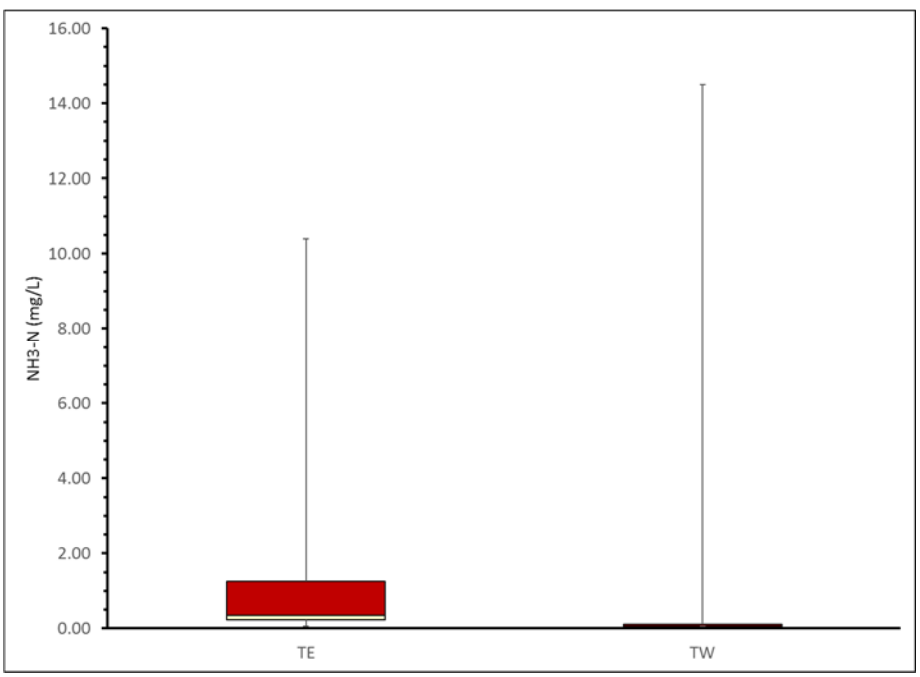
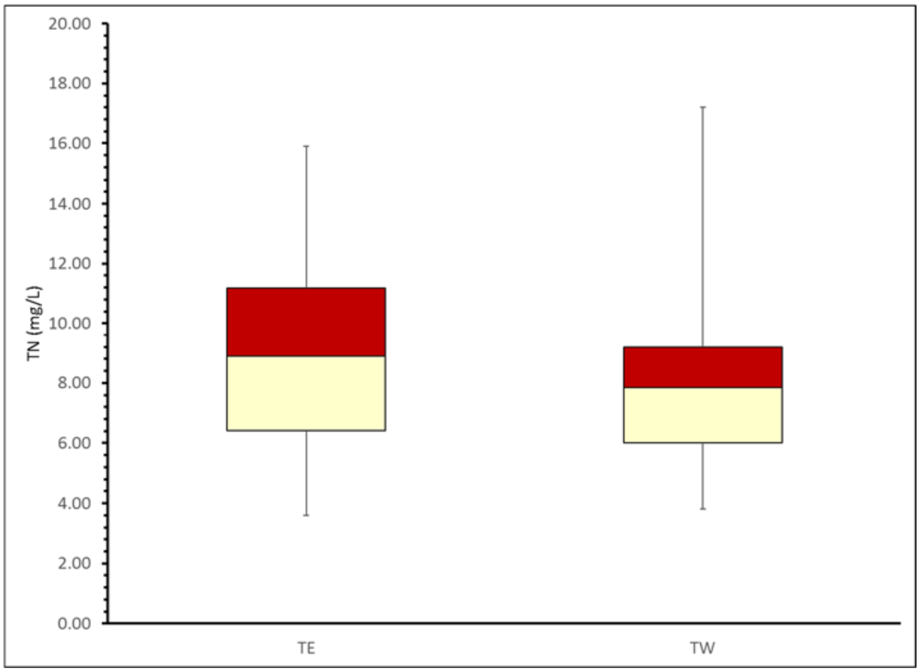


Figure 51. Box and whisker plots of ammonia-nitrogen (NH_3-N) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

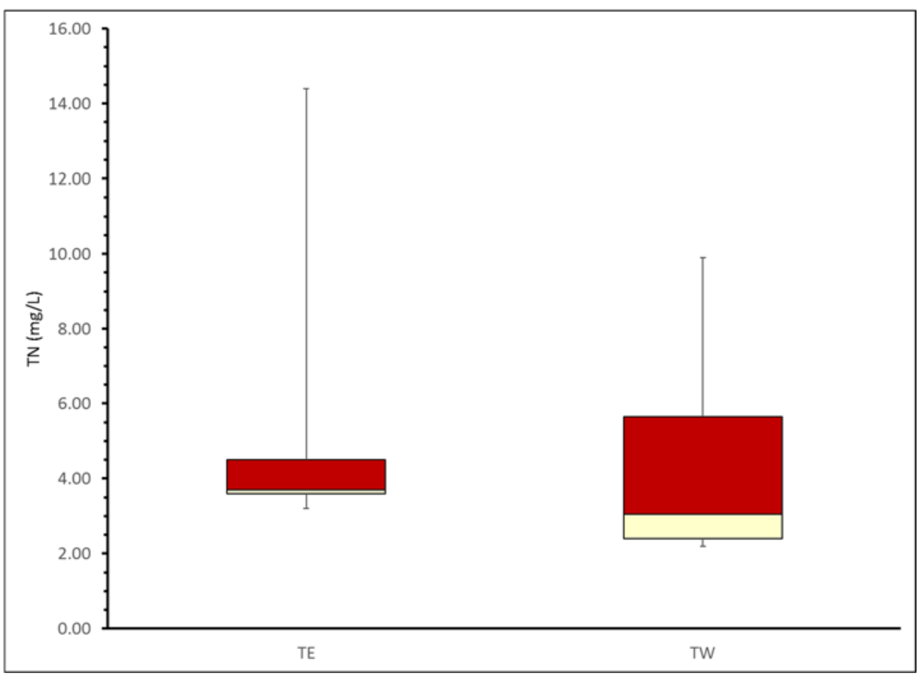


Figure 52. Box and whisker plots of total nitrogen (TN) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Table 29. Single factor ANOVA results for NO_3-N for first flush sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	19.00	59.78	3.15	5.56
TW	16.00	36.14	2.26	2.72

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	6.84	1.00	6.84	1.60	0.21	2.86
Within Groups	140.76	33.00	4.27			
Total	147.60	34.00				

Table 30. Single factor ANOVA results for NO_3-N for storm composite sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	9.00	9.68	1.08	0.51
TW	10.00	3.56	0.36	0.11

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	2.46	1.00	2.46	8.24	0.01	3.03
Within Groups	5.07	17.00	0.30			
Total	7.52	18.00				

Table 31. Single factor ANOVA results for NO_3-N for all sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	28.00	69.46	2.48	4.83
TW	26.00	39.70	1.53	2.56

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	12.26	1.00	12.26	3.28	0.08	2.80
Within Groups	194.30	52.00	3.74			
Total	206.57	53.00				

ANOVA results (Tables 32, 33 and 34) support these conclusions for NH_3-N concentrations. First flush, storm composite and combined data set NH_3-N concentrations were not significantly different between the TW treatment and TE control watersheds.

Table 32. Single factor ANOVA results for NH_3-N concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	16.00	66.40	4.15	3.82
TW	14.00	49.60	3.54	1.74

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.75	1.00	2.75	0.96	0.33	2.89
Within Groups	79.89	28.00	2.85			
Total	82.65	29.00				

Table 33. Single factor ANOVA results for NH_3-N for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
0.20	9.00	15.30	1.70	11.03
0.05	10.00	15.20	1.52	20.80

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.15	1.00	0.15	0.01	0.92	3.03
Within Groups	275.46	17.00	16.20			
Total	275.61	18.00				

Table 34. Single factor ANOVA results for NH_3-N concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	26.00	81.90	3.15	7.57
TW	25.00	64.85	2.59	10.02

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	3.94	1.00	3.94	0.45	0.51	2.81
Within Groups	429.59	49.00	8.77			
Total	433.53	50.00				

Additional ANOVA results (Tables 35, 36 and 37) do not support these conclusions for TN concentrations. First flush, storm composite and combined data set TN concentrations were not significantly different between the TW treatment and TE control watersheds.

Biogeochemical cycling of nitrogen compounds, specifically denitrification, in the rain gardens likely played a role in decreasing NO_3-N concentrations and perhaps TN concentrations. The oxidation-reduction environment produced in these units promotes active microbial communities contributing to net NO_3-N removal from solution. It is likely that, barring disturbance, these communities will mature and flourish in the rain gardens over the long term.

Table 35. Single factor ANOVA results for TN concentrations for first flush sampling events.

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
TE	26.00	81.90	3.15	7.57		
TW	25.00	64.85	2.59	10.02		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	3.94	1.00	3.94	0.45	0.51	2.81
Within Groups	429.59	49.00	8.77			
Total	433.53	50.00				

Table 36. Single factor ANOVA results for TN for storm composite sampling events.

SUMMARY						
Groups	*Count*	*Sum*	*Average*	*Variance*		
TE	9.00	52.50	5.83	17.36		
TW	10.00	45.40	4.54	8.33		
ANOVA						
Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	7.92	1.00	7.92	0.63	0.44	3.03
Within Groups	213.80	17.00	12.58			
Total	221.73	18.00				

Table 37. Single factor ANOVA results for TN concentrations for all sampling events.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	27.00	215.80	7.99	15.66
TW	26.00	172.20	6.62	11.83

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	24.84	1.00	24.84	1.80	0.19	2.81
Within Groups	702.76	51.00	13.78			
Total	727.61	52.00				

Summary statistics for phosphorus compounds for the first flush, storm composite and combined sampling regimes are presented in Table 38. Mean, median and maximum DRP and TP concentrations were higher exiting the TW treatment watershed than the TE control watershed, regardless of the sampling regime (Figures 53 and 54). First flush DRP concentrations from the TW watershed (0.42 ± 0.12 mg/L) were consistently greater than those from the TE control watershed (0.15 ± 0.04 mg/L). Likewise, storm composite DRP and TP concentrations from the TW watershed (0.07 ± 0.02 mg/L and 0.36 ± 0.10 mg/L, respectively) were consistently greater than DRP and TP concentrations from the TE control watershed (0.05 ± 0.01 mg/L and 0.17 ± 0.06 mg/L, respectively). For the combined data set, DRP and TP concentrations from the TW watershed were also consistently greater than DRP and TP concentrations from the TE control watershed. Means comparisons indicated significantly lower values in waters exiting the TE control watershed compared to the TW treatment watershed for first flush DRP concentrations ($p = 0.02$), storm composite TP concentrations ($p = 0.07$) and combined data set DRP ($p = 0.03$) and TP ($p = 0.06$) concentrations.

Furthermore, ANOVA results (Tables 39, 40 and 41) support these conclusions for DRP concentrations. First flush DRP concentrations were significantly greater for the TW treatment watershed ($p = 0.04$, $F = 4.64$, F-crit = 2.88) as were combined data set DRP concentrations ($p = 0.06$, $F = 3.72$, F-crit = 2.81). However, storm composite DRP concentrations were not significantly different for the TW treatment watershed compared to the TE control watershed ($p = 0.21$, $F = 1.69$, F-crit = 3.03). In addition, TP concentrations were not significantly different (Tables 42, 43 and 44) for the first flush sampling regime ($p = 0.68$, $F = 0.17$, F-crit = 2.86), storm composite sampling regime ($p = 0.13$, $F = 2.51$, F-crit = 3.03) or for the combined data set ($p = 0.12$, $F = 2.46$, F-crit = 2.81).

Table 38. Summary statistics for phosphorus compounds for first flush, storm composite and the combined data set. Std. Dev = standard deviation and Std. error = standard error. Student's t-test p-values are for comparison of the values for the two watersheds for each sampling regime.

	First Flush		Storm Composite		Combined	
	TE	TW	TE	TW	TE	TW
DRP (mg/L)						
Mean	0.15	0.42	0.05	0.07	0.12	0.30
Median	0.10	0.21	0.04	0.05	0.08	0.13
SD	0.16	0.48	0.03	0.05	0.14	0.41
Max	0.49	1.64	0.10	0.16	0.49	1.64
Min	0.00	0.01	0.02	0.02	0.00	0.01
SE	0.04	0.12	0.01	0.02	0.03	0.09
p	0.02		0.11		0.03	
TP (mg/L)						
Mean	0.07	0.08	0.17	0.36	0.10	0.18
Median	0.07	0.07	0.11	0.32	0.07	0.09
SD	0.04	0.04	0.17	0.32	0.11	0.24
Max	0.14	0.15	0.54	1.02	0.54	1.02
Min	0.00	0.00	0.03	0.01	0.00	0.00
SE	0.01	0.01	0.06	0.10	0.02	0.05
p	0.34		0.07		0.06	

Table 39. Single factor ANOVA results for DRP concentrations for first flush sampling events.

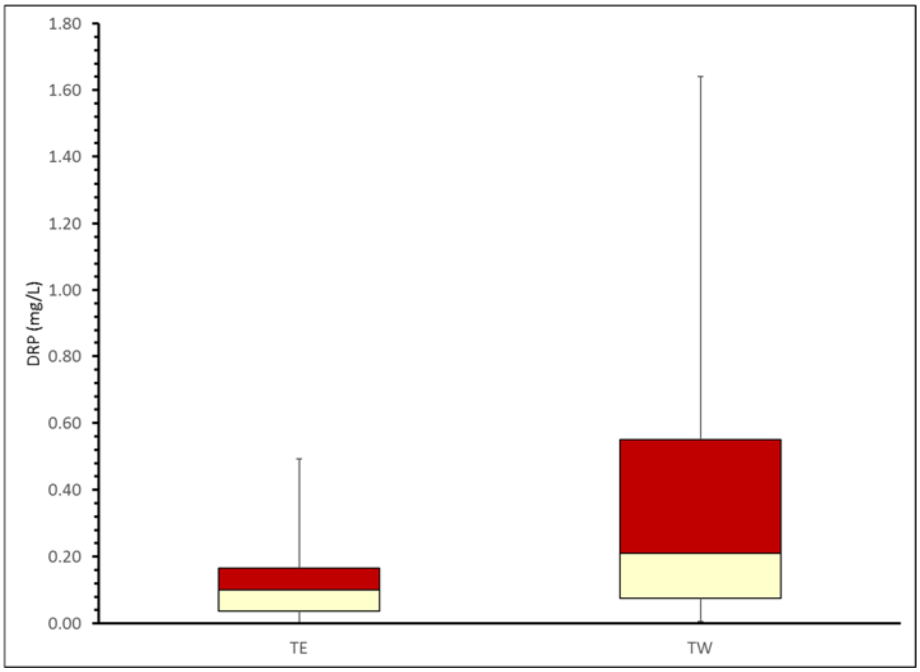
SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	17.00	2.63	0.15	0.03
TW	15.00	6.28	0.42	0.23

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.56	1.00	0.56	4.64	0.04	2.88
Within Groups	3.59	30.00	0.12			
Total	4.14	31.00				

a)



b)

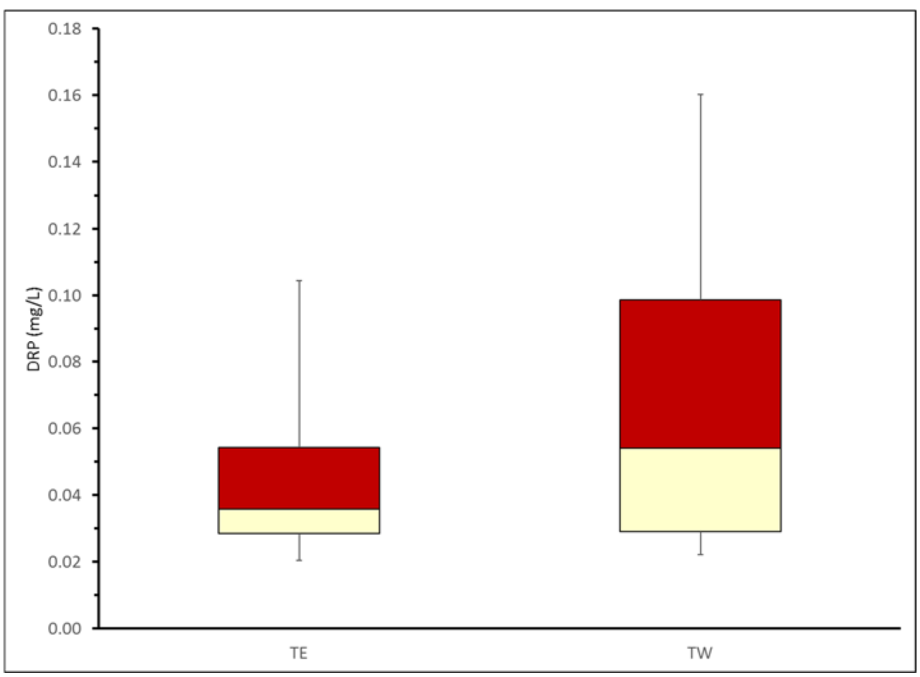
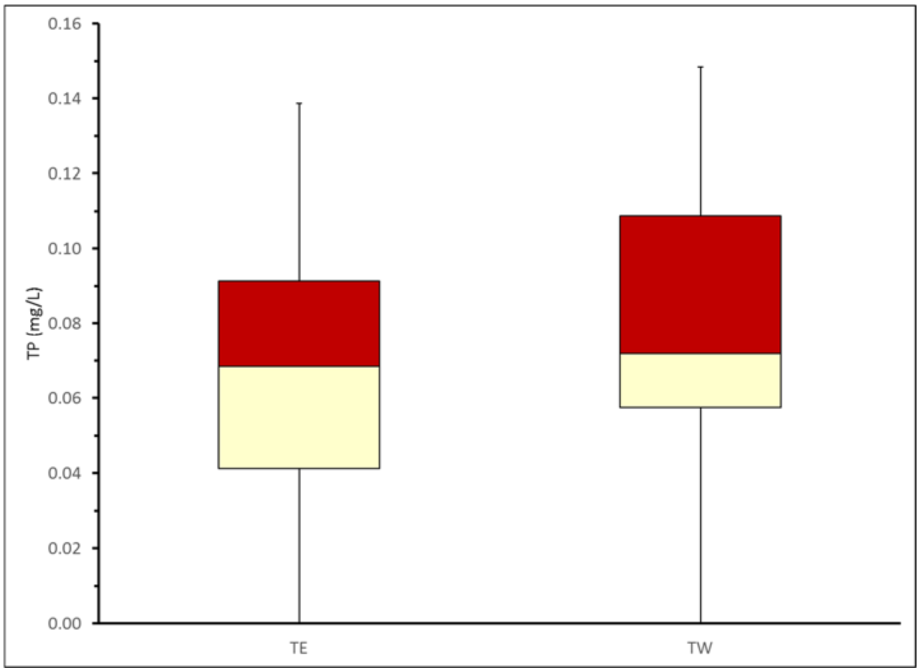


Figure 53. Box and whisker plots of dissolved reactive phosphorus (DRP) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

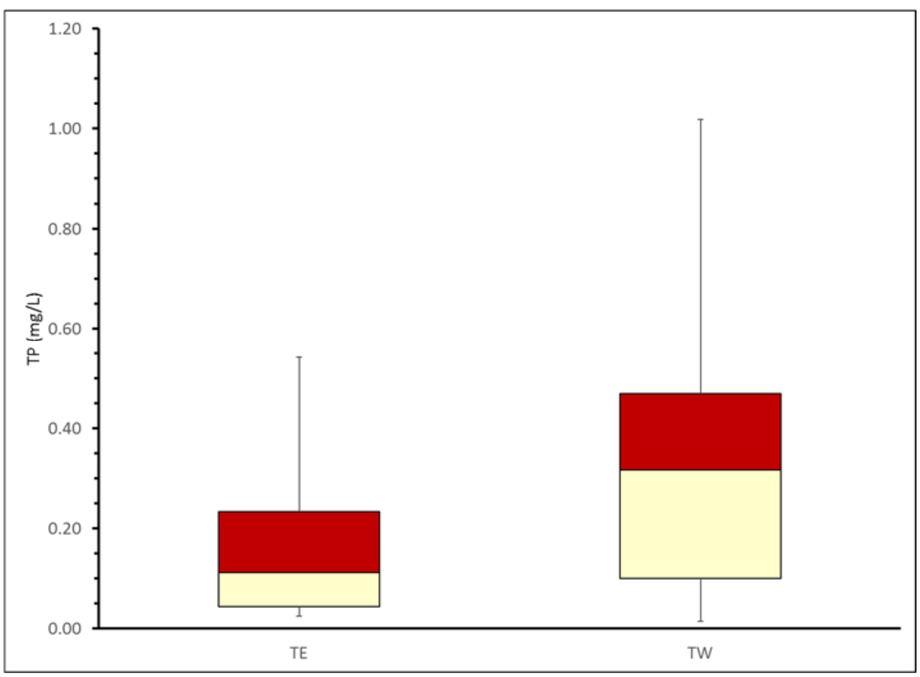


Figure 54. Box and whisker plots of total phosphorus (TP) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Table 40. Single factor ANOVA results for DRP for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	9.00	0.41	0.05	0.00
TW	10.00	0.70	0.07	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00	1.00	0.00	1.69	0.21	3.03
Within Groups	0.03	17.00	0.00			
Total	0.03	18.00				

Table 41. Single factor ANOVA results for DRP concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	26.00	3.04	0.12	0.02
TW	25.00	6.98	0.28	0.16

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.34	1.00	0.34	3.72	0.06	2.81
Within Groups	4.42	49.00	0.09			
Total	4.75	50.00				

Table 42. Single factor ANOVA results for TP for first flush sampling events.

Groups	Count	Sum	Average	Variance
Column 1	19.00	1.32	0.07	0.00
Column 2	17.00	1.28	0.08	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00	1.00	0.00	0.17	0.68	2.86
Within Groups	0.06	34.00	0.00			
Total	0.06	35.00				

Table 43. Single factor ANOVA results for TP for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	9.00	1.52	0.17	0.03
TW	10.00	3.56	0.36	0.10

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.17	1.00	0.17	2.51	0.13	3.03
Within Groups	1.13	17.00	0.07			
Total	1.29	18.00				

Table 44. Single factor ANOVA results for TP concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	27.00	2.79	0.10	0.01
TW	26.00	4.75	0.18	0.06

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.08	1.00	0.08	2.46	0.12	2.81
Within Groups	1.73	51.00	0.03			
Total	1.82	52.00				

The inconsistent results with regard to phosphorus concentrations, especially in a phosphorus-limited watershed like Lake Thunderbird, are not conducive to LID BMP implementation. Two factors may have played roles in these results. First, despite the study design, no institutional controls were in place for landowners with regard to lawn fertilization. Several lawns in the TW treatment watershed were chemically treated on numerous occasions throughout the study period, in at least one instance, immediately prior to a sampled storm event. Despite the presence of rain barrels and rain gardens and other LID BMPs, improper and excessive lawn fertilization would directly contribute to elevated phosphorus concentrations. Although impossible to determine in this study, it is possible that fertilization rates may have differed between the TW treatment and TE control watersheds. In addition, the mixed media utilized in the rain gardens may have contributed phosphorus to runoff waters, at least initially. The compost mix likely contained phosphorus in the organic phase which may have been mobilized during initial flooding through leaching. Identification and quantification of phosphorus concentrations in the media is needed to verify it as a potential source.

3.3.2.3 Total Metals Concentrations

Samples for analysis of 15 metals were collected under both the first flush and storm composite sampling regimes. Nine potentially toxic trace metals were evaluated: Al, As, Cd, Co, Cr, Cu, Ni, Pb and Zn. No samples collected by either sampling regime contained As concentrations greater than the practical quantification limit (PQL). Therefore, As data are not reported. Of the remaining eight trace metals, values below PQLs were found for specific metals for several storm events. Sample sizes ranged from 1 to 29. Summary statistics for trace metals for the first flush, storm composite and combined sampling regimes are presented in Tables 45 and 46.

Although not a focus in the Lake Thunderbird watershed, trace metals are commonly found in urban stormwater runoff. Overall, when measurable concentrations were found in this study, significantly lower values were found in waters exiting the TW treatment watershed compared to the TE control watershed ($p < 0.10$). This was true for Al, Cr, Cu and Zn in the first flush and combined data sets and Cd in all data sets. Trace metals data are presented in Figures 55 through 62 for the first flush and storm composite sampling regimes. Generally, a greater number of samples with measurable concentrations occurred in the first flush samples as compared to the storm composite samples. The more concentrated initial runoff (collected as first flush samples) may have simply been diluted by the larger volumes collected by the storm composite sampling regime. A greater number of samples with measureable concentrations also occurred in waters exiting the TE control watershed compared to the TW treatment watershed. It is likely that substantial trace metal sorption occurred in the rain garden organic media, a process well-documented in the metals contamination and treatment literature (e.g., Nairn et al. 2010). ANOVA results generally supported the means comparisons presented in Tables 45 and 46. These results (Table 47 through Table 66) demonstrate significantly lower ($p < 0.10$) trace metals concentrations in waters exiting the TW treatment watershed compared to the TE control watershed, supporting the means comparisons when an adequate number of measurable concentrations was obtained.

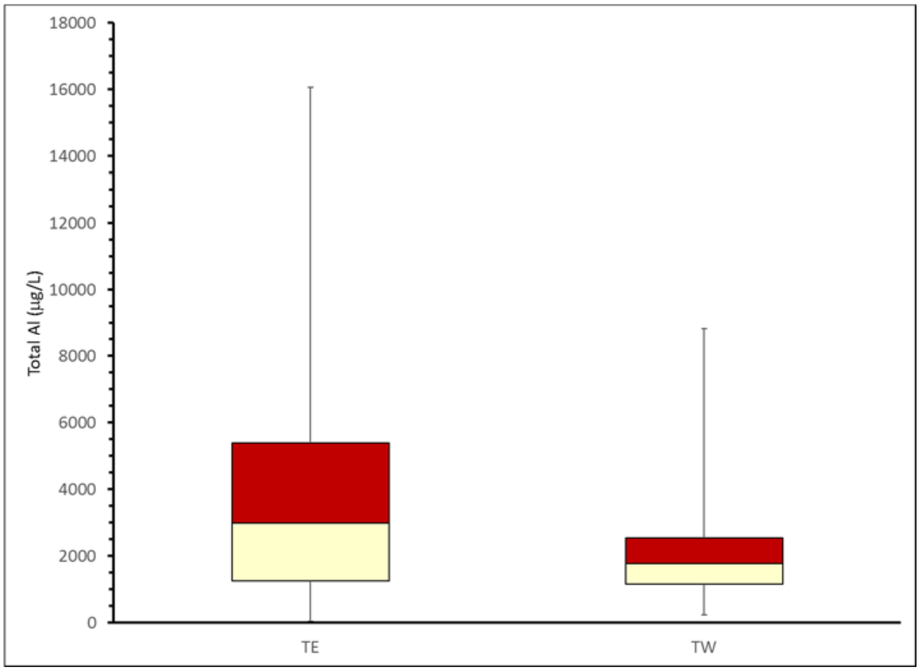
Table 45. Summary statistics for selected metals. Std. Dev = standard deviation, Std. error = standard error, N =sample size. Student's t-test p-values compare the two watersheds for each sampling regime.

	First Flush		Storm Composite		Combined	
	TE	TW	TE	TW	TE	TW
Al (µg/L)						
Mean	4161	2239	1710	1155	3485	1878
Median	2994	1780	753	1150	2278	1765
Std. Dev.	4163	2108	1970	797	3820	1834
Maximum	16058	8825	6142	2004	16058	8825
Minimum	35.65	238.39	490.11	218.08	35.65	218.08
Std. Error	908	527	696	282	709	374
N	21	16	8	8	29	24
p	0.05		0.24		0.03	
Cd (µg/L)						
Mean	1.0922	0.0009	0.7115		1.0446	0.0009
Median	0.8637	0.0008	0.7115		0.8399	0.0008
Std. Dev.	0.4695	0.0003	0.0034		0.4560	0.0003
Maximum	2.1030	0.0015	0.7140		2.1030	0.0015
Minimum	0.7154	0.0005	0.7091		0.7091	0.0005
Std. Error	0.1255	0.0001	0.0024		0.1140	0.0001
N	14	6	2	0	16	6
p	1.28E-05		---		1.05E-05	
Co (µg/L)						
Mean	1.42		1.09	1.18	1.38	1.18
Median	1.17		1.09	1.18	1.15	1.18
Std. Dev.	0.65				0.62	
Maximum	2.90				2.90	
Minimum	1.08				1.08	
Std. Error	0.25				0.22	
N	7	0	1	1	8	1
p	---		---			
Cr (µg/L)						
Mean	8.09	4.34	3.56	2.82	6.94	3.88
Median	4.87	2.86	2.56	2.66	4.48	2.73
Std. Dev.	7.41	3.46	1.68	0.43	6.74	2.96
Maximum	28.43	15.03	6.57	3.81	28.43	15.03
Minimum	1.98	1.81	2.48	2.48	1.98	1.81
Std. Error	1.62	0.87	0.59	0.15	1.27	0.62
N	21.00	16.00	8.00	8.00	29.00	24.00
p	0.04		0.12		0.02	

Table 46. Summary statistics for additional metals. Std. Dev = standard deviation, Std. error = standard error, N =sample size. Student's t-test p-values compare the two watersheds for each sampling regime.

	First Flush		Storm Composite		Combined	
	TE	TW	TE	TW	TE	TW
Cu (μg/L)						
Mean	44.86	15.01	10.60	6.46	35.41	12.16
Median	30.36	10.68	7.75	5.27	22.52	7.06
Std. Dev.	41.75	10.94	8.52	5.93	38.81	10.28
Maximum	159.63	36.58	31.61	20.56	159.63	36.58
Minimum	6.63	4.41	6.01	2.54	6.01	2.54
Std. Error	9.11	2.73	3.01	2.10	7.21	2.10
N	21	16	8	8	29	24
p	4.35E-03		0.14		3.15E-03	
Ni (μg/L)						
Mean	17.63	13.39	12.14	8.83	14.14	9.48
Median	18.26	13.39	6.20	9.70	14.51	10.54
Std. Dev.	2.16		11.06	3.19	9.08	3.38
Maximum	19.50		36.02	12.49	36.02	13.39
Minimum	14.51		5.57	4.67	5.57	4.67
Std. Error	1.08		4.18	1.30	2.74	1.28
N	4	1	7	6	11	7
p	---		0.25		0.11	
Pb (μg/L)						
Mean	30.53	25.25	21.34		28.23	25.25
Median	31.34	25.65	21.34		26.78	25.65
Std. Dev.	5.67	0.89	0.25		6.41	0.89
Maximum	37.58	25.88	21.52		37.58	25.88
Minimum	23.81	24.23	21.17		21.17	24.23
Std. Error	2.31	0.52	0.18		2.26	0.52
N	6	2	2	0	8	2
p	0.08		---		0.23	
Zn (μg/L)						
Mean	102.13	49.31	15.01	18.45	78.09	39.03
Median	51.33	25.91	10.06	10.18	30.59	19.58
Std. Dev.	108.59	52.15	12.43	25.85	100.15	46.88
Maximum	391.46	208.99	43.04	82.13	391.46	208.99
Minimum	13.57	11.52	6.16	5.57	6.16	5.57
Std. Error	23.70	13.04	4.39	9.14	18.60	9.57
N	21	16	8	8	29	24
p	0.04		0.37		0.04	

a)



b)

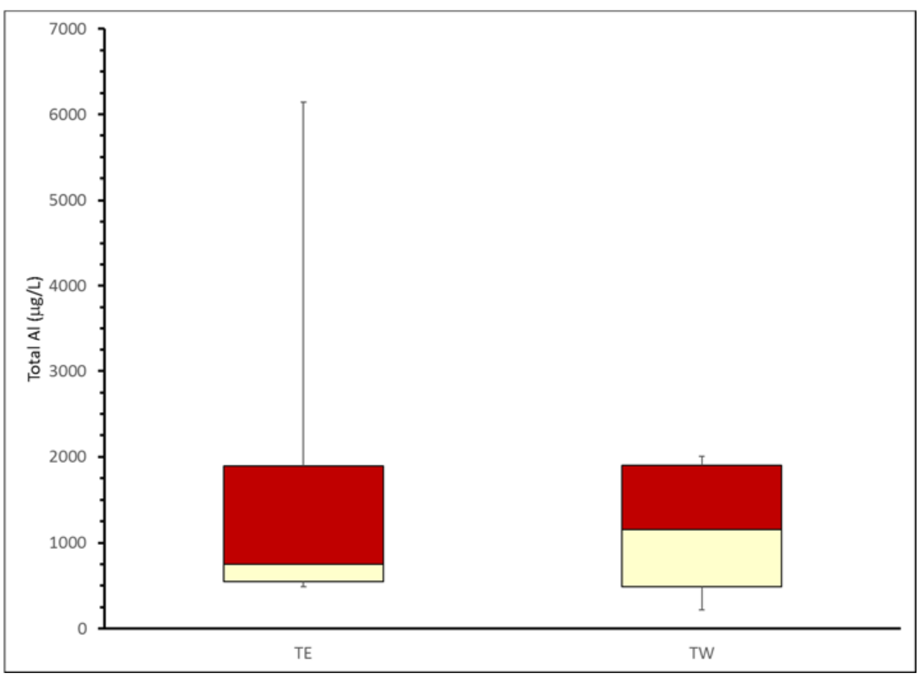
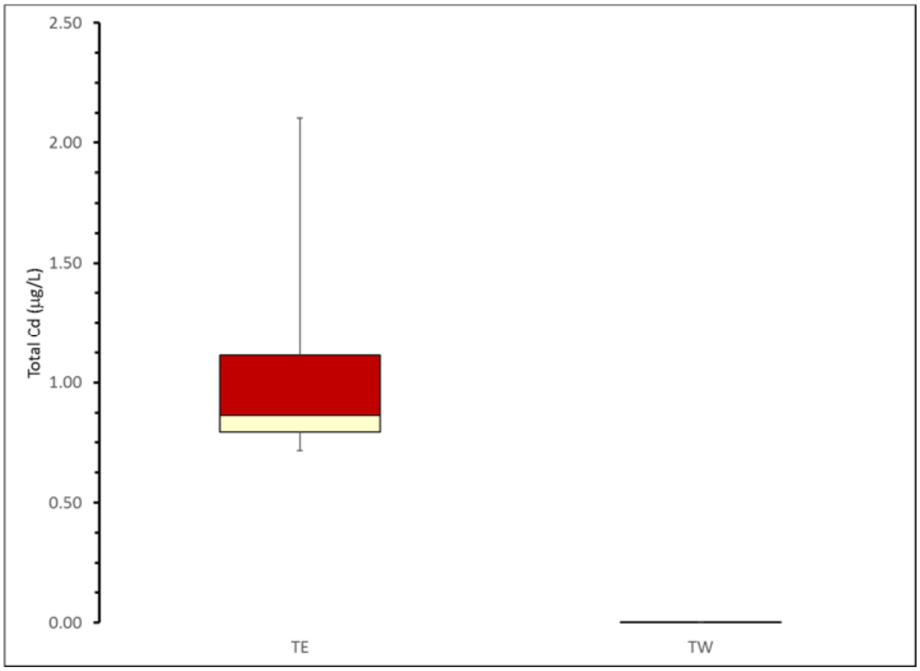


Figure 55. Box and whisker plots of total aluminum (Al) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

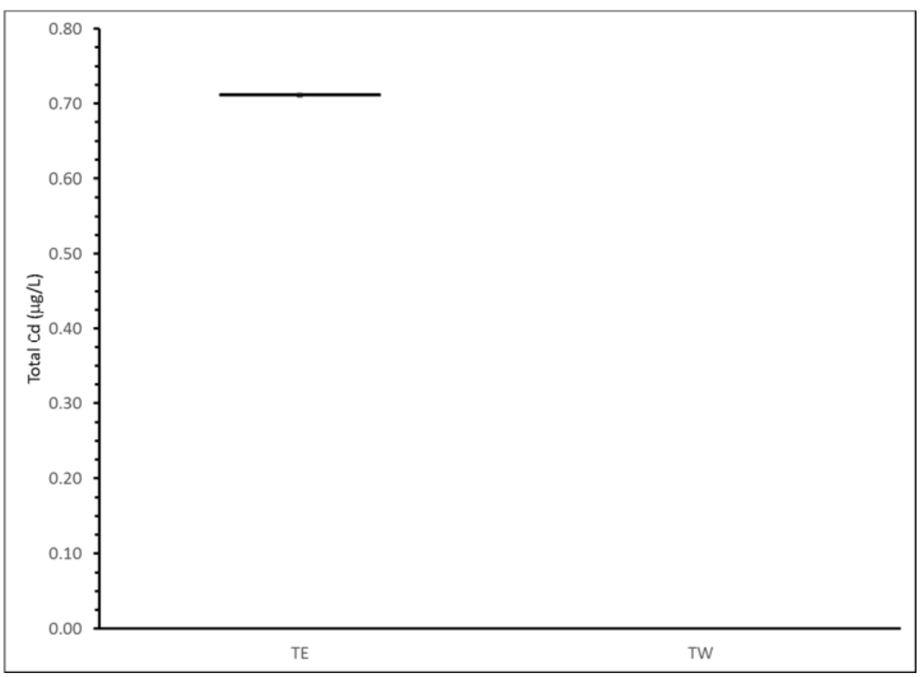
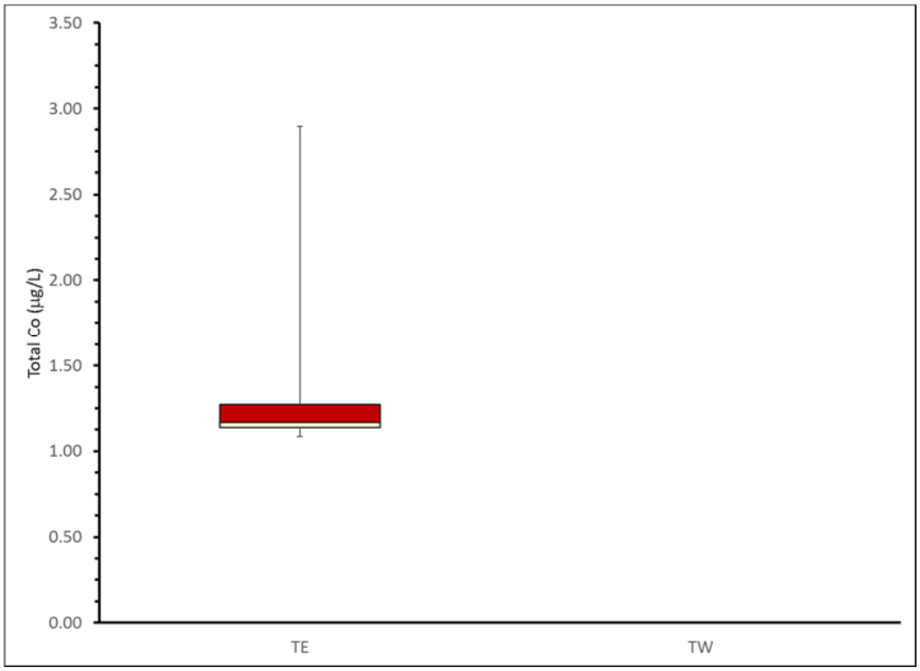


Figure 56. Box and whisker plots of total cadmium (Cd) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

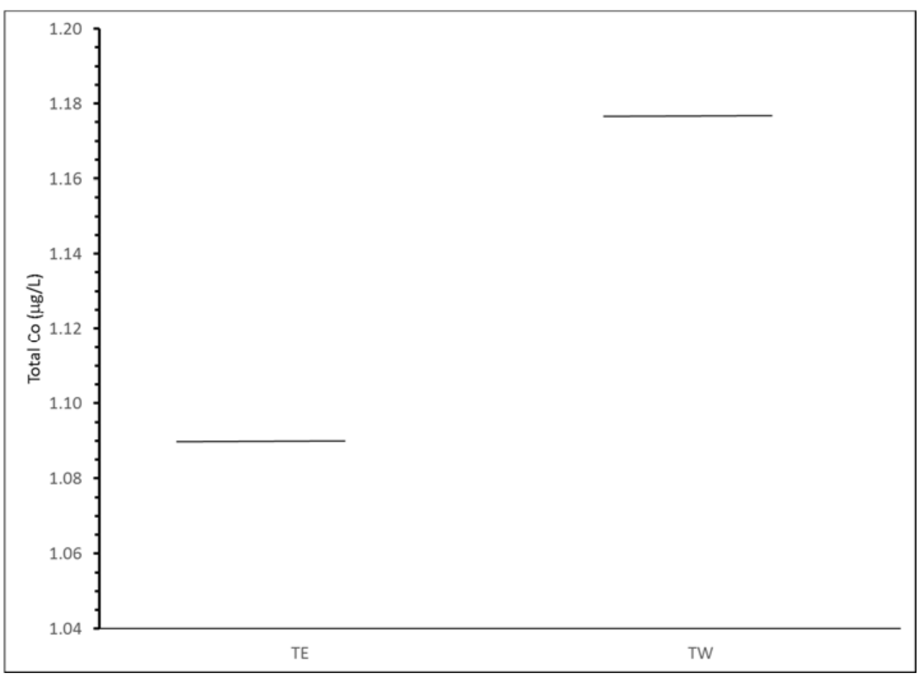
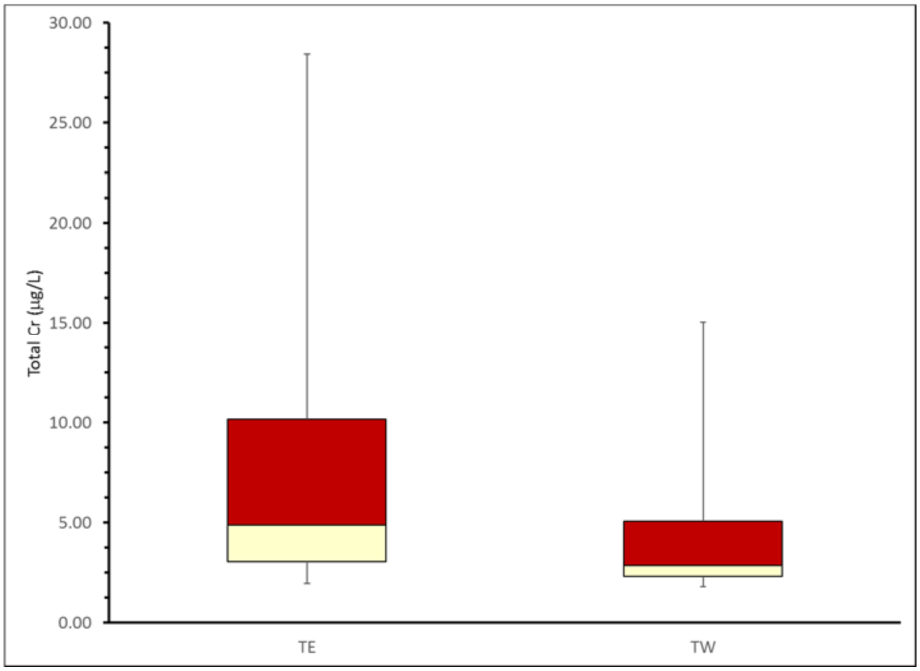


Figure 57. Box and whisker plots of total cobalt (Co) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

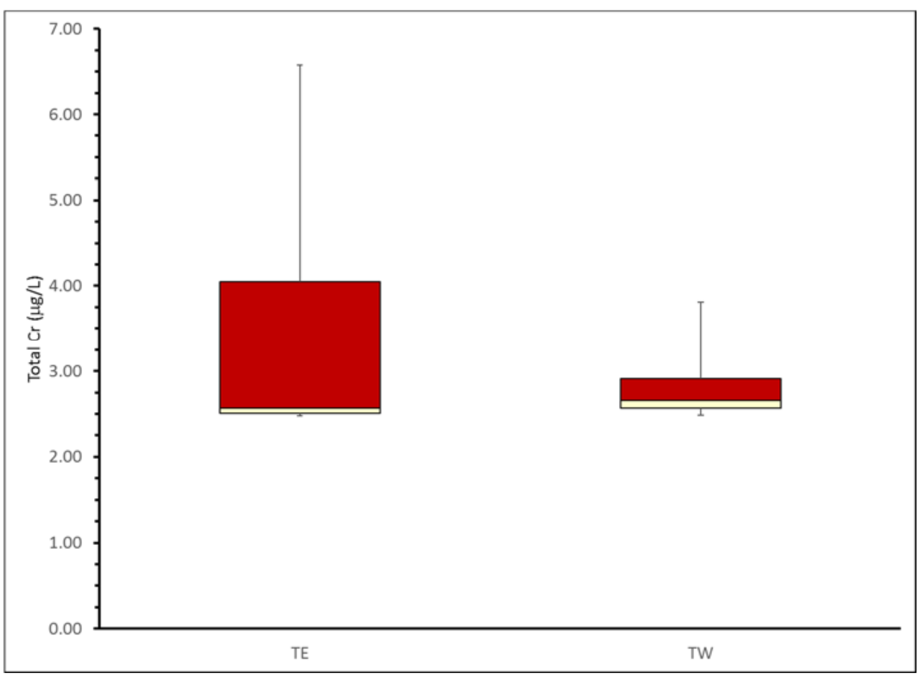
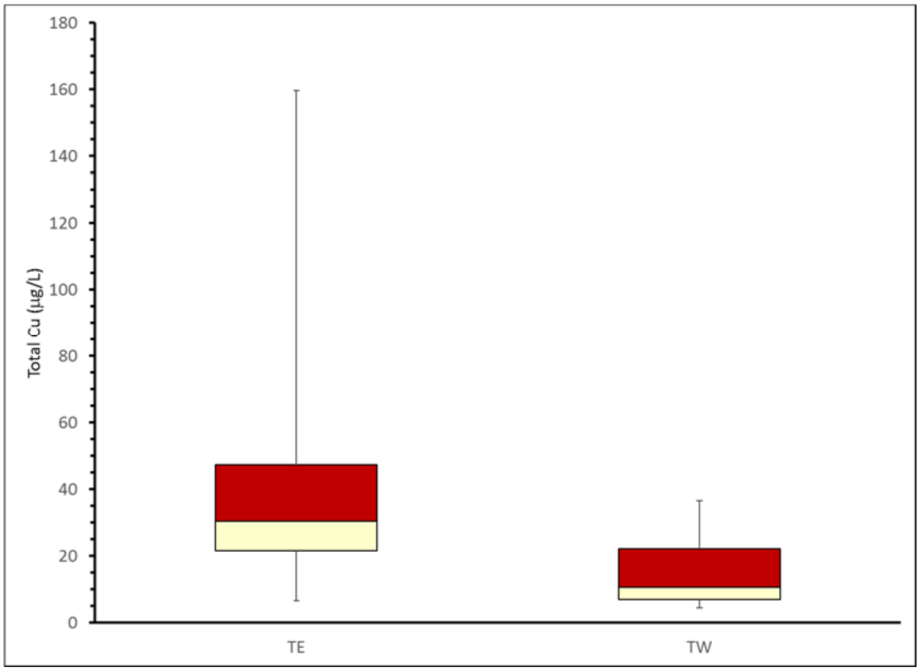


Figure 58. Box and whisker plots of total chromium (Cr) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

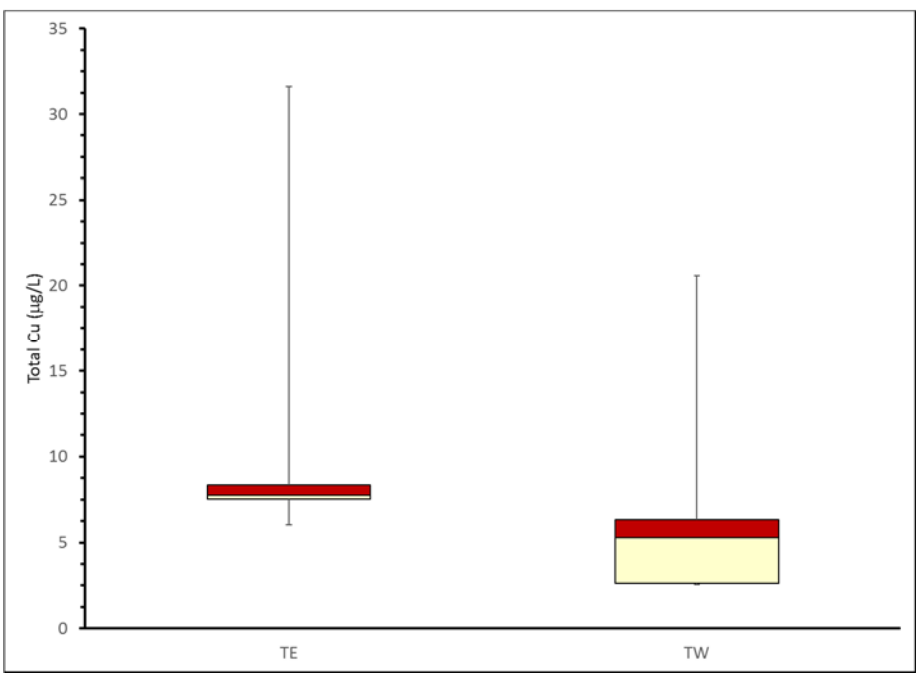
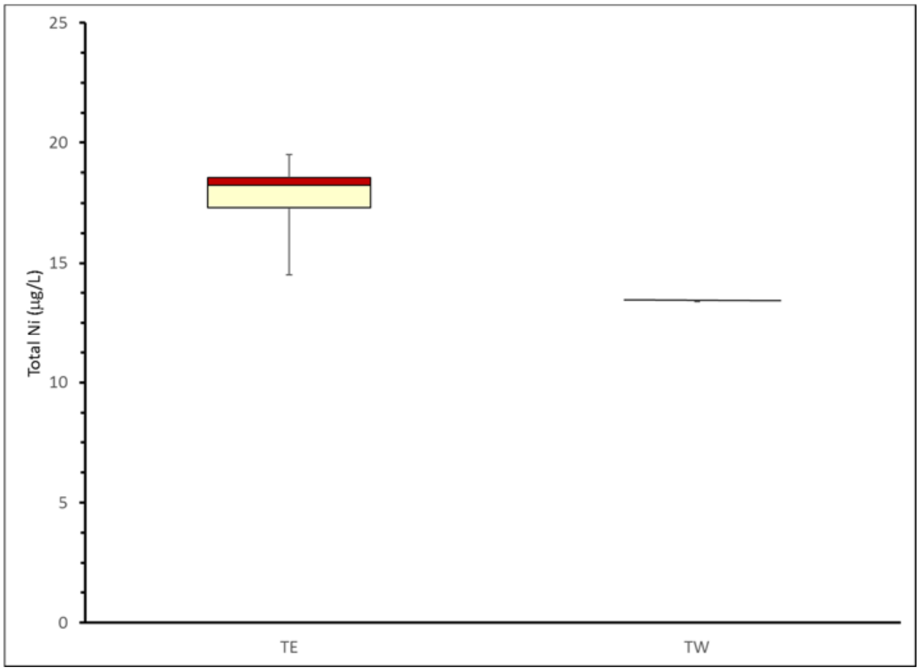


Figure 59. Box and whisker plots of total copper (Cu) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

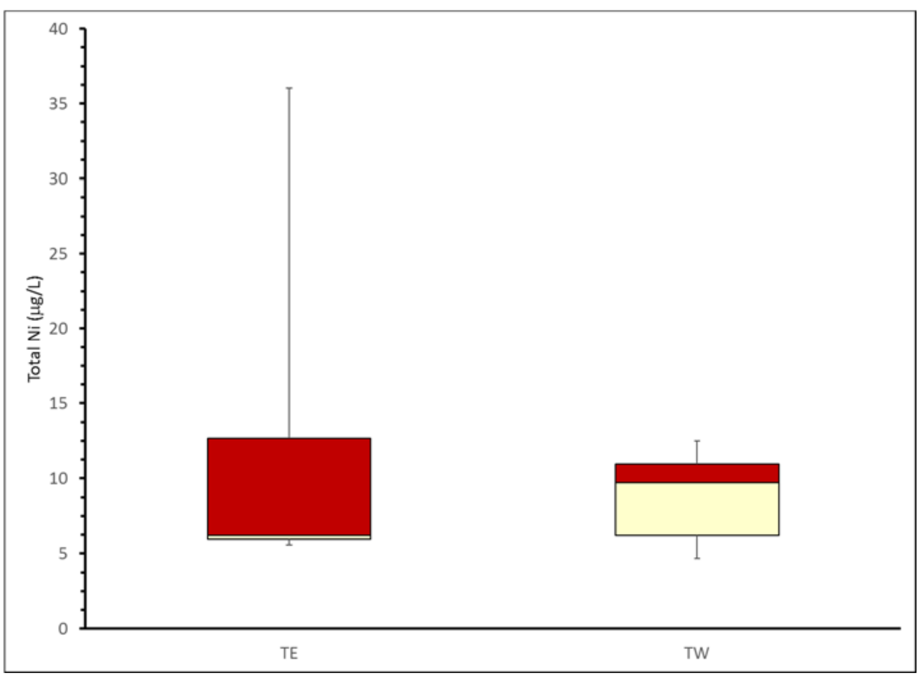
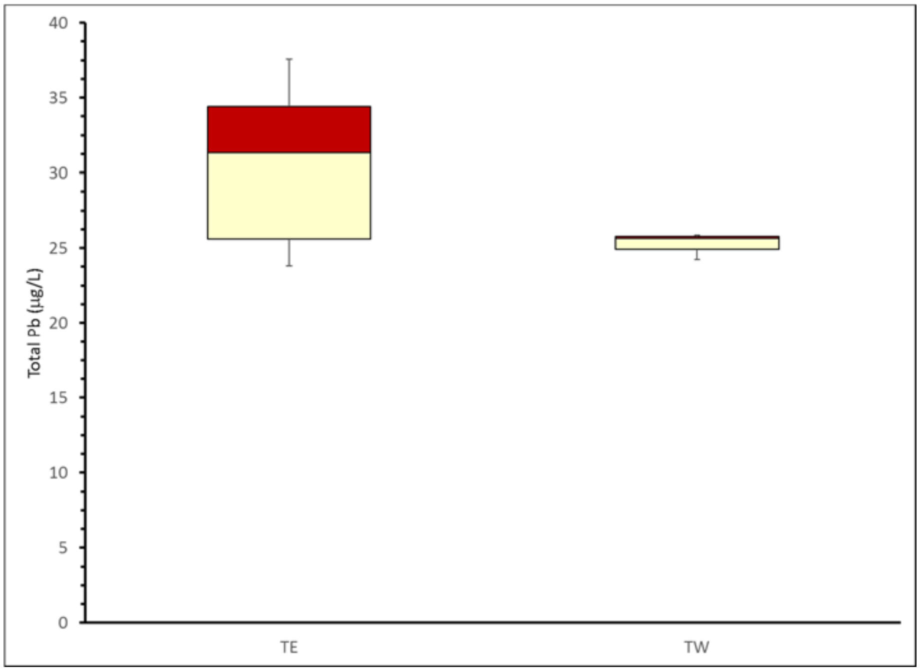


Figure 60. Box and whisker plots of total nickel (Ni) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

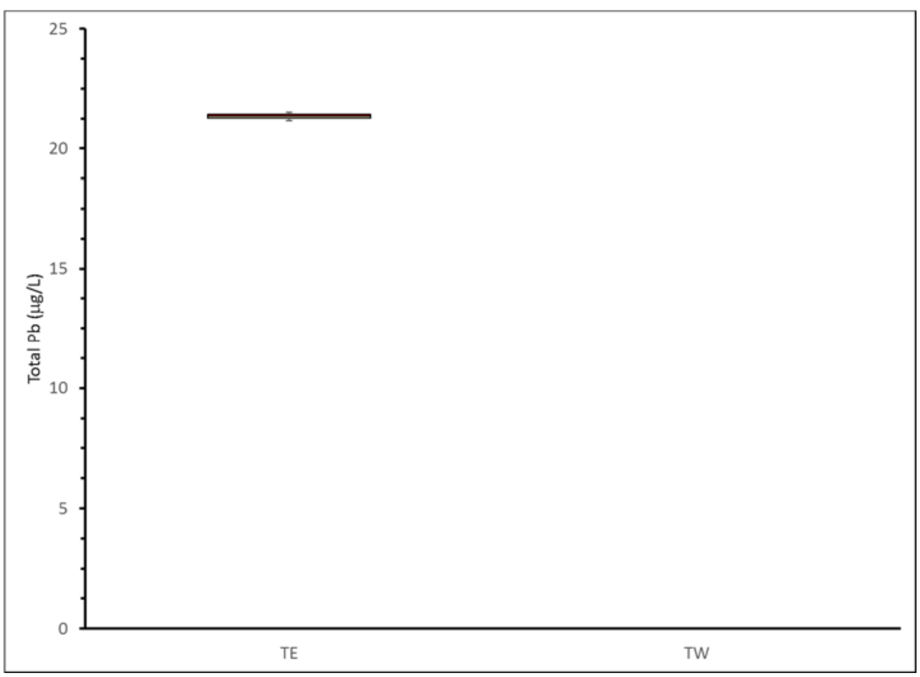
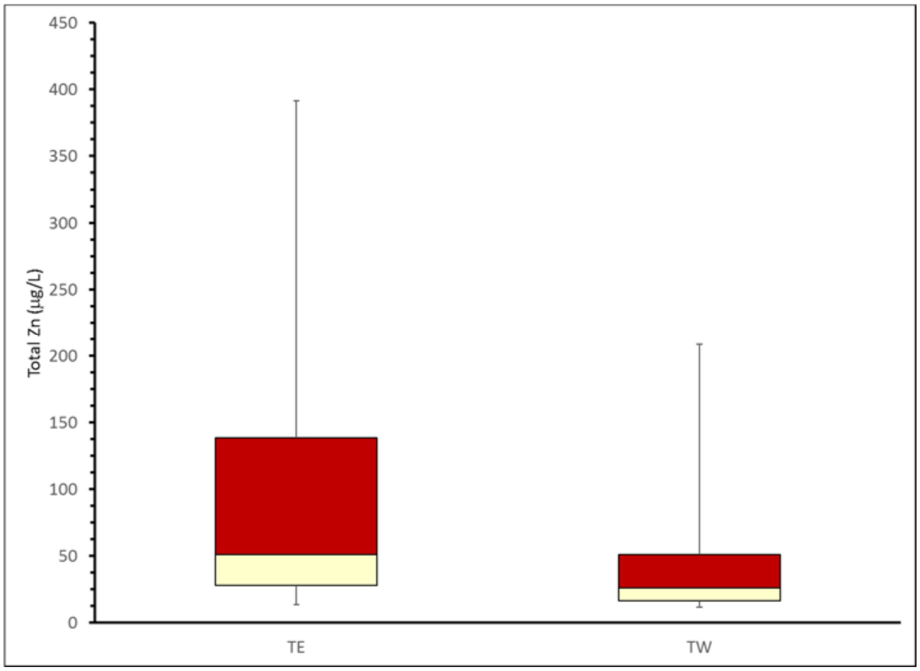


Figure 61. Box and whisker plots of total lead (Pb) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

a)



b)

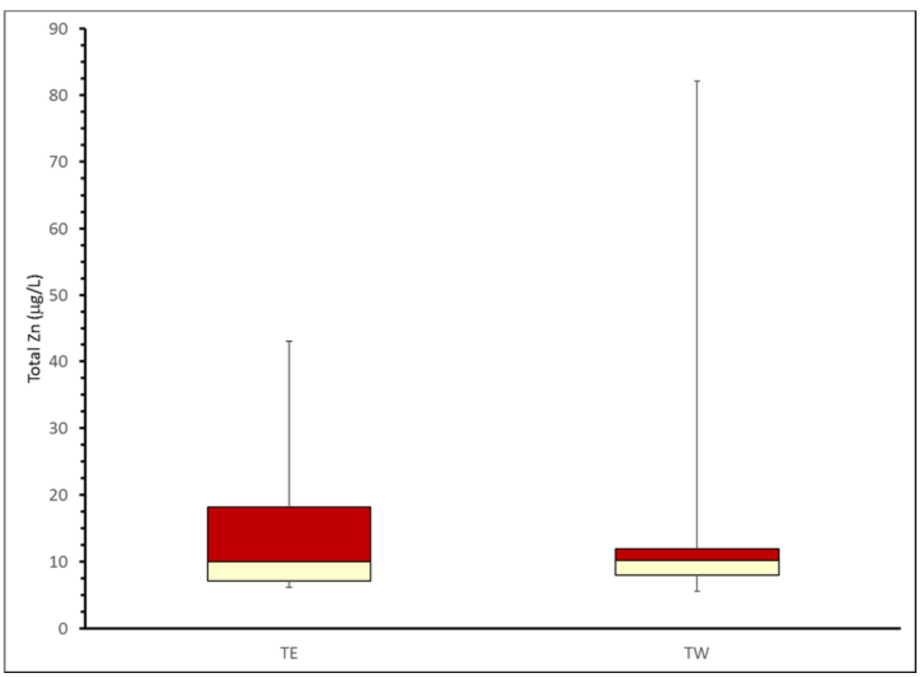


Figure 62. Box and whisker plots of total zinc (Zn) concentrations for a) the first flush sampling regime, conducted from September 2013 to April 2015 (n = 19) and b) the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Table 47. Single factor ANOVA results for total Al concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	21.00	87380.70	4160.99	17329341.23
TW	16.00	35820.23	2238.76	4445495.43

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	33554000.21	1.00	33554000.21	2.84	0.10	2.85
Within Groups	413269256.19	35.00	11807693.03			
Total	446823256.39	36.00				

Table 48. Single factor ANOVA results for total Al for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8.00	13679.73	1709.97	3880306.84
TW	8.00	9242.03	1155.25	635565.66

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	1230821.75	1.00	1230821.75	0.55	0.47	3.10
Within Groups	31611107.45	14.00	2257936.25			
Total	32841929.20	15.00				

Table 49. Single factor ANOVA results for total Al concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	29.00	101060.42	3484.84	14591108.28
TW	24.00	45062.26	1877.59	3364899.97

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	33923385.57	1.00	33923385.57	3.56	0.06	2.81
Within Groups	485943731.23	51.00	9528308.46			
Total	519867116.79	52.00				

Table 50. Single factor ANOVA results for total Cd concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	14.00	15.29	1.09	0.22
TW	6.00	0.01	0.00	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	5.00	1.00	5.00	31.42	2.56E-05	3.01
Within Groups	2.87	18.00	0.16			
Total	7.87	19.00				

Table 51. Single factor ANOVA results for total Cd for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	2.00	1.42	0.71	0.00
TW	0.00	0.00		

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.00	1.00	0.00	0.00		
Within Groups	0.00	0.00	65535.00			
Total	0.00	1.00				

Table 52. Single factor ANOVA results for total Cd concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	16.00	16.71	1.04	0.21
TW	6.00	0.01	0.00	0.00

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	4.75	1.00	4.75	30.48	2.10E-05	2.97
Within Groups	3.12	20.00	0.16			
Total	7.87	21.00				

Table 53. Single factor ANOVA results for total Cr concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	21.00	169.87	8.09	54.86
TW	16.00	69.50	4.34	11.98

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	127.38	1.00	127.38	3.49	0.07	2.85
Within Groups	1276.83	35.00	36.48			
Total	1404.21	36.00				

Table 54. Single factor ANOVA results for total Cr for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8.00	28.50	3.56	2.83
TW	8.00	22.59	2.82	0.19

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	2.19	1.00	2.19	1.45	0.25	3.10
Within Groups	21.10	14.00	1.51			
Total	23.29	15.00				

Table 55. Single factor ANOVA results for total Cr concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	28.00	194.33	6.94	45.46
TW	23.00	89.31	3.88	8.74

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	118.04	1.00	118.04	4.07	0.05	2.81
Within Groups	1419.60	49.00	28.97			
Total	1537.63	50.00				

Table 56. Single factor ANOVA results for total Cu concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	21.00	942.11	44.86	1742.89
TW	16.00	240.18	15.01	119.63

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	8092.13	1.00	8092.13	7.73	0.01	2.85
Within Groups	36652.26	35.00	1047.21			
Total	44744.39	36.00				

Table 57. Single factor ANOVA results for total Cu for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8.00	84.83	10.60	72.61
TW	8.00	51.68	6.46	35.22

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	68.68	1.00	68.68	1.27	0.28	3.10
Within Groups	754.75	14.00	53.91			
Total	823.44	15.00				

Table 58. Single factor ANOVA results for total Cu concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	29.00	1026.94	35.41	1505.90
TW	24.00	291.86	12.16	105.70

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	7099.33	1.00	7099.33	8.12	0.01	2.81
Within Groups	44596.34	51.00	874.44			
Total	51695.67	52.00				

Table 59. Single factor ANOVA results for total Ni concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	4.00	70.54	17.63	4.68
TW	1.00	13.39	13.39	

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	14.40	1.00	14.40	3.08	0.18	5.54
Within Groups	14.04	3.00	4.68			
Total	28.44	4.00				

Table 60. Single factor ANOVA results for total Ni for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	7.00	85.00	12.14	122.33
TW	6.00	52.97	8.83	10.16

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	35.51	1.00	35.51	0.50	0.50	3.23
Within Groups	784.77	11.00	71.34			
Total	820.28	12.00				

Table 61. Single factor ANOVA results for total Ni concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	11.00	155.54	14.14	82.47
TW	7.00	66.36	9.48	11.44

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	92.90	1.00	92.90	1.66	0.22	3.05
Within Groups	893.40	16.00	55.84			
Total	986.29	17.00				

Table 62. Single factor ANOVA results for total Pb concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	6.00	183.19	30.53	32.11
TW	3.00	75.76	25.25	0.80

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	55.72	1.00	55.72	2.41	0.16	3.59
Within Groups	162.13	7.00	23.16			
Total	217.86	8.00				

Table 63. Single factor ANOVA results for total Pb concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8.00	225.88	28.23	41.03
TW	3.00	75.76	25.25	0.80

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	19.39	1.00	19.39	0.60	0.46	3.36
Within Groups	288.84	9.00	32.09			
Total	308.23	10.00				

Table 64. Single factor ANOVA results for total Zn concentrations for first flush sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	21.00	2144.65	102.13	11791.05
TW	16.00	789.04	49.31	2719.96

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	25327.39	1.00	25327.39	3.20	0.08	2.85
Within Groups	276620.52	35.00	7903.44			
Total	301947.91	36.00				

Table 65. Single factor ANOVA results for total Zn for storm composite sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8.00	120.10	15.01	154.50
TW	8.00	147.59	18.45	668.23

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	47.25	1.00	47.25	0.11	0.74	3.10
Within Groups	5759.12	14.00	411.37			
Total	5806.37	15.00				

Table 66. Single factor ANOVA results for total Zn concentrations for all sampling events.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	29.00	2264.75	78.09	10030.91
TW	24.00	936.63	39.03	2198.18

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	20044.05	1.00	20044.05	3.08	0.09	2.81
Within Groups	331423.51	51.00	6498.50			
Total	351467.56	52.00				

3.4. Comparison of Mass Loading Data

Mass loads were calculated using storm composite sampling regime water quality and quantity data. Because the first flush sampling regime targeted water quality sample collection to a discrete interval at the initiation of flow into the test flumes, applying those concentration data to storm event hydrographs provides erroneous mass loading results. Essentially, elevated concentrations in samples collected shortly after runoff initiation would be applied to larger than realistic flow volumes such that the resulting mass loads are not representative. Therefore, because the storm composite sampling regime provides a water quality sample truly representative of conditions over the entire storm event, mass loads were calculated using these data. Concentration data were converted to mass load using total storm event discharge and making appropriate unit conversions. Resulting loads (mass per unit time) were divided by watershed area to provide area-adjusted mass loading rates from each watershed.

Summary statistics for calculated mass loads are presented in Table 67 for nitrogen compounds, Table 68 for total suspended solids and phosphorus compounds and Tables 69 and 70 for trace metals. Figures 63, 64 and 65 graphically compare mass loads for NO_3-N, NH_3-N and TN, respectively. Figures 66, 67 and 68 graphically compare mass loads for TSS, TP and DRP. Figures 69 through 76 compare trace metal mass loads.

Table 67. Summary statistics for nitrogen compound mass loading. Std. Dev = standard deviation, Std. error = standard error.

	NO_3-N (g acre^{-1} yr^{-1})		NH_3-N (g acre^{-1} yr^{-1})		TN (g acre^{-1} yr^{-1})	
	TE	TW	TE	TW	TE	TW
Mean	3.52	0.86	2.04	2.38	12.77	10.05
Median	0.85	0.41	1.29	0.69	5.44	3.43
Std. Dev.	6.29	1.42	2.05	3.81	16.03	16.54
Maximum	19.39	4.49	5.74	8.05	41.33	55.51
Minimum	0.10	0.05	0.24	0.10	2.56	2.19
Std. Error	2.10	0.47	0.72	1.91	5.34	5.23

Table 68. Summary statistics for TSS and phosphorus compound mass loading. Std. Dev = standard deviation, Std. error = standard error.

	TSS (g acre^{-1} yr^{-1})		TP (g acre^{-1} yr^{-1})		DRP (g acre^{-1} yr^{-1})	
	TE	TW	TE	TW	TE	TW
Mean	387.99	117.00	0.55	0.93	0.12	0.19
Median	56.60	23.75	0.20	0.20	0.04	0.05
Std. Dev.	690.10	194.95	0.77	1.52	0.17	0.29
Maximum	1898.46	524.36	2.16	4.41	0.43	0.82
Minimum	1.28	1.19	0.04	0.02	0.02	0.01
Std. Error	260.83	73.68	0.27	0.48	0.06	0.09

Estimated median mass loads from the TE control watershed exceeded those from the TW treatment watershed for all nitrogen compounds. Due to the non-normality of the data set, the same was not true for means, where mean mass loads from the TE control watershed exceeded those from the TW treatment watershed for NO_3-N and TN, but not for NH_3-N. For the TE control watershed, mass loads ranged 0.10 – 19.39 g acre^{-1} yr^{-1} for NO_3-N, 0.24 – 5.74 g acre^{-1} yr^{-1} for NH_3-N and 2.56 – 41.33 g acre^{-1} yr^{-1} for TN. For the TW treatment watershed, mass loads ranged 0.05 - 4.49 g acre^{-1} yr^{-1} for NO_3-N, 0.10 – 8.05 g acre^{-1} yr^{-1} for NH_3-N and 2.19 – 55.51 g acre^{-1} yr^{-1} for TN. Statistically, only mean NO_3-N mass loads were lower from the TW watershed compared to the TE control watershed (p = 0.10). However, results of ANOVA did not support this finding (Tables 71, 72 and 73).

Estimated median and mean TSS mass loads from the TE control watershed (57 and 388 g $acre^{-1}$ yr^{-1}) exceeded those from the TW treatment watershed. Calculated maximum TSS mass loads from the TE control watershed (almost 1900 g $acre^{-1}$ yr^{-1}) greatly exceeded those from the TW treatment watershed (524 g $acre^{-1}$ yr^{-1}). Median TP mass loads from the TW treatment and TE control watersheds did not differ. Mean TP mass loads from the TW treatment watershed exceeded those from the TE control watershed (0.93 vs. 0.55 g $acre^{-1}$ yr^{-1}). Both median and mean DRP mass loads from the TW treatment watershed slightly exceeded those from the TE control watershed. Statistically, TSS mass loads were significantly lower from the TW treatment watershed (p = 0.10), but TP and DRP mass loads were significantly higher from the TW treatment watershed (p = 0.07 and 0.09, respectively). However, results of ANOVA did not support this finding (Tables 74, 75 and 76).

Table 69. Summary statistics for selected trace metal mass loading. Std. Dev = standard deviation, Std. error = standard error.

	Al (g $acre^{-1}$ yr^{-1})		Cd (g $acre^{-1}$ yr^{-1})		Co (g $acre^{-1}$ yr^{-1})		Cr (g $acre^{-1}$ yr^{-1})	
	TE	TW	TE	TW	TE	TW	TE	TW
Mean	10.36	3.35	5.47E-04	0	8.59E-04	9.96E-04	1.39E-02	6.31E-03
Median	0.89	0.89	5.47E-04	0	8.59E-04	9.96E-04	3.66E-03	2.95E-03
Std. Dev.	23.08	4.87	3.33E-05				2.22E-02	6.80E-03
Maximum	67.01	11.71	5.70E-04				6.40E-02	1.79E-02
Minimum	0.39	0.22	5.23E-04				1.97E-03	2.05E-03
Std. Error	8.16	1.72	2.35E-05				7.84E-03	2.40E-03

Table 70. Summary statistics for additional selected trace metal mass loading. Std. Dev = standard deviation, Std. error = standard error.

	Cu (g $acre^{-1}$ yr^{-1})		Ni (g $acre^{-1}$ yr^{-1})		Pb (g $acre^{-1}$ yr^{-1})		Zn (g $acre^{-1}$ yr^{-1})	
	TE	TW	TE	TW	TE	TW	TE	TW
Mean	0.0302	0.0129	0.0721	0.0262	0.1252	0	0.0453	0.0238
Median	0.0083	0.0043	0.0078	0.0069	0.1252	0	0.0152	0.0149
Std. Dev.	0.0381	0.0150	0.1435	0.0312	0.1550		0.0693	0.0186
Maximum	0.0921	0.0383	0.3930	0.0684	0.2348		0.2079	0.0526
Minimum	0.0060	0.0026	0.0044	0.0045	0.0156		0.0049	0.0055
Std. Error	0.0135	0.0053	0.0543	0.0127	0.1096		0.0245	0.0066

Trace metal mass loads were generally lower from the TW treatment watershed compared to the TE control watershed, for those metals with detectable concentrations for more than one event. Overall, trace metal mass loads were small in magnitude with the exception of aluminum. Elevated Al concentrations are most likely due to incorporation, digestion and analysis of clay particles from soil minerals. Most other trace metals mass loadings were less than 0.1 g $acre^{-1}$ yr^{-1}. Results from ANOVA (not presented) showed no significant differences in mass loadings from the two watersheds.

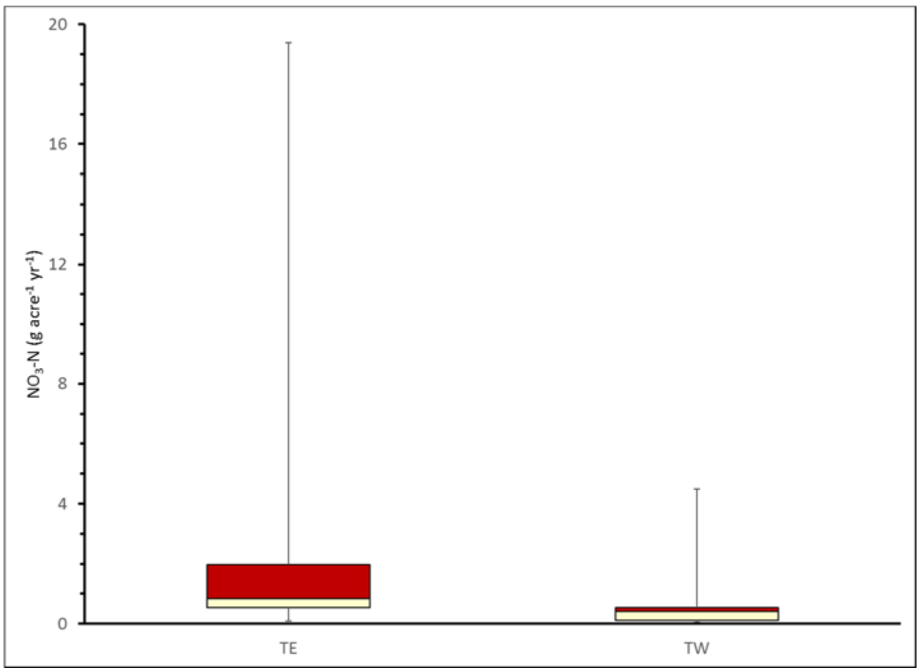


Figure 63. Box and whisker plots of NO_3-N for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

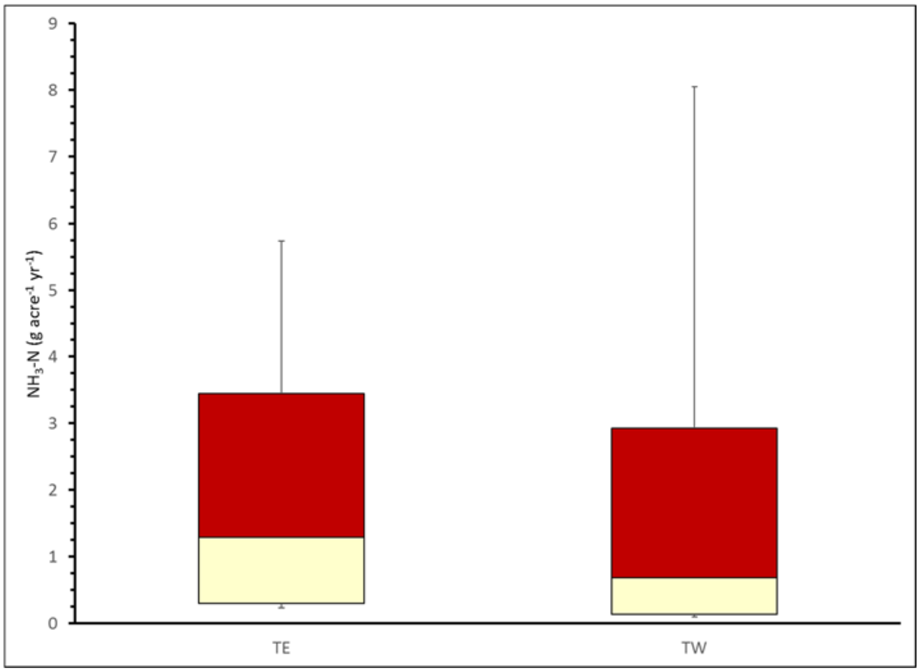


Figure 64. Box and whisker plots of NH_3-N for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

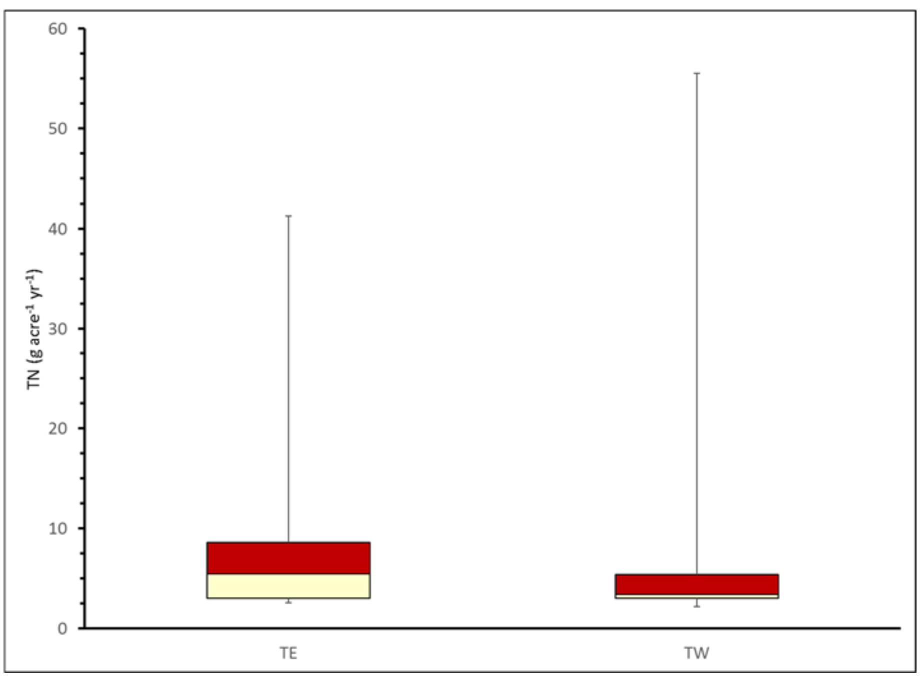


Figure 65. Box and whisker plots of TN for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

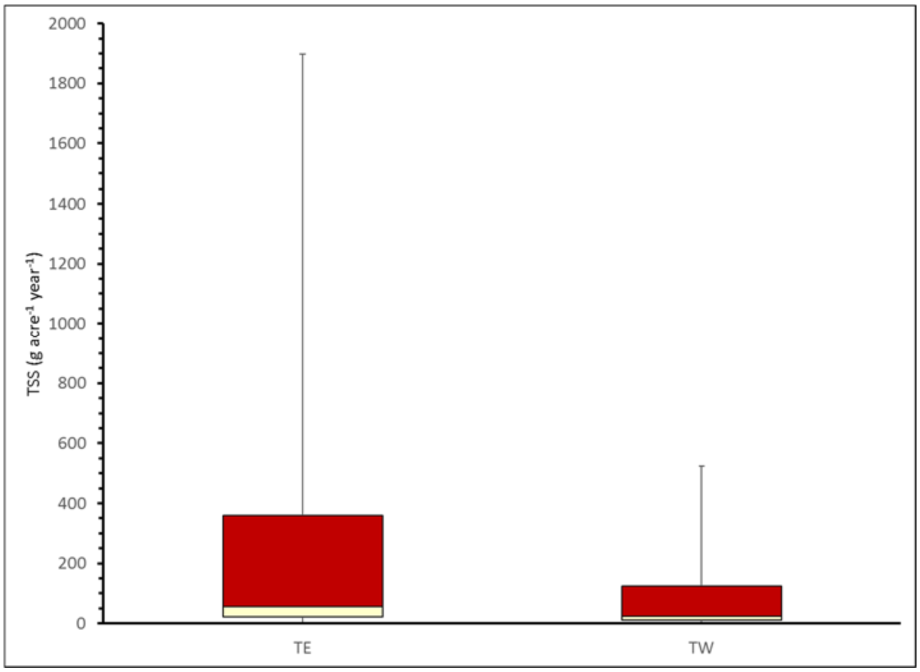


Figure 66. Box and whisker plots of TSS for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

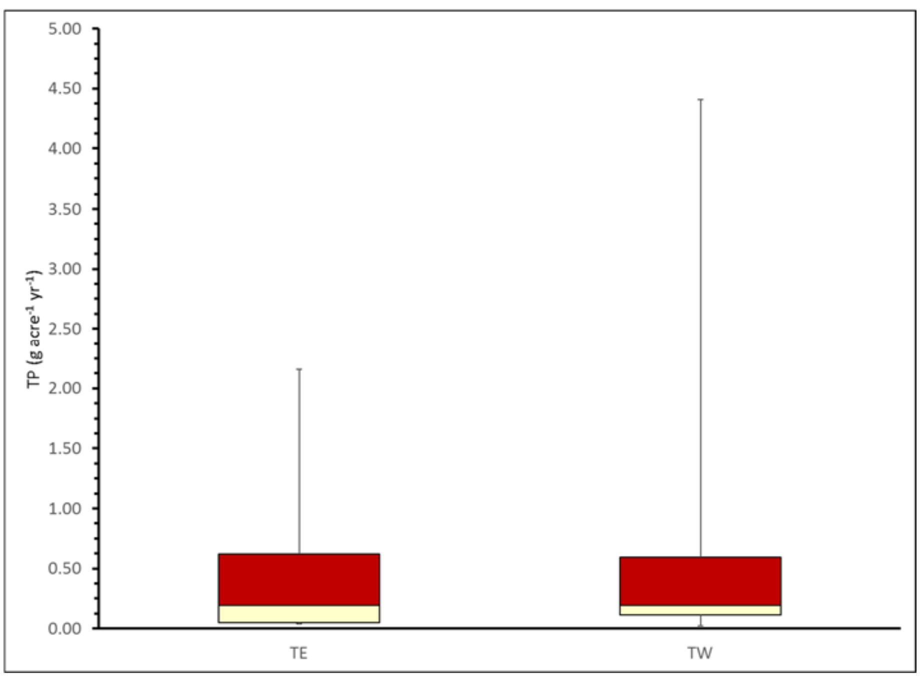


Figure 67. Box and whisker plots of TP for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

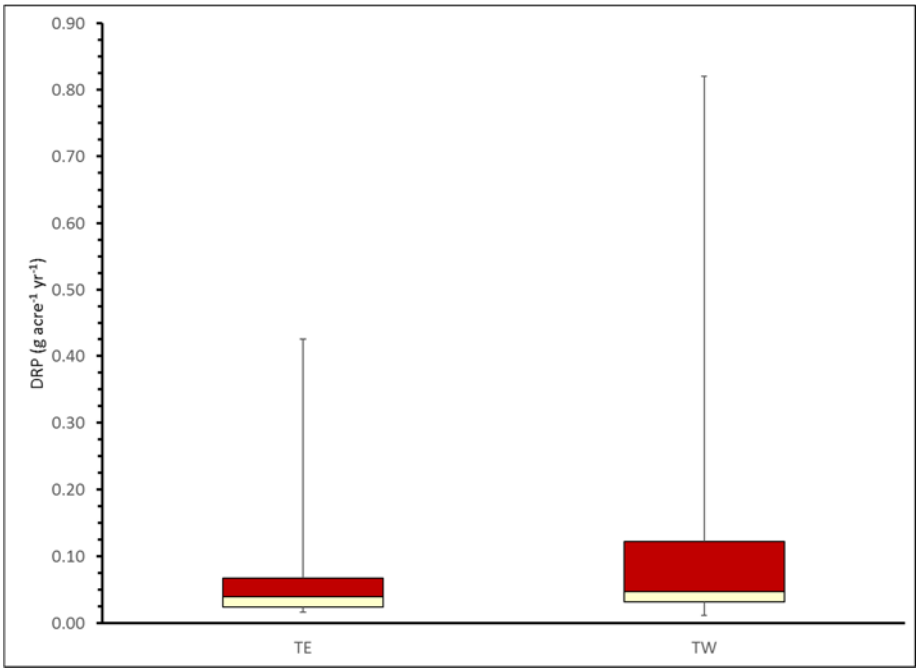


Figure 68. Box and whisker plots of DRP for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

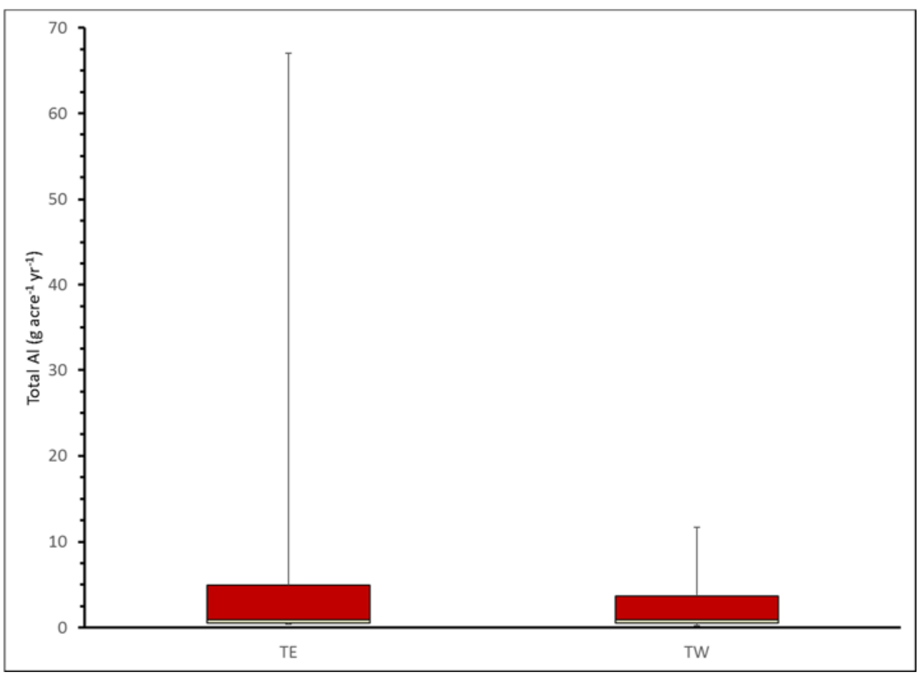


Figure 69. Box and whisker plots of total Al for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

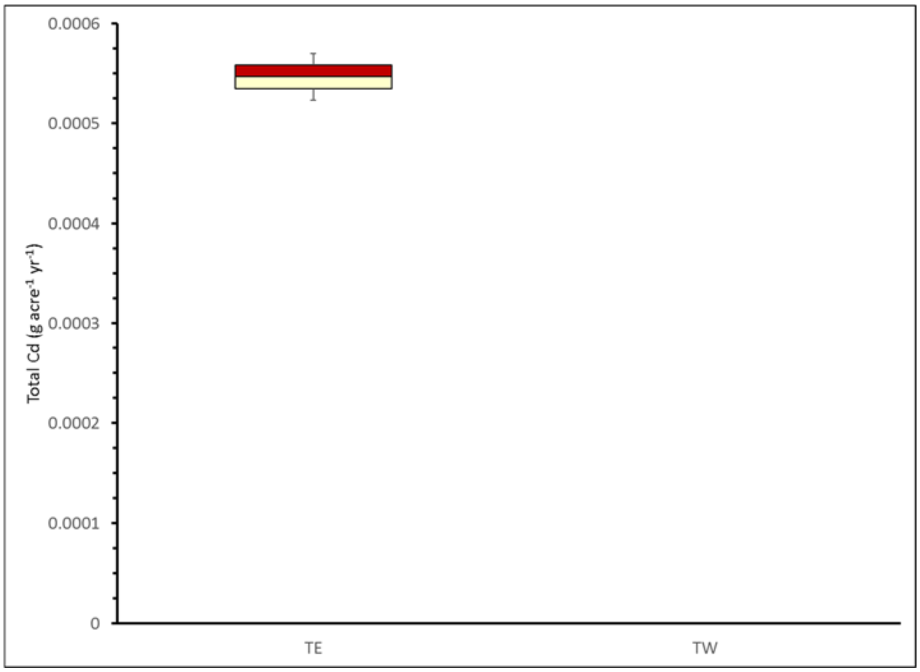


Figure 70. Box and whisker plots of total Cd for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

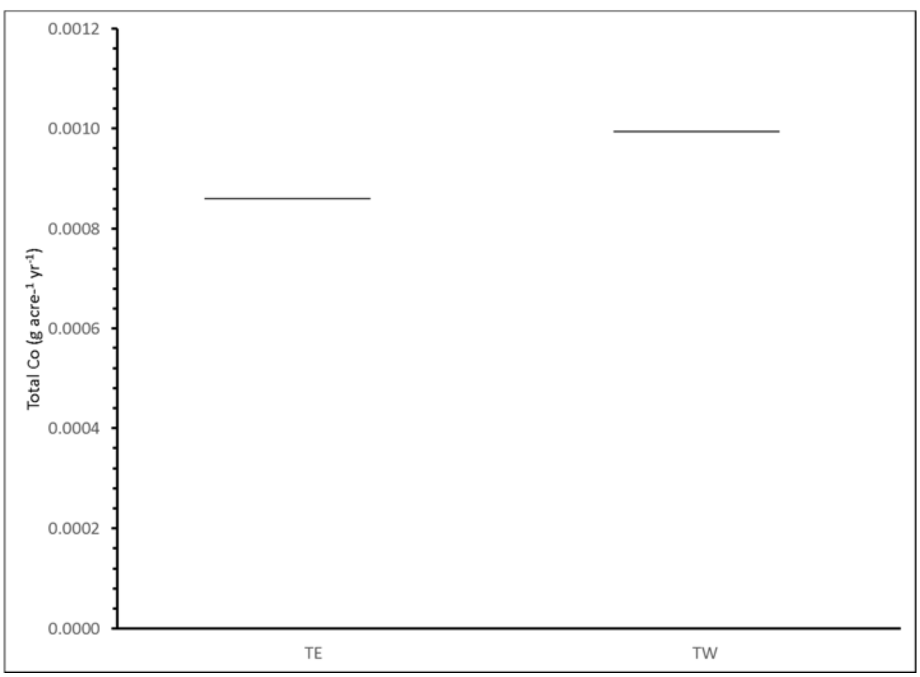


Figure 71. Box and whisker plots of total Co for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

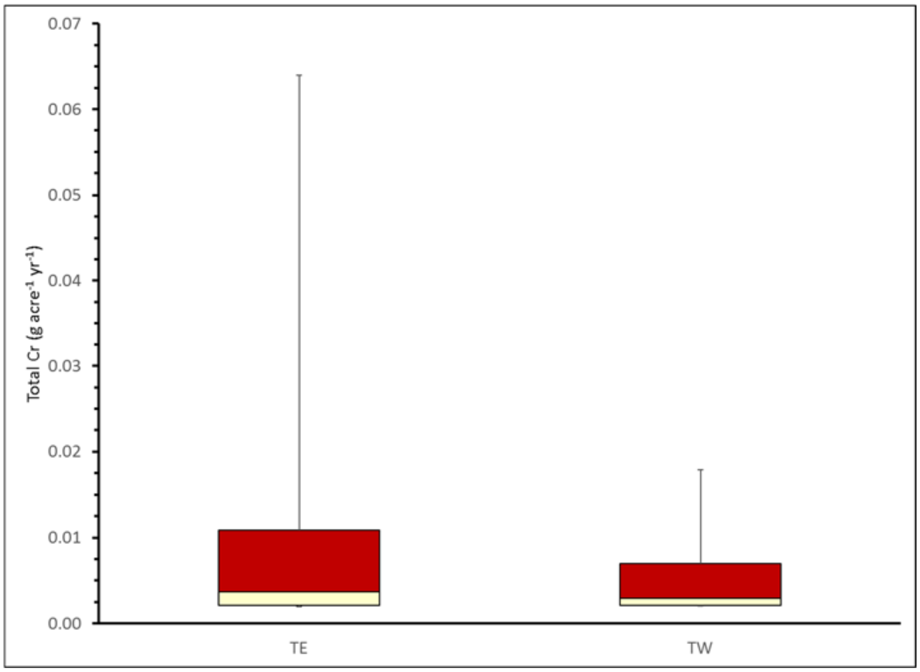


Figure 72. Box and whisker plots of total Cr for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

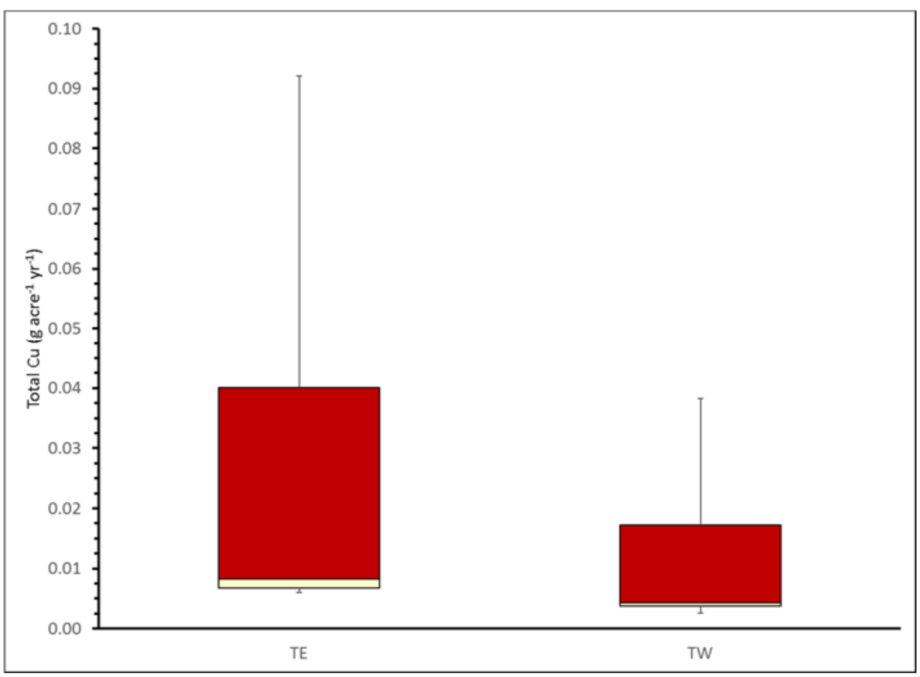


Figure 73. Box and whisker plots of total Cu for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

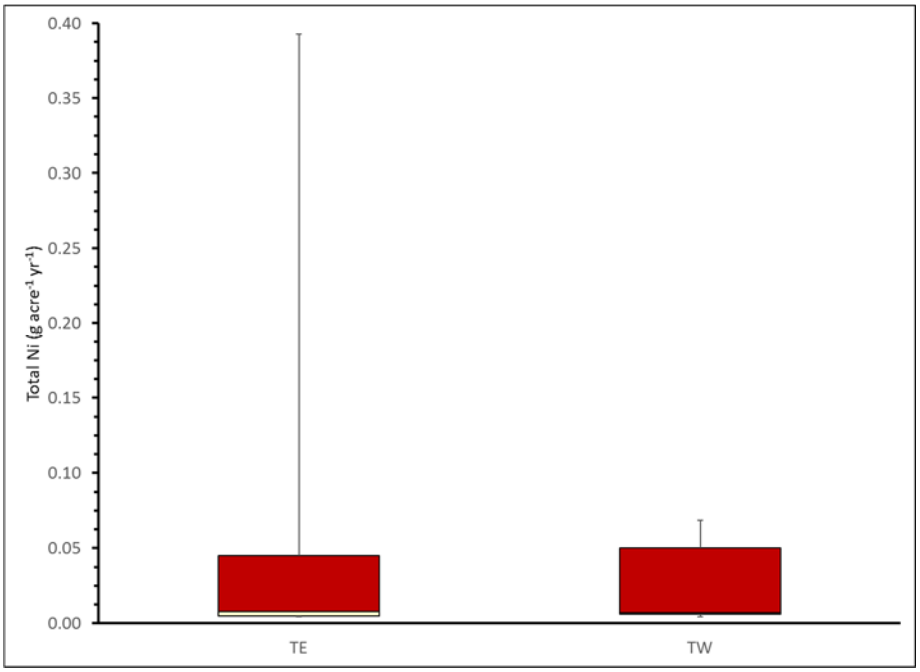


Figure 74. Box and whisker plots of total Ni for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

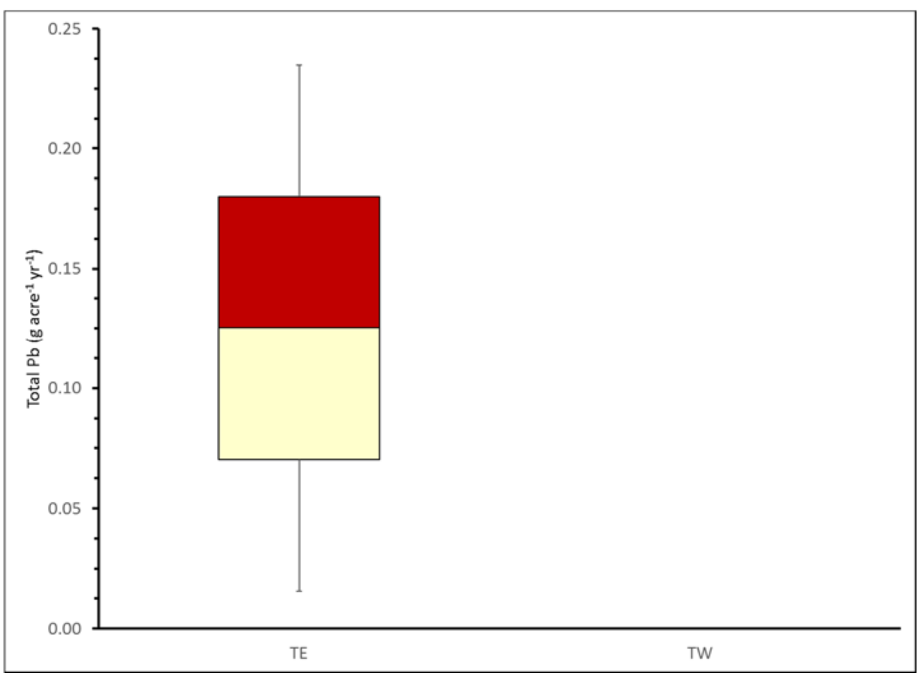


Figure 75. Box and whisker plots of total Pb for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

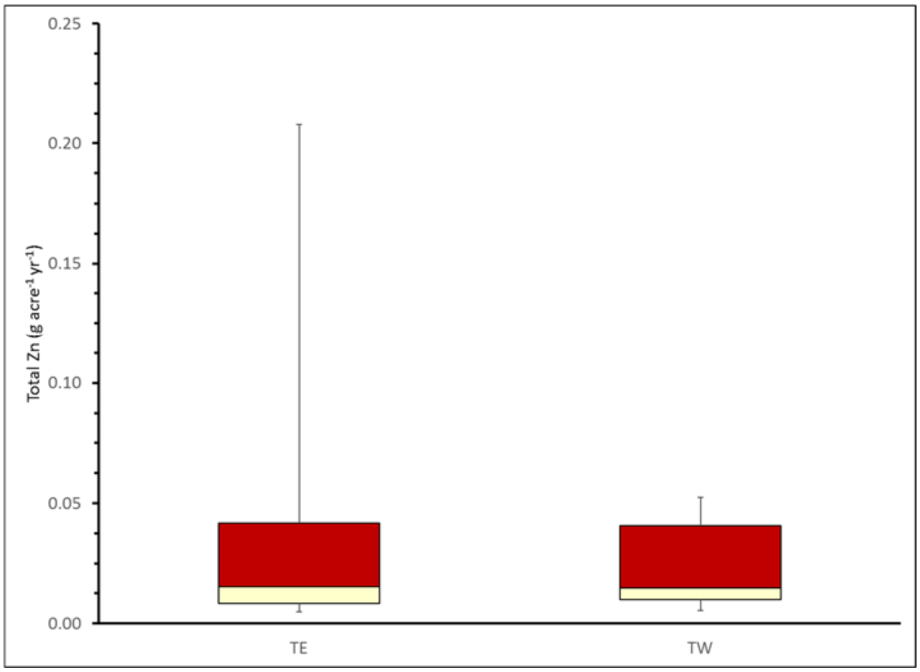


Figure 76. Box and whisker plots of total Zn for the storm composite sampling regime, conducted from May to September 2015 (n = 10).

Table 71. Single factor ANOVA results for NO_3-N mass loads.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	9	31.69113	3.521237	39.54484
TW	9	7.698792	0.855421	2.027992

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	31.97957	1	31.97957	1.538484	0.232726	3.04811
Within Groups	332.5827	16	20.78642			
Total	364.5622	17				

Table 72. Single factor ANOVA results for NH_3-N mass loads.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	8	16.34948	2.043685	4.198383
TW	4	9.526027	2.381507	14.54783

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	0.304329	1	0.304329	0.041671	0.842344	3.285015
Within Groups	73.03216	10	7.303216			
Total	73.33649	11				

Table 73. Single factor ANOVA results for TN mass loads.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	9	114.9496	12.77217	256.9661
TW	10	100.4743	10.04743	273.4514

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	35.16735	1	35.16735	0.132361	0.720482	3.026232
Within Groups	4516.792	17	265.6936			
Total	4551.959	18				

Table 74. Single factor ANOVA results for TSS mass loads.

SUMMARY

Groups	*Count*	*Sum*	*Average*	*Variance*
TE	7	2715.96	387.9943	476237.4
TW	7	818.988	116.9983	38003.97

ANOVA

Source of Variation	*SS*	*df*	*MS*	*F*	*P-value*	*F crit*
Between Groups	257036	1	257036	0.999671	0.337126	3.176549
Within Groups	3085448	12	257120.7			
Total	3342484	13				

Table 75. Single factor ANOVA results for TP mass loads.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	8	4.374677	0.546835	0.598471
TW	10	9.315685	0.931569	2.300831

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.657868	1	0.657868	0.422781	0.52478	3.04811
Within Groups	24.89678	16	1.556049			
Total	25.55465	17				

Table 76. Single factor ANOVA results for DRP mass loads.

SUMMARY

Groups	Count	Sum	Average	Variance
TE	9	1.071941	0.119105	0.027262
TW	10	1.87211	0.187211	0.083551

ANOVA

Source of Variation	SS	df	MS	F	P-value	F crit
Between Groups	0.021972	1	0.021972	0.385053	0.543141	3.026232
Within Groups	0.97005	17	0.057062			
Total	0.992022	18				

4.0 Conclusions

A total of 35 storm events were monitored in this paired watershed study to attempt to evaluate the performance of green infrastructure LID BMPs. Storm event rainfall total amounts ranged over three orders of magnitude and represented wide variations in intensities and durations. The study period included one of the driest and one of the wettest years on record for this location. Maximum event total discharge rates were greater than 716 and 411 cfs for the TE control and TW treatment watersheds. Median discharge rates for the TE control (76.57 ± 29.14 cfs) and TW treatment (72.83 ± 15.66 cfs) were not significantly different. Likewise, mean discharge rates for the TE control (129.90 cfs) and TW treatment (102.31 cfs) were not significantly different. Peak discharge rates were significantly lower in the TW treatment watershed ($p = 0.09$). Runoff depths, runoff ratios and lag times were not significantly different. Two sampling regimes (first flush and storm composite) yielded similar results with regard to TSS concentrations. TE control watershed TSS concentrations (44.40 ± 27.27 mg/L) were greater than TW treatment watershed values (30.35 ± 24.75) but not significantly. TN and NO_3-N concentrations were significantly lower in the TW treatment watershed runoff waters than in the TE control watershed waters ($p = 0.09$ and 0.04, respectively). However, the TW treatment watershed produced waters with significantly higher concentrations of both DRP ($p = 0.03$) and TP ($p = 0.06$) than the TE control watershed. Trace metal concentrations demonstrated generally lower values from the TW treatment watershed than the TE control watershed. Mass loadings responded in similar fashion to concentrations for TSS, nitrogen and phosphorus compounds and trace metals.

Overall, the presence of LID BMPs had a positive influence on storm water hydrology. Peak discharge rates decreased and total discharge rates, while variable, were typically lower in the TW treatment watershed. Solids retention and denitrification influenced effluent water quality in a positive manner. Phosphorus values, however, were generally greater from the TW treatment watershed compared to the TE control watershed, likely due to uncontrolled fertilization or release of phosphorus from the rain garden media. Although the great variability in the data sets makes statistically valid arguments difficult, the hydrologic impacts of the LID BMPs (knocking the peaks off the storm hydrographs) did influence water quality in a positive way, especially with regard to TSS, nitrogen compounds and trace metals concentrations. Initial problems with site construction completion and autosampler malfunctions likely influenced the results. The first flush and storm composite sampling regimes both proved to be useful evaluative tools for different reasons. In conclusion, evaluation of the utility of green infrastructure technologies from both water quantity and water quality perspectives proved challenging. Results may perhaps best be described as mixed. Hydrologic differences, and changes in selected water quality constituents, were positive. Mass loadings were generally positively influenced, thus providing some degree of protection of downstream resources.

5.0 Recommendations

Several recommendations may be provided for future work.

- Closer coordination between the LID BMP designers and monitoring team, prior to initiation of data collection, would be beneficial to the evaluative process. In retrospect, mutual understanding about the design of specific BMPs may have influenced the monitoring program, allowing more targeted and useful information to be generated. The potential role of the rain garden media as a phosphorus source must be resolved.
- Closer coordination between the construction and monitoring teams, again prior to initiation of data collection, would be beneficial to the evaluative process. Questions arose about the timing of specific activities (e.g., sod laying) and their influence on water

quality and quantity data generation. Again, changes in monitoring plans may have allowed more targeted and useful information to be generated.

- Residential landowners participating in a demonstration neighborhood should be required by covenant to maintain their lawns and the LID BMPs in a specific manner. The noticeable traditional lawn care management (fertilizer and herbicide application) in the "experimental basin" compromised the results. Uncontrollable factors such as these will compromise the most well-planned of experimental designs.
- Like any study dependent on the weather to generate results, a stormwater monitoring project such as this one occurs at the whim of natural phenomena. Given these inherent difficulties, reliable equipment and personnel are key to project success. Well-maintained and functional samplers (both automatic and human) are necessary to collect reliable data.
- Given advances in sensor technologies, much water quality data (e.g., NO_3-N, chlorophyll, etc.) are now able to be generated remotely. Deployment of data-recording sensors would eliminate some of the errors in data collection.

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7.0 Appendix A. Summary of Hydrologic Calculations.

TrailEast Total Q	85.6409	CF	**10/31/2013**	
TrailWest Total Q	62.9485	cfs	Reduction in Total Q (CF)	22.6924
TrailEast Peak Q	1.5272	CFS	Reduction in Total Q (%)	26.4971
TrailWest Peak Q	0.8914	CFS	Reduction in Peak Q (CFS)	0.6357
			Reduction in Peak Q (%)	41.6292
Runoff Depth	TrailEast	0.0009	<-ft----in->	0.0103
	TrailWest	0.0006	<-ft----in->	0.0075
Runoff Ratio	TrailEast	0.0334		
	TrailWest	0.0242		
Lag Time	TrailEast	1	min	
	TrailWest	0	min	

TrailEast Total Q	59.8824	CF	**11/25/2013**	
TrailWest Total Q	53.8059	CF	Reduction in Total Q (CF)	6.0765
TrailEast Peak Q	0.2624	CFS	Reduction in Total Q (%)	10.1474
TrailWest Peak Q	0.2474	CFS	Reduction in Peak Q (CFS)	0.0151
			Reduction in Peak Q (%)	5.7416
Runoff Depth	TrailEast	0.0006	<-ft----in->	0.0072
	TrailWest	0.0005	<-ft----in->	0.0064
Runoff Ratio	TrailEast	0.0402		
	TrailWest	0.0357		
Lag Time	TrailEast	23.2500	hr	
	TrailWest	23.5833	hr	

TrailEast Total Q	43.5035	CF	**12/12/2013**	
TrailWest Total Q	55.4090	CF	Reduction in Total Q (CF)	-11.9055
TrailEast Peak Q	0.0788	CFS	Reduction in Total Q (%)	-27.3666
TrailWest Peak Q	0.1184	CFS	Reduction in Peak Q (CFS)	-0.0395
			Reduction in Peak Q (%)	-50.1511
Runoff Depth	TrailEast	0.0004	<-ft----in->	0.0053
	TrailWest	0.0006	<-ft----in->	0.0066
Runoff Ratio	TrailEast	0.1309		
	TrailWest	0.1645		
Lag Time	TrailEast	-19.0000	min	
	TrailWest	10.0000	min	

TrailEast Total Q	No data	CF	**3/15/2014**	
TrailWest Total Q	134.7976	CF	Reduction in Total Q (CF)	
TrailEast Peak Q	No data	CFS	Reduction in Total Q (%)	
TrailWest Peak Q	0.4968	CFS	Reduction in Peak Q (CFS)	
			Reduction in Peak Q (%)	
Runoff Depth	TrailEast	No data	<-ft----in->	No data
	TrailWest	0.0013	<-ft----in->	0.0161
Runoff Ratio	TrailEast	No data		
	TrailWest	0.0125		
Lag Time	TrailEast	No data	min	
	TrailWest	-11	min	

TrailEast Total Q	31.4769	CF	**4/27/2014**	
TrailWest Total Q	32.5531	CF	Reduction in Total Q (CF)	-1.0763
TrailEast Peak Q	0.2053	CFS	Reduction in Total Q (%)	-3.4192
TrailWest Peak Q	0.2009	CFS	Reduction in Peak Q (CFS)	0.0044
			Reduction in Peak Q (%)	2.1352
Runoff Depth	TrailEast	0.0003	<-ft----in->	0.0038
	TrailWest	0.0003	<-ft----in->	0.0039
Runoff Ratio	TrailEast	0.0636		
	TrailWest	0.0649		
Lag Time	TrailEast	2.0000	min	
	TrailWest	3.0000	min	

TrailEast Total Q	59.0566	CF	**5/27/2014**	
TrailWest Total Q	56.9760	CF	Reduction in Total Q (CF)	2.0806
TrailEast Peak Q	0.2474	CFS	Reduction in Total Q (%)	3.5231
TrailWest Peak Q	0.2053	CFS	Reduction in Peak Q (CFS)	0.0420
			Reduction in Peak Q (%)	16.9963
Runoff Depth	TrailEast	0.0006	<-ft----in->	0.0071
	TrailWest	0.0006	<-ft----in->	0.0068
Runoff Ratio	TrailEast	0.0188		
	TrailWest	0.0179		
Lag Time	TrailEast	3.0000	min	
	TrailWest	4.0000	min	

TrailEast Total Q	51.7957	CF	**6/6/2014**	
TrailWest Total Q	54.6313	CF	Reduction in Total Q (CF)	-2.8356
TrailEast Peak Q	0.7789	CFS	Reduction in Total Q (%)	-5.4746
TrailWest Peak Q	0.5299	CFS	Reduction in Peak Q (CFS)	0.2490
			Reduction in Peak Q (%)	31.9691
Runoff Depth	TrailEast	0.0005	<-ft----in->	0.0063
	TrailWest	0.0005	<-ft----in->	0.0065
Runoff Ratio	TrailEast	0.0125		
	TrailWest	0.0130		
Lag Time	TrailEast	2.0000	min	
	TrailWest	2.0000	min	

TrailEast Total Q	119.3255	CF	**6/7/2014**	
TrailWest Total Q	120.7808	CF	Reduction in Total Q (CF)	-1.4553
TrailEast Peak Q	0.7789	CFS	Reduction in Total Q (%)	-1.2196
TrailWest Peak Q	0.4968	CFS	Reduction in Peak Q (CFS)	0.2821
			Reduction in Peak Q (%)	36.2204
Runoff Depth	TrailEast	0.0012	<-ft----in->	0.0144
	TrailWest	0.0012	<-ft----in->	0.0144
Runoff Ratio	TrailEast	0.0121		
	TrailWest	0.0121		
Lag Time	TrailEast	4.0000	min	
	TrailWest	5.0000	min	

TrailEast Total Q	222.6348	CF	**6/12/2014**	
TrailWest Total Q	No data	CF	Reduction in Total Q (CF)	
TrailEast Peak Q	2.3141	CFS	Reduction in Total Q (%)	
TrailWest Peak Q	No data	CFS	Reduction in Peak Q (CFS)	
			Reduction in Peak Q (%)	
Runoff Depth	TrailEast	0.0022	<-ft----in->	0.0269
	TrailWest	No data	<-ft----in->	No data
Runoff Ratio	TrailEast	0.0183		
	TrailWest	No data		
Lag Time	TrailEast	0	min	
	TrailWest	No data	min	

TrailEast Total Q	72.6465	CF	**6/19/2014**	
TrailWest Total Q	70.3556	CF	Reduction in Total Q (CF)	2.2909
TrailEast Peak Q	2.7028	CFS	Reduction in Total Q (%)	3.1535
TrailWest Peak Q	1.5916	CFS	Reduction in Peak Q (CFS)	1.1112
			Reduction in Peak Q (%)	41.1126
Runoff Depth	TrailEast	0.0007	<-ft----in->	0.0088
	TrailWest	0.0007	<-ft----in->	0.0084
Runoff Ratio	TrailEast	0.0266		
	TrailWest	0.0254		
Lag Time	TrailEast	1.0000	min	
	TrailWest	3.0000	min	

TrailEast Total Q	62.7352	CF	**6/23/2014**	
TrailWest Total Q	68.5241	CF	Reduction in Total Q (CF)	-5.7889
TrailEast Peak Q	0.6875	CFS	Reduction in Total Q (%)	-9.2276
TrailWest Peak Q	0.4344	CFS	Reduction in Peak Q (CFS)	0.2531
			Reduction in Peak Q (%)	36.8188
Runoff Depth	TrailEast	0.0006	<-ft----in->	0.0076
	TrailWest	0.0007	<-ft----in->	0.0082
Runoff Ratio	TrailEast	0.0131		
	TrailWest	0.0141		
Lag Time	TrailEast	6.0000	min	
	TrailWest	3.0000	min	

TrailEast Total Q	73.8914	CF	**7/9/2014**	
TrailWest Total Q	55.2436	CF	Reduction in Total Q (CF)	18.6478
TrailEast Peak Q	0.7059	CFS	Reduction in Total Q (%)	25.2368
TrailWest Peak Q	0.4483	CFS	Reduction in Peak Q (CFS)	0.2575
			Reduction in Peak Q (%)	36.4839
Runoff Depth	TrailEast	0.0007	<-ft----in->	0.0089
	TrailWest	0.0005	<-ft----in->	0.0066
Runoff Ratio	TrailEast	0.0131		
	TrailWest	0.0097		
Lag Time	TrailEast	1.0000	min	
	TrailWest	3.0000	min	

TrailEast Total Q	120.8084	CF	**7/30/2014**	
TrailWest Total Q	126.1858	CF	Reduction in Total Q (CF)	-5.3774
TrailEast Peak Q	0.6487	CFS	Reduction in Total Q (%)	-4.4512
TrailWest Peak Q	0.4795	CFS	Reduction in Peak Q (CFS)	0.1692
			Reduction in Peak Q (%)	26.0856
Runoff Depth	TrailEast	0.0012	<-ft----in->	0.0146
	TrailWest	0.0013	<-ft----in->	0.0150
Runoff Ratio	TrailEast	0.0105		
	TrailWest	0.0108		
Lag Time	TrailEast		min	
	TrailWest		min	

TrailEast Total Q	222.2883	CF	**8/9/2014**	
TrailWest Total Q	147.4025	CF	Reduction in Total Q (CF)	74.8859
TrailEast Peak Q	10.3833	CFS	Reduction in Total Q (%)	33.6886
TrailWest Peak Q	6.4759	CFS	Reduction in Peak Q (CFS)	3.9074
			Reduction in Peak Q (%)	37.6315
Runoff Depth	TrailEast	0.0022	<-ft----in->	0.0269
	TrailWest	0.0015	<-ft----in->	0.0176
Runoff Ratio	TrailEast	0.0353		
	TrailWest	0.0231		
Lag Time	TrailEast		min	
	TrailWest		min	

TrailEast Total Q	117.9406	CF	**8/18/2014**	
TrailWest Total Q	88.9058	CF	Reduction in Total Q (CF)	29.0348
TrailEast Peak Q	3.6988	CFS	Reduction in Total Q (%)	24.6181
TrailWest Peak Q	1.7466	CFS	Reduction in Peak Q (CFS)	1.9523
			Reduction in Peak Q (%)	52.7807
Runoff Depth	TrailEast	0.0012	<-ft----in->	0.0143
	TrailWest	0.0009	<-ft----in->	0.0106
Runoff Ratio	TrailEast	0.0279		
	TrailWest	0.0208		
Lag Time	TrailEast		min	
	TrailWest		min	

TrailEast Total Q	63.5352	CF	**9/6/2014**	
TrailWest Total Q	72.3183	CF	Reduction in Total Q (CF)	-8.7830
TrailEast Peak Q	0.6967	CFS	Reduction in Total Q (%)	-13.8239
TrailWest Peak Q	0.5299	CFS	Reduction in Peak Q (CFS)	0.1667
			Reduction in Peak Q (%)	23.9333
Runoff Depth	TrailEast	0.0006	<-ft----in->	0.0077
	TrailWest	0.0007	<-ft----in->	0.0086
Runoff Ratio	TrailEast	0.0116		
	TrailWest	0.0131		
Lag Time	TrailEast	1.0000	min	
	TrailWest	2.0000	min	

TrailEast Total Q	146.0369	CF	**10/10/2014**	
TrailWest Total Q	118.7422	CF	Reduction in Total Q (CF)	27.2946
TrailEast Peak Q	2.7514	CFS	Reduction in Total Q (%)	18.6902
TrailWest Peak Q	1.4787	CFS	Reduction in Peak Q (CFS)	1.2727
			Reduction in Peak Q (%)	46.2576
Runoff Depth	TrailEast	0.0015	<-ft----in->	0.0176
	TrailWest	0.0012	<-ft----in->	0.0142
Runoff Ratio	TrailEast	0.0123		
	TrailWest	0.0099		
Lag Time	TrailEast		min	
	TrailWest		min	

TrailEast Total Q	130.1532	CF	**10/12/2014**	
TrailWest Total Q	118.2211	CF	Reduction in Total Q (CF)	11.9321
TrailEast Peak Q	1.2414	CFS	Reduction in Total Q (%)	9.1677
TrailWest Peak Q	0.7371	CFS	Reduction in Peak Q (CFS)	0.5043
			Reduction in Peak Q (%)	40.6209
Runoff Depth	TrailEast	0.0013	<-ft----in->	0.0157
	TrailWest	0.0012	<-ft----in->	0.0141
Runoff Ratio	TrailEast	0.0156		
	TrailWest	0.0140		
Lag Time	TrailEast	1.0000	min	
	TrailWest	2.0000	min	

TrailEast Total Q	130.5171	CF	**11/4/2014**	
TrailWest Total Q	111.6625	CF	Reduction in Total Q (CF)	18.8546
TrailEast Peak Q	0.5834	CFS	Reduction in Total Q (%)	14.4461
TrailWest Peak Q	0.4117	CFS	Reduction in Peak Q (CFS)	0.1717
			Reduction in Peak Q (%)	29.4307
Runoff Depth	TrailEast	0.0013	<-ft----in->	0.0158
	TrailWest	0.0011	<-ft----in->	0.0133
Runoff Ratio	TrailEast	0.0119		
	TrailWest	0.0101		
Lag Time	TrailEast	20.0000	min	
	TrailWest	2.0000	min	

TrailEast Total Q	95.6677	CF	**3/25/2015**	
TrailWest Total Q	72.8253	CF	Reduction in Total Q (CF)	22.8424
TrailEast Peak Q	4.2729	CFS	Reduction in Total Q (%)	23.8768
TrailWest Peak Q	1.9610	CFS	Reduction in Peak Q (CFS)	2.3119
			Reduction in Peak Q (%)	54.1062
Runoff Depth	TrailEast	0.0010	<-ft----in->	0.0116
	TrailWest	0.0007	<-ft----in->	0.0087
Runoff Ratio	TrailEast	0.0246		
	TrailWest	0.0185		
Lag Time	TrailEast	-1.0000	min	
	TrailWest	1.0000	min	

TrailEast Total Q	181.0536	CF	**4/13/2015**	
TrailWest Total Q	120.9975	CF	Reduction in Total Q (CF)	60.0562
TrailEast Peak Q	2.2518	CFS	Reduction in Total Q (%)	33.1704
TrailWest Peak Q	1.0362	CFS	Reduction in Peak Q (CFS)	1.2155
			Reduction in Peak Q (%)	53.9814
Runoff Depth	TrailEast	0.0018	<-ft----in->	0.0219
	TrailWest	0.0012	<-ft----in->	0.0144
Runoff Ratio	TrailEast	0.0144		
	TrailWest	0.0095		
Lag Time	TrailEast	0.0000	min	
	TrailWest	1.0000	min	

TrailEast Total Q	76.5710	CF	**5/22/2015**	
TrailWest Total Q	42.7670	CF	Reduction in Total Q (CF)	33.8040
TrailEast Peak Q	0.6665	CFS	Reduction in Total Q (%)	44.1473
TrailWest Peak Q	0.2360	CFS	Reduction in Peak Q (CFS)	0.4305
			Reduction in Peak Q (%)	64.5911
Runoff Depth	TrailEast	0.0008	<-ft----in->	0.0093
	TrailWest	0.0004	<-ft----in->	0.0051
Runoff Ratio	TrailEast	0.0140		
	TrailWest	0.0077		
Lag Time	TrailEast		hr	
	TrailWest	1.0667	hr	

TrailEast Total Q	716.2800	CF	**5/24/2015**	
TrailWest Total Q	411.2800	CF	Reduction in Total Q (CF)	305.0000
TrailEast Peak Q	9.9258	CFS	Reduction in Total Q (%)	42.5811
TrailWest Peak Q	4.2096	CFS	Reduction in Peak Q (CFS)	5.7162
			Reduction in Peak Q (%)	57.5893
Runoff Depth	TrailEast	0.0072	<-ft----in->	0.0865
	TrailWest	0.0041	<-ft----in->	0.0490
Runoff Ratio	TrailEast	0.0217		
	TrailWest	0.0123		
Lag Time	TrailEast	8.0000	min	
	TrailWest		min	

TrailEast Total Q	37.6810	CF	**6/29/2015**	
TrailWest Total Q	55.8380	CF	Reduction in Total Q (CF)	-18.1570
TrailEast Peak Q	0.6665	CFS	Reduction in Total Q (%)	-48.1861
TrailWest Peak Q	0.4554	CFS	Reduction in Peak Q (CFS)	0.2111
			Reduction in Peak Q (%)	31.6729
Runoff Depth	TrailEast	0.0004	<-ft----in->	0.0046
	TrailWest	0.0006	<-ft----in->	0.0067
Runoff Ratio	TrailEast	0.0091		
	TrailWest	0.0133		
Lag Time	TrailEast		min	
	TrailWest	5.0000	min	

TrailEast Total Q	622.9700	CF	**7/3/2015**	
TrailWest Total Q	335.4100	CF	Reduction in Total Q (CF)	287.5600
TrailEast Peak Q	9.2627	CFS	Reduction in Total Q (%)	46.1595
TrailWest Peak Q	5.1270	CFS	Reduction in Peak Q (CFS)	4.1357
			Reduction in Peak Q (%)	44.6490
Runoff Depth	TrailEast	0.0063	<-ft----in->	0.0753
	TrailWest	0.0033	<-ft----in->	0.0400
Runoff Ratio	TrailEast	0.0217		
	TrailWest	0.0115		
Lag Time	TrailEast	155.0000	min	
	TrailWest		min	

TrailEast Total Q	91.8210	CF	**7/7/2015**	
TrailWest Total Q	76.9970	CF	Reduction in Total Q (CF)	14.8240
TrailEast Peak Q	1.7466	CFS	Reduction in Total Q (%)	16.1445
TrailWest Peak Q	0.8020	CFS	Reduction in Peak Q (CFS)	0.9446
			Reduction in Peak Q (%)	54.0822
Runoff Depth	TrailEast	0.0009	<-ft----in->	0.0111
	TrailWest	0.0008	<-ft----in->	0.0092
Runoff Ratio	TrailEast	0.0059		
	TrailWest	0.0049		
Lag Time	TrailEast	0.0000	min	
	TrailWest		min	

TrailEast Total Q	152.2500	CF	**7/21/2015**	
TrailWest Total Q	191.8300	CF	Reduction in Total Q (CF)	-39.5800
TrailEast Peak Q	1.2544	CFS	Reduction in Total Q (%)	-25.9967
TrailWest Peak Q	0.7789	CFS	Reduction in Peak Q (CFS)	0.4755
			Reduction in Peak Q (%)	37.9066
Runoff Depth	TrailEast	0.0015	<-ft----in->	0.0184
	TrailWest	0.0019	<-ft----in->	0.0229
Runoff Ratio	TrailEast	0.0242		
	TrailWest	0.0301		
Lag Time	TrailEast		min	
	TrailWest	15.0000	min	

TrailEast Total Q	41.7590	CF	**8/4/2015**	
TrailWest Total Q	45.1440	CF	Reduction in Total Q (CF)	-3.3850
TrailEast Peak Q	0.3623	CFS	Reduction in Total Q (%)	-7.4982
TrailWest Peak Q	0.2250	CFS	Reduction in Peak Q (CFS)	0.1373
			Reduction in Peak Q (%)	37.8968
Runoff Depth	TrailEast	0.0004	<-ft----in->	0.0050
	TrailWest	0.0004	<-ft----in->	0.0054
Runoff Ratio	TrailEast	0.0101		
	TrailWest	0.0108		
Lag Time	TrailEast		min	
	TrailWest	45.0000	min	

TrailEast Total Q	50.4500	CF	**8/19/2015**	
TrailWest Total Q	92.3040	CF	Reduction in Total Q (CF)	-41.8540
TrailEast Peak Q	0.6665	CFS	Reduction in Total Q (%)	45.3436
TrailWest Peak Q	0.5724	CFS	Reduction in Peak Q (CFS)	0.0941
			Reduction in Peak Q (%)	14.1185
Runoff Depth	TrailEast	0.0005	<-ft----in->	0.0061
	TrailWest	0.0009	<-ft----in->	0.0110
Runoff Ratio	TrailEast	0.0117		
	TrailWest	0.0212		
Lag Time	TrailEast		min	
	TrailWest	6.0000	min	

TrailEast Total Q	36.5280	CF	**9/8/2015**	
TrailWest Total Q	27.2730	CF	Reduction in Total Q (CF)	9.2550
TrailEast Peak Q	0.8808	CFS	Reduction in Total Q (%)	25.3367
TrailWest Peak Q	0.7371	CFS	Reduction in Peak Q (CFS)	0.1437
			Reduction in Peak Q (%)	16.3147
Runoff Depth	TrailEast	0.0004	<-ft----in->	0.0044
	TrailWest	0.0003	<-ft----in->	0.0033
Runoff Ratio	TrailEast	0.0130		
	TrailWest	0.0096		
Lag Time	TrailEast		min	
	TrailWest	3.0000	min	

TrailEast Total Q	72.88900	CF	**9/20/2015**	
TrailWest Total Q	79.77100	CF	Reduction in Total Q (CF)	-6.88200
TrailEast Peak Q	0.72770	CFS	Reduction in Total Q (%)	8.62720
TrailWest Peak Q	0.61130	CFS	Reduction in Peak Q (CFS)	0.11640
			Reduction in Peak Q (%)	15.99560
Runoff Depth	TrailEast	0.00073	ft	0.00881
	TrailWest	0.00079	ft	0.00951
Runoff Ratio	TrailEast	0.00667		
	TrailWest	0.00721		
Lag Time	TrailEast		min	
	TrailWest	31	min	

8.0 Appendix B. Professional Presentations and Publications Resulting from Task 5.3.4d

Oral and Poster Presentations

1. Holzbauer-Schweitzer, B. and R.W. Nairn. 2016. Evaluating Low Impact Development Best Management Practices for Urban Storm Water Management: A Paired Watershed Approach. 18th Annual EPA Region 6 Stormwater Conference, October 2-6, 2016, Oklahoma City, OK (scheduled for oral presentation)

2. Nairn, R.W., B. Holzbauer-Schweitzer, N. Berg-Mattson and M.J. Rice. 2016. A Paired Watershed Approach to Evaluate Low Impact Development Best Management Practices on Urban Stormwater Quality and Quantity. Oklahoma Clean Lakes and Watersheds Association 25th Annual Conference, March 29-30, 2016, Stillwater, OK (oral presentation)

3. Holzbauer-Schweitzer, B., N. Berg-Mattson and R.W. Nairn. 2016. Evaluating Low Impact Development Best Management Practices for Urban Storm Water Management: A Paired Watershed Approach. Oklahoma Clean Lakes and Watersheds Association 25th Annual Conference, March 29-30, 2016, Stillwater, OK (poster, *student competition winner)

4. Holzbauer-Schweitzer, B., N. Berg-Mattson and R.W. Nairn. 2016. Evaluating Low Impact Development Best Management Practices for Urban Storm Water Management: A Paired Watershed Approach. Great Plains Low Impact Development Research and Innovation Symposium, March 7-9, 2016, Omaha, NE (poster)

5. Holzbauer-Schweitzer, B. 2015. Urban Stormwater Runoff Quality and Quantity Abatement: A Paired Watershed Approach. University of Oklahoma Gallogly College of Engineering Graduate

Student Community Poster Fair, November 13, 2015, Norman, OK (poster, *student competition winner)

6. Holzbauer-Schweitzer, B., N. Berg-Mattson and R.W. Nairn. 2015. Urban Stormwater Runoff Quality and Quantity Abatement: A Paired Watershed Approach. 17th Annual EPA Region 6 Stormwater Conference, October 18-22, 2015, Hot Springs, AR (poster)

7. Holzbauer-Schweitzer, B., N. Berg-Mattson and R.W. Nairn. 2015. Urban Stormwater Runoff Quality and Quantity Abatement: A Paired Watershed Approach. Oklahoma Clean Lakes and Watersheds Association 24th Annual Conference, April 8-9, 2015, Stillwater, OK (poster, *student competition winner)

Graduate Student Theses*

1. Rice, M.J. 2015. An Evaluation of Retrofitting Best Management Practices for Stormwater Quality Improvement. Masters of Science in Environmental Engineering Non-thesis Special Topics Paper. 35 pp.

2. Holzbauer-Schweitzer, B. 2016. Evaluating Low Impact Development Best Management Practices for Urban Storm Water Management: A Paired Watershed Approach. Masters of Environmental Science Thesis, Defense proposed for summer 2016.

3. Berg-Mattson, N. 2016. Urban Runoff Quality and Quantity Abatement Using Various Development Strategies. Masters of Environmental Science Thesis, Defense proposed for fall 2016.

*Several manuscripts for publication in refereed journals are in preparation for submission.