# Carters Creek Total Maximum Daily Load Implement-ation Project

## Routine, Reconnaissance and Stormwater Monitoring Report: Tasks 4 and 5

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**Texas Water Resources Institute**
**Technical Report TR-485**
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Texas Water Resources Institute
*make every drop count*

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## List of Acronyms

| | |
|---|---|
| AU | Assessment Unit |
| BRA | Brazos River Authority |
| CCWWTF | Carters Creek Waste Water Treatment Facility |
| cfs | Cubic Foot per Second |
| CFU | Colony Forming Unit |
| COB | City of Bryan |
| COCS | City of College Station |
| FDC | Flow Duration Curve |
| LDC | Load Duration Curve |
| QAPP | Quality Assurance Protection Plan |
| SAML | Soil and Aquatic Microbiology Lab |
| SCSC | Soil and Crop Sciences |
| SWQM | Surface Water Quality Monitoring |
| SWQMIS | Surface Water Quality Monitoring Information System |
| TAMU | Texas A&M University |
| TCEQ | Texas Commission on Environmental Quality |
| TMDL | Total Maximum Daily Load |
| TST | Texas Stream Team |
| TWRI | Texas Water Resources Institute |
| USEPA | United States Environmental Protection Agency |
| WWTF | Waste Water Treatment Facility |

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# Introduction

## Background

The Carters Creek watershed is a tributary of the Navasota River and covers an area of about 56.9 square miles in Brazos County. Approximately 57% of this area is urbanized (Figure 1), primarily by the cities of Bryan and College Station. Within the Carters Creek watershed, Carters Creek, Burton Creek and Country Club Branch are all considered impaired due to elevated levels of *Escherichia coli (E. coli)*. The Texas Commission on Environmental Quality (TCEQ) denotes these waterbodies as segments 1209C, 1209L and 1209D respectively. These waterbodies were listed on the TCEQ's 303(d) list for bacterial impairments starting in 1999 for Carters Creek and 2006 for Burton Creek and Country Club Branch (TCEQ 2012). Each of these waterbodies was listed impaired for not meeting the *E. coli* standard for Primary Contact Recreation which is a geometric mean of 126 colony forming units (CFU)/100 mL of water. Initial listing of these waterbodies was supported by monitoring conducted by TCEQ and the Brazos River Authority (BRA). In 2014, a Total Maximum Daily Load (TMDL) was completed for each creek and as a result, they are proposed for delisting in the 2014 Texas Integrated Report (TCEQ 2014).

In association with the TMDL, a stakeholder group was formed to provide input on the development of a TMDL Implementation Plan (I-Plan). Through a facilitated process, stakeholders provided input regarding ways to address bacteria loading in the watershed and meet the TMDL established in the watershed. A variety of management measures and control actions were included in the I-Plan that described means to address bacteria loading from agricultural lands and urban areas alike. A common theme of discussion throughout this process was the need for more water quality data from the watershed. At the time, data from only four water quality monitoring stations across the watershed was available. Through these discussions, the need to develop a better understanding of *E. coli* contributions from across the watershed surfaced and initiated this monitoring effort.

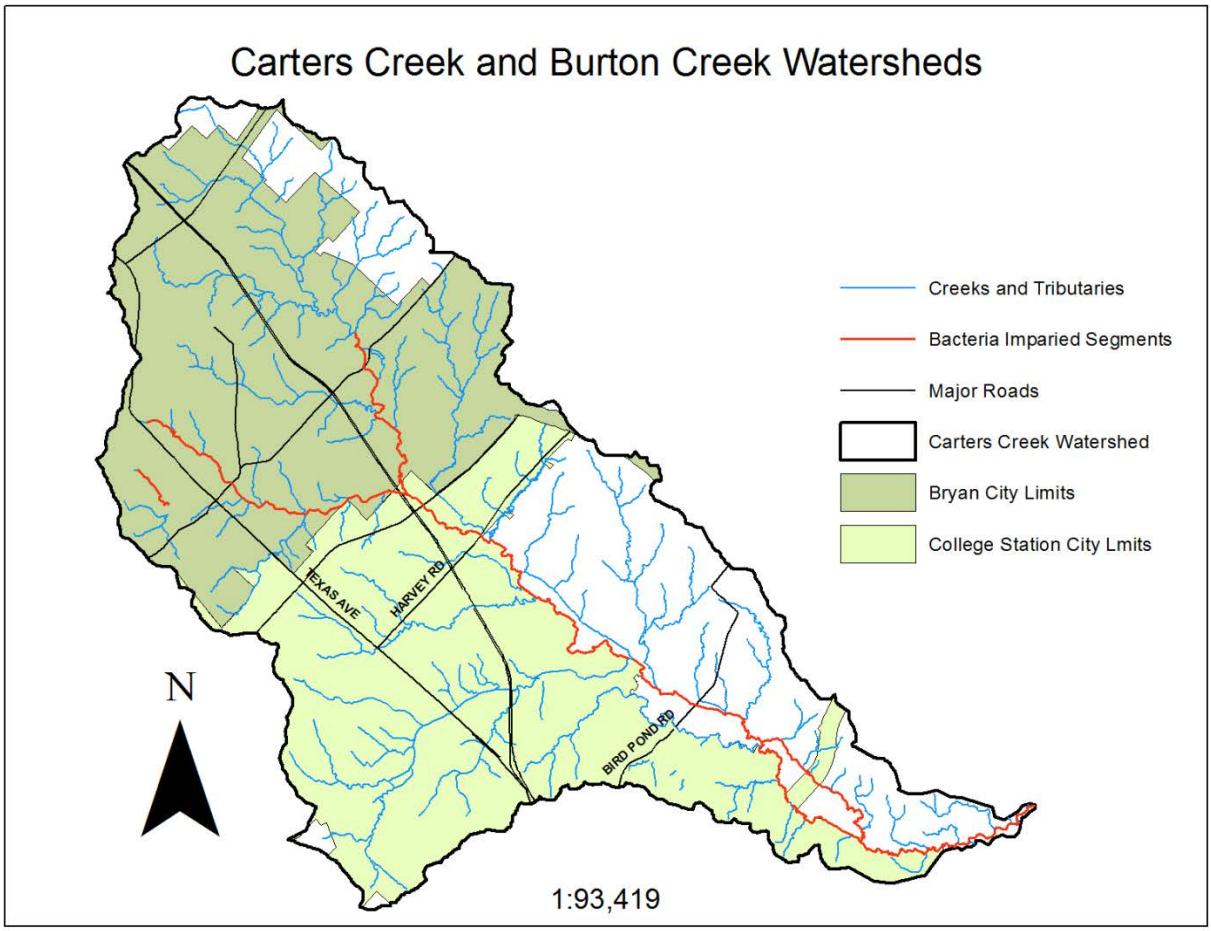


**Figure 1. Carters Creek Watershed**

## Project Scope

Three different types of monitoring were employed to accomplish the stakeholder's goal of developing a more in-depth understanding of water quality across the watershed over time. Routine and Stormflow Water Quality Monitoring (Task 4) were paired with Reconnaissance Sampling (Task 5) and focused on improving the availability and distribution of water quality data for the Carters Creek Watershed. This improved data set would provide stakeholders with a better understanding of the bacterial impairments in the watershed and aid them in implementing management decisions described in the TMDL I-Plan. Both Task 4 and 5 have several similar subtasks, including Station Establishment for future monitoring, Water Quality Monitoring, Data Management, and Water Quality Data Assessment. Major differences of these two tasks were the approaches to monitoring. Further discussion of these subtasks will be discussed in subsequent sections.

## Monitoring Approach

### Routine Water Quality Monitoring

The first type of monitoring planned was routine monitoring. This type of monitoring occurs in routine fashion and is scheduled well in advance of each sampling event. As a result, this approach does not target any specific flow condition. Monitoring is conducted regardless of conditions, unless personnel safety is an issue. Data collected under this sampling regime adhere to strict quality guidelines and are integrated into the TCEQ Surface Water Quality Monitoring Information System (SWQMIS). These data are later used by the state to assess the general status of water quality and determine if the waterbodies meet or exceeds the Primary Contact Recreation Standard for bacteria.

After discussion with TWRI, Texas A&M University (TAMU) Department of Soil and Crop Sciences (SCSC), City of Bryan (COB), and City of College Station (COCS), and conducting reconnaissance trips to each monitoring location, 4 monitoring stations were selected to collect routine water quality monitoring data (Table 1 and Figure 2). These stations included three on Carters Creek (TCEQ Station 11785, Station 11782, and Station 21259), and one on Burton Creek (Station 11783). Sampling occurred monthly, starting in February 2013 and continuing through February 2015 by TWRI staff trained in TCEQ Surface Water Quality Monitoring (SWQM) procedures (TCEQ 2012b).

**Table 1. Routine Water Quality Monitoring Locations**

| TCEQ Station # | Sampling Site Name | Sampling Frequency | GPS Coordinates | |
|---|---|---|---|---|
| | | | Latitude | Longitude |
| 11785 | Carters Creek @ Bird Pond Road | Monthly | 30.602718 | -96.249428 |
| 11782 | Carters Creek @ SH 6 (upstream of Burton Creek confluence) | Monthly | 30.644069 | -96.311698 |
| 21259 | Carter Creek @ William D. Fitch | Monthly | 30.588628 | -96.224594 |
| 11783 | Burton Creek @ SH6 (downstream of WWTF) | Monthly | 30.644267 | -96.313952 |

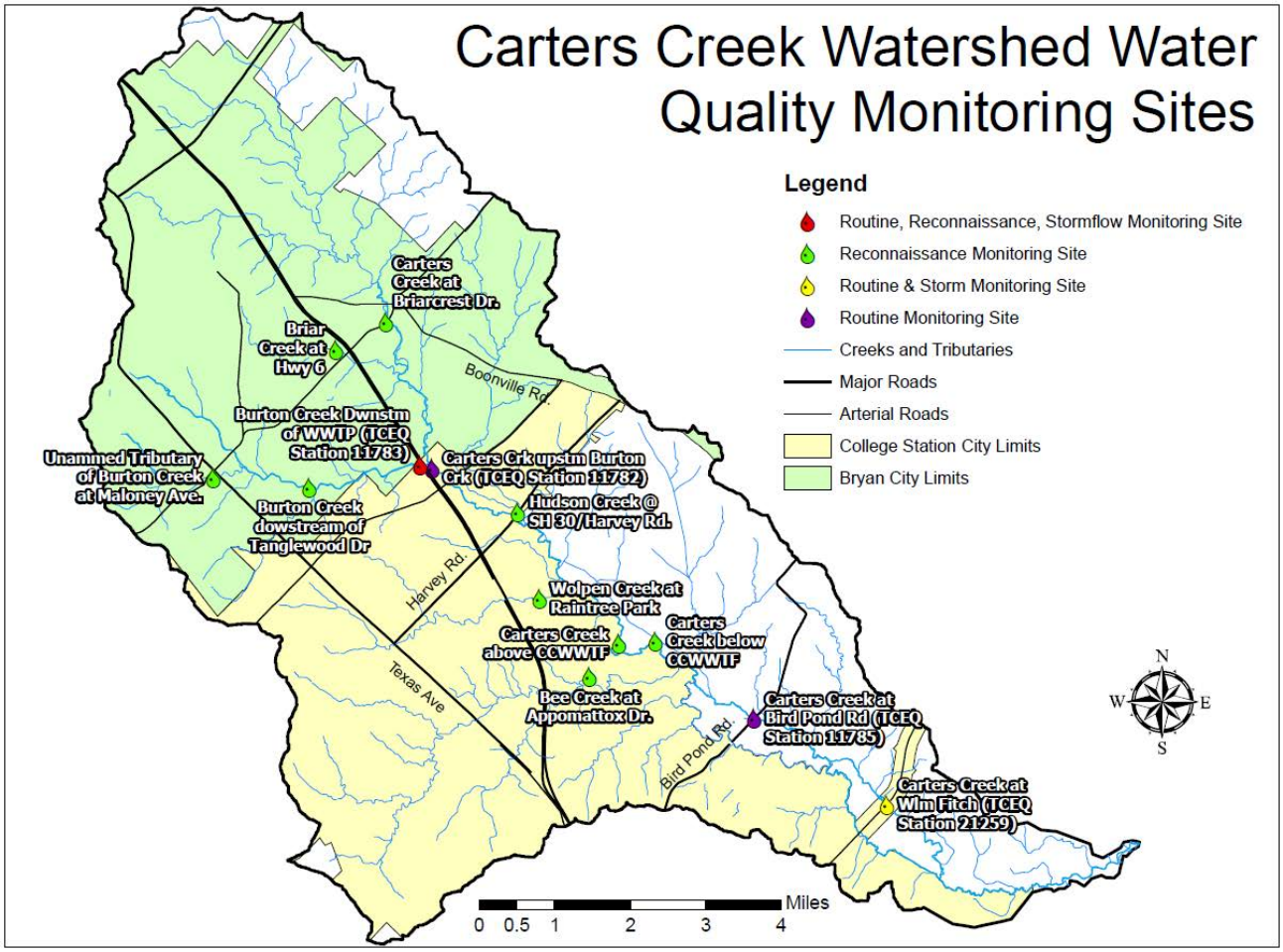


**Figure 2. Monitoring locations within the Carters Creek Watershed**

During monthly routine monitoring trips, flow measurements were taken using a SonTek FlowTracker. A YSI 556 MPS or EXO1 multiprobe was used to collect dissolved oxygen (DO), pH, specific conductance, and water temperature. Observations about the water body were made in the field, and included days since last precipitation event, flow severity, present weather, water surface conditions, and other remarks related to the conditions of the stream and stream banks.

Water samples were collected in a pre-labeled container and transported to the Soil and Aquatic Microbiology Lab (SAML) on ice, in accordance with the project's Quality Assurance Protection Plan (QAPP). Samples were analyzed for *E. coli* using the USEPA 1603 method (TCEQ Parameter Code 31648) which produces results in CFU/100 mL.

## Reconnaissance Sampling

The reconnaissance sampling approach was designed to collect samples at a variety of locations across the watershed through the use of Texas Stream Team (TST) volunteers. Sampling was focused in areas where no previous monitoring had been conducted and thus no prior knowledge of the water quality at these sites existed. Sampling sites were

selected based on discussions with TWRI, TAMU SCSC, COB, and COCS, and reconnaissance trips to each monitoring location. In total, 10 monitoring stations were created (Table 2 and Figure 2). Four of these stations were located in Bryan (TST Stations 80909, 80910, 80912, and 80915), and six were located in College Station (Stations 80908, 80911, 80913, 80914, 80916, and 80917). Sampling at each of these sites occurred on the same days and the same general time as the routine water quality monitoring trips occurred. TST Station 80908 was situation at the same location as TCEQ Station 11783 in order to provide a comparison of the data collected through routine and reconnaissance sampling teams.

**Table 2. Reconnaissance Sampling Stations**

| TST Station # | Sampling Site Name | Sampling Frequency | GPS Coordinates | |
|---|---|---|---|---|
| | | | Latitude | Longitude |
| 80908 | Burton Creek @ SH6 (downstream of WWTF) | Monthly | 30.644428 | -96.313953 |
| 80909 | Carters Creek @ Briarcrest | Monthly | 30.671092 | -96.320336 |
| 80911 | Bee Creek @ Appomattox Dr. | Monthly | 30.609689 | -96.281514 |
| 80912 | Burton Creek downstream of Tanglewood | Monthly | 30.640814 | -96.335192 |
| 80910 | Unnamed tributary of Burton Creek @ Maloney Ave. | Monthly | 30.642361 | -96.353539 |
| 80915 | Briar Creek @ Hwy 6 | Monthly | 30.663617 | -96.329931 |
| 80913 | Carters Creek below CCWWTF outfall | Monthly | 30.615506 | -96.268889 |
| 80916 | Carters Creek above CCWWTF outfall | Monthly | 30.615175 | -96.275872 |
| 80917 | Hudson Creek @ FM 60 | Monthly | 30.636861 | -96.295269 |
| 80914 | Wolfpen Creek @ Hwy 6 | Monthly | 30.622572 | -96.2911 |

Prior to the start of monitoring in February of 2013, volunteers were trained in proper field monitoring procedures by TST staff. Other trainings occurred throughout the monitoring process in order to allow for new volunteers to be trained in proper sampling and data collection techniques. Volunteers used procedures set out in the *Texas Stream Team Water Quality Monitoring Manual* (TST 2012). Volunteers used a Standard TST kit to measure DO, pH, conductance, and water temperature. Field observations were also collected and included days since last precipitation event, flow severity, present weather, water surface conditions, and other observations related to the conditions of the stream and stream banks.

All water samples were collected in a pre-labeled container, and those collected in Bryan were transported to city's Thompson Creek Wastewater Treatment Facility (WWTF) lab while those collected in College Station were transported to the city's Carters Creek WWTF lab. Immediately after sampling, all samples were placed in a cooler on ice and transported to the respective lab in accordance with the project's QAPP. Samples were analyzed for *E. coli* using the IDEXX Colilert-18 method which produces results in a most probable number (MPN) of *E. coli* per 100 mL. While this method is different than the one used for routine sample analysis, results from these tests have been statistically evaluated and found to produce significantly similar results.

### Storm Sampling

Rainfall runoff was sampled at two locations during the course of the project. Automated sampling devices (ISCO Model 6712 Portable Samplers, Teledyne-ISCO, Lincoln, NE) were deployed on Burton Creek and Carters Creek at Stations 11783 and 21259 respectively. Samplers were set to collect flow-weighted composite samples during rainfall runoff events. Initially, samplers were deployed and allowed to record water level for several months to determine appropriate sampling thresholds. The sampler at Station 11783 was set to begin sampling at 20.3 cfs while the sampler at Station 21259 was set to begin sampling at 45 cfs. Samples were processed for *E. coli* concentrations by SAML using the USEPA 1603 method described previously. Only *E. coli* concentrations and water depth were recorded for these samples.

## Monitoring Findings and Assessment

### Routine Monitoring

Routine water quality in Carters and Burton Creeks were monitored from February 2013 until February of 2015. Graphical representations of the water quality parameters are presented in Figures 3 through 9 and summaries of the major findings are presented in Table 3 through Table 7. For a complete listing of all water quality available, please refer to http://www80.tceq.texas.gov/SwqmisPublic/public/default.htm. Statistical analysis for this data used a Linear Regression Analysis to calculate correlation between the water quality parameter and streamflow, Spearman's Rho was used to calculate correlation between the water quality parameter and *E. coli*, and a Wilcoxon/Kruskal-Wallis Sum-Rank Test was used to determine if data collected under this project differed from previously collected data or between sites.

#### Instantaneous Stream Flow

Instantaneous stream flow measurements were taken during each monitoring trip to determine the volume of stream flow at the time the sample was taken. When combined with *E. coli* concentrations, the load of *E. coli* transported by the creek at a specific location and point in time can be determined. Flow varied by site (Table 3, Figure 3)

with Station 11782 having the lowest flow average at 0.98 cubic foot per second (cfs) and Station 11785 having the highest average stream flow at 19.83 cfs. Station 11782 is located on Carters Creek above its confluence with Burton Creek. At this point, the only contributions of water to the creek are groundwater base flows, irrigation runoff and rainfall runoff. No known wastewater contributions occur at this site. As a result, the recorded flows were often extremely low. In more than one instance, flow was low enough that wind blowing upstream was moving water sufficiently for the recorded flow volume to be negative. Evidence of very high flow was present at this site as large trees were washed downstream during the course of the monitoring project. The other three sampling stations all had higher average flow values due in part to the presence of wastewater inputs. These inputs provide a relatively consistent source of water to the streams which provides for a consistent maintenance of flow. High flows were also observed at these locations and produced significant erosion in some locations.

**Table 3. Measured stream flow at each routine monitoring station over the two year study, mean, median, minimum and maximum flow rate (cfs)**

| Site # | Flow Rate (cfs) | | | |
|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum |
| 11785 | 19.83 | 15.00 | 10.00 | 136.00 |
| 11782 | 0.793 | 0.200 | -0.136 | 10 |
| 21259 | 18.99 | 18.50 | 12.00 | 33.00 |
| 11783 | 6.53 | 6.15 | 0.28 | 15.00 |

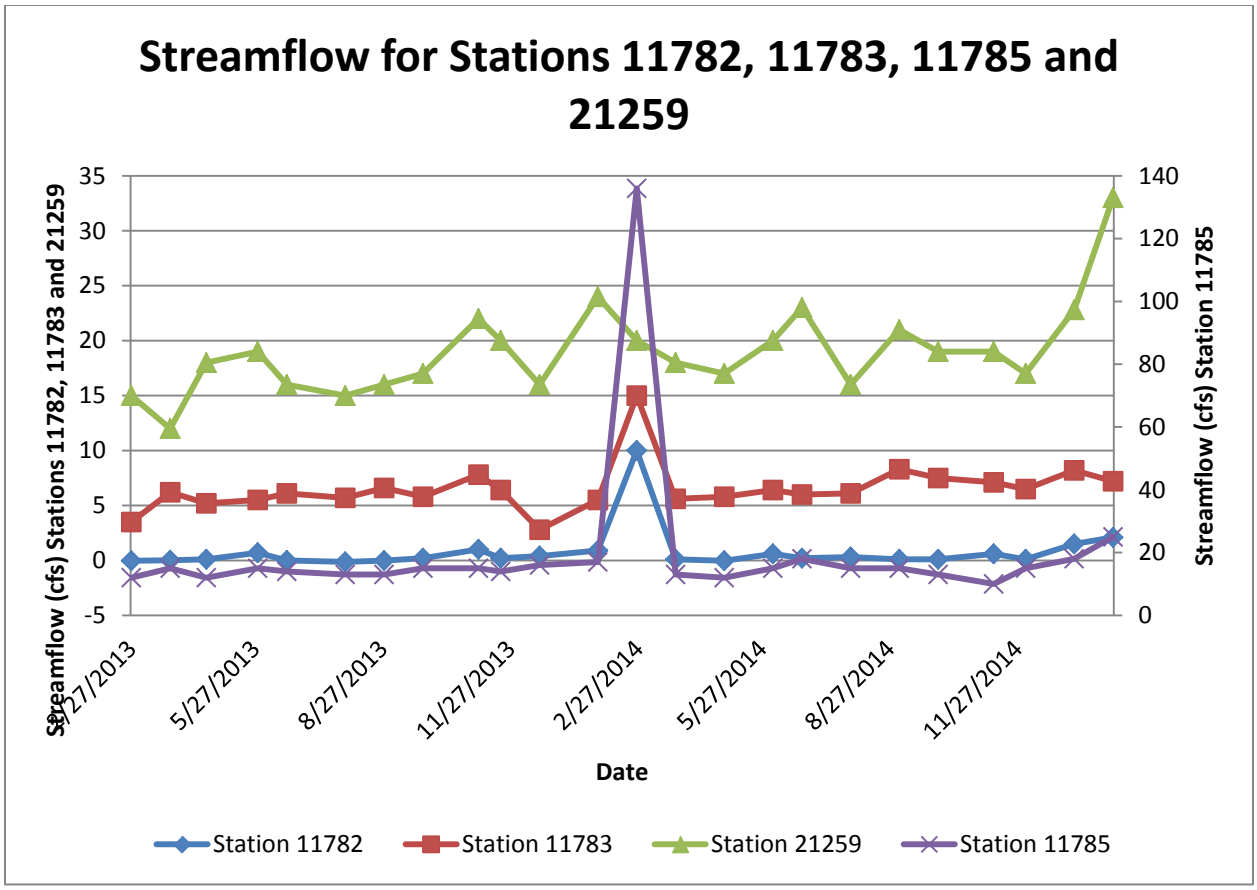


**Figure 3. Streamflow for TCEQ Stations 11782, 11783, 11785, and 21259**

### Dissolved Oxygen

DO concentrations were similar between all four sites (Figure 4, Table 4). The data presents a seasonality of DO concentrations, with DO concentrations increasing during the winter months when water temperatures are the coldest. This observation is expected as the solubility of oxygen in water increases as temperature decreases; thus colder water is able to hold more dissolved oxygen than warm water. DO concentrations at each of the routine monitoring stations were significantly correlated to water temperature as is expected (Table 4). All measurements recorded were above the TCEQ minimum DO concentration standard of 3 mg/L, while the average DO concentration for all stations were well above the TCEQ standard of 4 mg/L (TAC 2013, TCEQ 2012). There were no statistically significant correlations between streamflow and DO concentrations or *E. coli* and DO concentrations (Table 4).

The minimum (4.96 mg/L), median (8.1 mg/L), and mean (8.29 mg/L) DO concentrations were higher for data collected by BRA and TCEQ (values in parenthesis) when compared to data collected by TWRI at Station 11783. Data collected by the BRA and TCEQ at Station 11782 had lower minimum (1.7), median (6), mean (5.9), and maximum (8.8) concentrations when compared to data collected by TWRI. Data

collected by the BRA and TCEQ at Station 11785 had higher median (8.9), mean (8.9), and maximum (14.49) DO concentrations when compared to data collected by TWRI. Data collected by TWRI had a statistically significant difference in the mean of DO concentration when compared to DO collected by BRA and TCEQ at Station 11783 ($p<0.01$) and Station 11785 ($p=0.02$). These differences in the means of DO concentrations was not seen at Station 11782 ($p=0.28$). No previous DO data had been collected at Station 21259.

**Table 4. Summary statistics of measured DO concentration at each routine monitoring station over the two year study**

| Site # | Summary Statistics | | | | Correlation to Streamflow | | Correlation to *E. coli* | | Correlation to Water Temp. | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | r | p-value | r | p-value | r | p-value |
| 11785 | 7.9 | 7.7 | 4.8 | 12.0 | 0.03 | 0.89 | -0.20 | 0.35 | **-0.86** | ***<0.01*** |
| 11782 | 7.3 | 7.3 | 3.9 | 11.8 | 0.21 | 0.32 | 0.18 | 0.39 | **-0.89** | ***<0.01*** |
| 21259 | 7.7 | 7.6 | 4.4 | 11.3 | 0.17 | 0.42 | 0.04 | 0.87 | **-0.89** | ***<0.01*** |
| 11783 | 6.8 | 6.2 | 3.9 | 13.3 | 0.26 | 0.22 | -0.39 | 0.06 | **-0.75** | ***<0.01*** |

*Bold values are statistically significance values ($\alpha<0.05$).

**Carters Creek at Bird Pond Road**

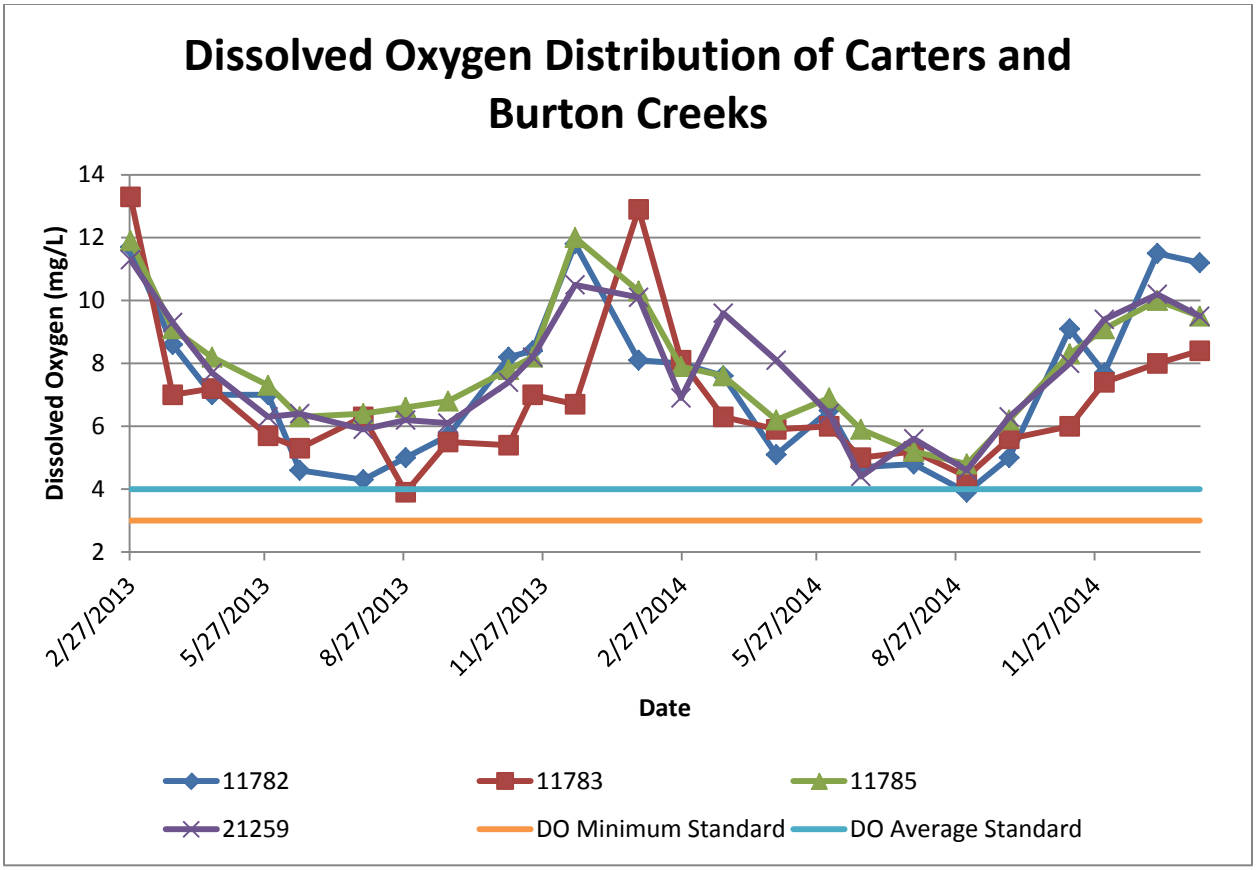


**Figure 4. Carters and Burton Creek DO distribution**

## pH

pH values were similar between all stations (Figure 5, Table 5). Three values were located outside of the TCEQ acceptable range of 6.5 to 9.0, with Station 11782 having two values (6.3 and 9.5) and Station 21259 has one value (9.4) outside of this range (TAC 2013, TCEQ 2012). There were no statistically significant correlations between streamflow and pH (Table 6). *E. coli* concentrations at Station 21259 were significantly correlated to pH ($r=-0.68$; $p<0.01$); the other three stations were not significantly correlated to *E. coli* (Table 5).

At Station 11782, BRA and TCEQ had lower median (7.6), mean (7.63), and maximum (7.9) pH values when compared to data collected by TWRI. BRA and TCEQ found a lower minimum pH value (6.34) when compared to TWRI at Station 11785. Data collected by TWRI had a statistically significant difference in the mean of pH when compared to pH values by BRA and TCEQ at Station 11783 ($p<0.01$). However, data collected by TWRI and TCEQ/BRA did not have statistically significant differences in their means at Station 11782 ($p=0.21$) and Station 11785 ($p=0.71$). No previous pH data had been collected at Station 21259.

**Table 5. Summary statistics of measured pH values at each routine monitoring station over the two year study**

| Site # | Summary Statistics | | | | Correlation to Streamflow | | Correlation to *E. coli* | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | r | p-value | r | p-value |
| 11785 | 8.1 | 8.1 | 7.2 | 8.9 | 0.09 | 0.66 | 0.01 | 0.95 |
| 11782 | 7.3 | 7.3 | 6.3 | 9.5 | 0.09 | 0.67 | -0.13 | 0.54 |
| 21259 | 8.3 | 8.4 | 6.7 | 9.4 | 0.07 | 0.73 | **-0.68** | **<0.01** |
| 11783 | 7.6 | 7.6 | 7.0 | 8.1 | 0.30 | 0.16 | 0.25 | 0.23 |

*Bold values are statistically significance values (α<0.05).

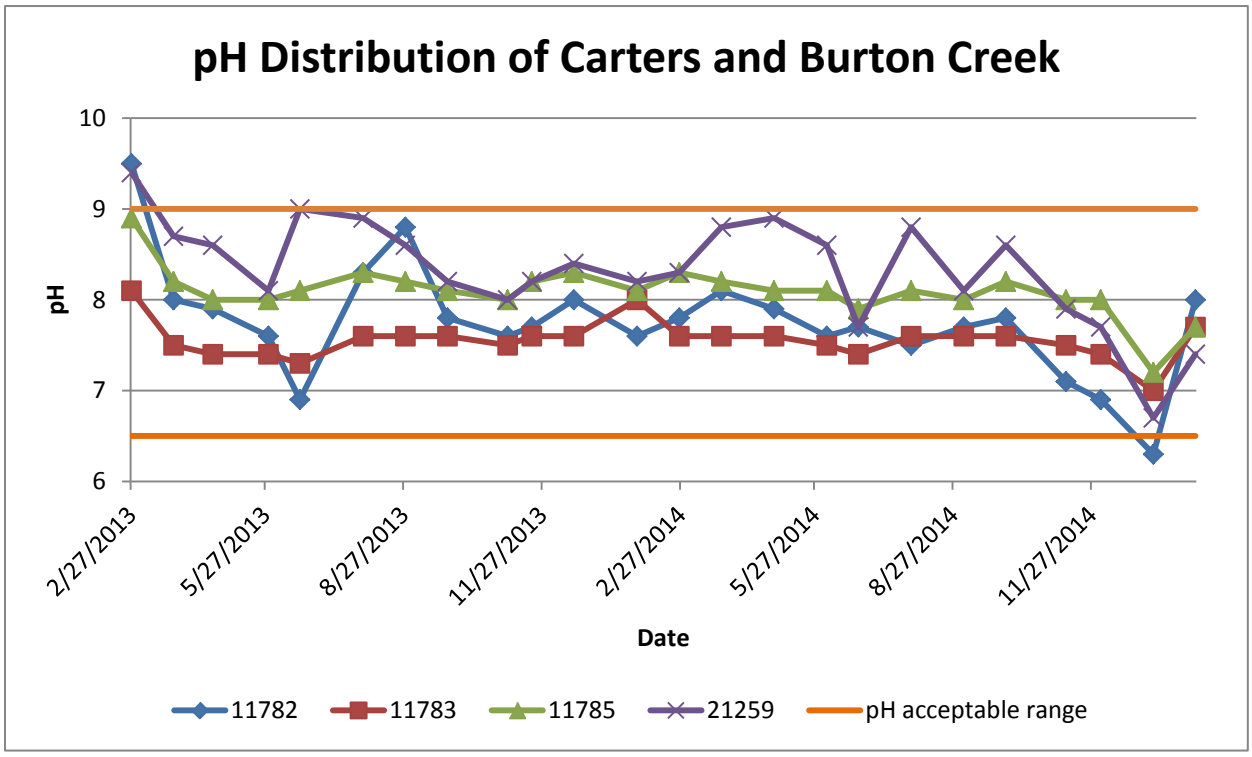


**Figure 5. Carters and Burton Creek pH distribution**

## Specific Conductance

Only Stations 11785 and 21259 had similar specific conductance concentrations and patterns (Figure 6, Table 6). Station 11783 had the highest specific conductance concentration (with the exception of the January 29, 2014 monitoring event) and Station 11782 had the lowest specific conductance distribution (with the exception of two monitoring events: 8/28/2013 and 1/29/2014). Only 23 measurements were taken due to improper calibration of the YSI 556 MPS during the February 2015 monitoring event. There were no statistically significant correlations between streamflow and

specific conductance (Table 6). *E. coli* concentrations at all stations showed no significant correlations (Table 6). Many specific conductance measurements that were low can be explained by having high flow events.

Data collected by BRA and TCEQ at Station 11783 had lower minimum (176 µs/cm), mean (1001 µs/cm), median (1194 µ/cm), and maximum (1349 µs/cm) specific conductance concentrations when compared to data collected by TWRI. At Station 11782, minimum (398 µs/cm), mean (680µs/cm), and median (735 µs/cm) concentrations of data collected by BRA and TCEQ where larger than data collected by TWRI. Station 11785 had larger median (1139 µs/cm) and maximum values (1346 µs/cm) for data collected by BRA and TCEQ. Data collected by TWRI at Station 11783 ($p=0.01$) was significantly higher mean and Station 11782 ($P<0.01$) had a statistically lower mean than the data collected by BRA and TCEQ. However, data collected at Station 11875 by TWRI, TCEQ and BRA did not have any statistically significant difference in their means ($p=0.18$). No previous data had been collected at Station 21259.

**Table 6. Summary statistics of measured specific conductance at each routine monitoring station over the two year study**

| Site # | Summary Statistics | | | | Correlation to Streamflow | | Correlation to *E. coli* | |
|---|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | r | p-value | r | p-value |
| 11785 | 1039 | 1060 | 768 | 1210 | 0.22 | 0.30 | 0.18 | 0.41 |
| 11782 | 431 | 410 | 238 | 1230 | 0.04 | 0.86 | -0.28 | 0.18 |
| 21259 | 1022 | 1030 | 681 | 1230 | 0.10 | 0.64 | -0.40 | 0.06 |
| 11783 | 1205 | 1230 | 444 | 1370 | 0.33 | 0.13 | -0.02 | 0.93 |

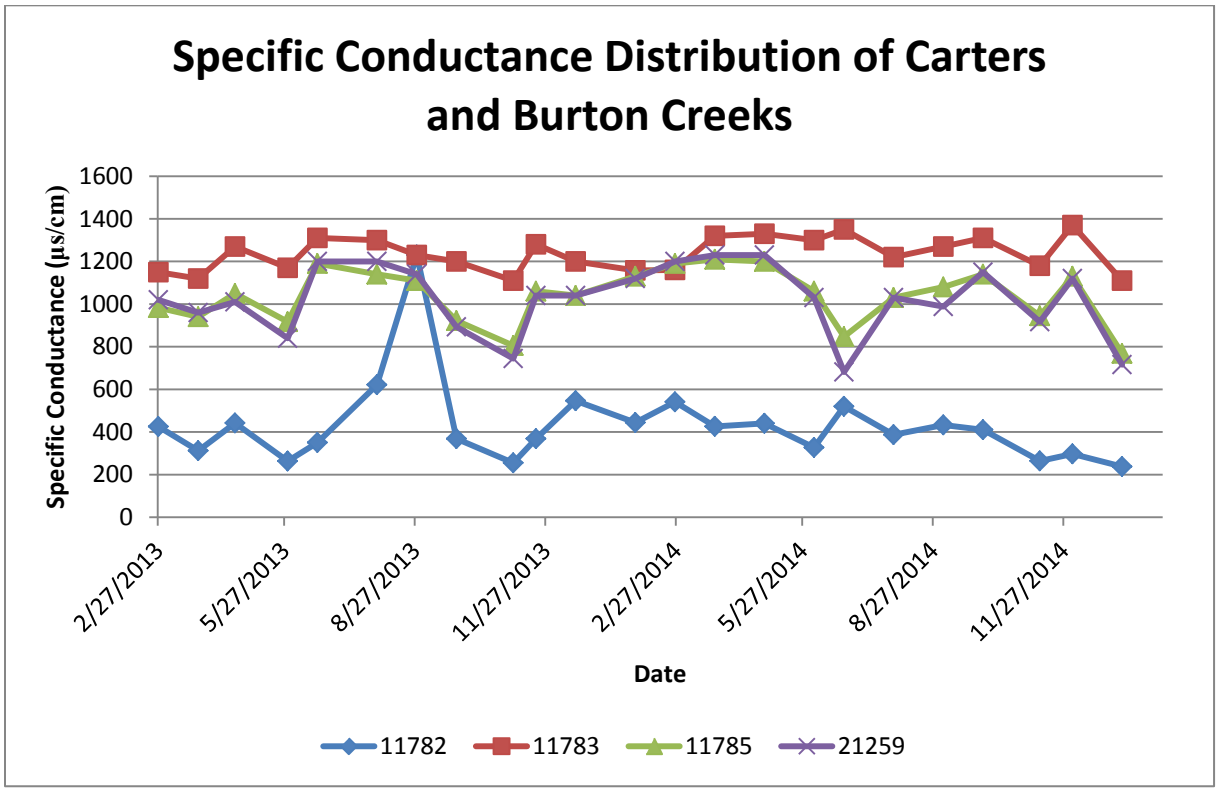


**Figure 6. Specific Conductance distribution of Carters and Burton Creeks**

### *E. coli*

*E. coli* concentrations recorded at each of the four stations were found to vary widely. The geometric means of the values recorded at each site during the course of this monitoring project were found to be over the Primary Contact Recreation standard of 126 cfu/100mL (Figure 7 and 8, Table 7) (TAC 2013, TCEQ 2012). Station 11782, the most upstream site, had the lowest geometric mean of 154 CFU/100 mL and was followed by station 21259, station 11783 and station 11785 with geometric means of 399, 431 and 591 CFU/100 mL respectively. Stations 11783 and 11785 did not have a statistically significant correlation between *E. coli* and streamflow (Table 7); however, the two remaining stations did have statistically significant correlations between streamflow and *E. coli* (Table 7). The strong correlations between streamflow and *E. coli* can be explained by significant rainfall events (greater than 0.5 inches) occurring within six days of monitoring. After removal of these events, no stations had statistically significant correlations. The spike in *E. coli* concentrations during the February 2014 monitoring event occurred during the highest flows at Stations 11782, 11783 and 11785. Evidence of animals in or near the creeks was observed during the September 2013, October 2013, December 2014, January 2015, and February 2015 monitoring events and could have potentially influenced water quality.

*E. coli* concentrations were also collected by the BRA at Station 11783 (between 2001 and 2007) and Station 11785 (between 2001 and 2015). Data collected by BRA had a

larger distribution when compared to data collected by TWRI (Figure 9). Geometric means of the data collected by TWRI were lower than data collected by BRA. However, the data collected by TWRI at Stations 11783 (p=0.81) and 11875 (p= 0.23) did not have any statistically significant differences in their geometric means when compared to data collected by BRA. No previous *E. coli* data had been collected at Stations 11782 and 21259.

**Table 7. Summary statistics of measured *E. coli* concentrations at each routine monitoring station over the two year study**

| Site # | Summary Statistics | | | | Correlation to Streamflow | | Correlation to Streamflow with Rainfall Events Removed± | |
|---|---|---|---|---|---|---|---|---|
| | Geometric Mean | Median | Minimum | Maximum | r | p-value | r | p-value |
| 11785 | 591 | 625 | 253 | 2300 | -0.18 | 0.41 | 0.31 | 0.19 |
| 11782 | 154 | 118 | 16 | 7400 | **0.46** | **0.02** | -0.17 | 0.49 |
| 21259 | 399 | 470 | 100 | 1900 | **0.54** | **<0.01** | 0.43 | 0.06 |
| 11783 | 431 | 355 | 140 | 4500 | 0.26 | 0.23 | 0.38 | 0.11 |

*Bold values are statistically significance values (α<0.05).
±Monitoring events were removed if greater than 0.5 inches of rainfall occurred within 6 days of sampling

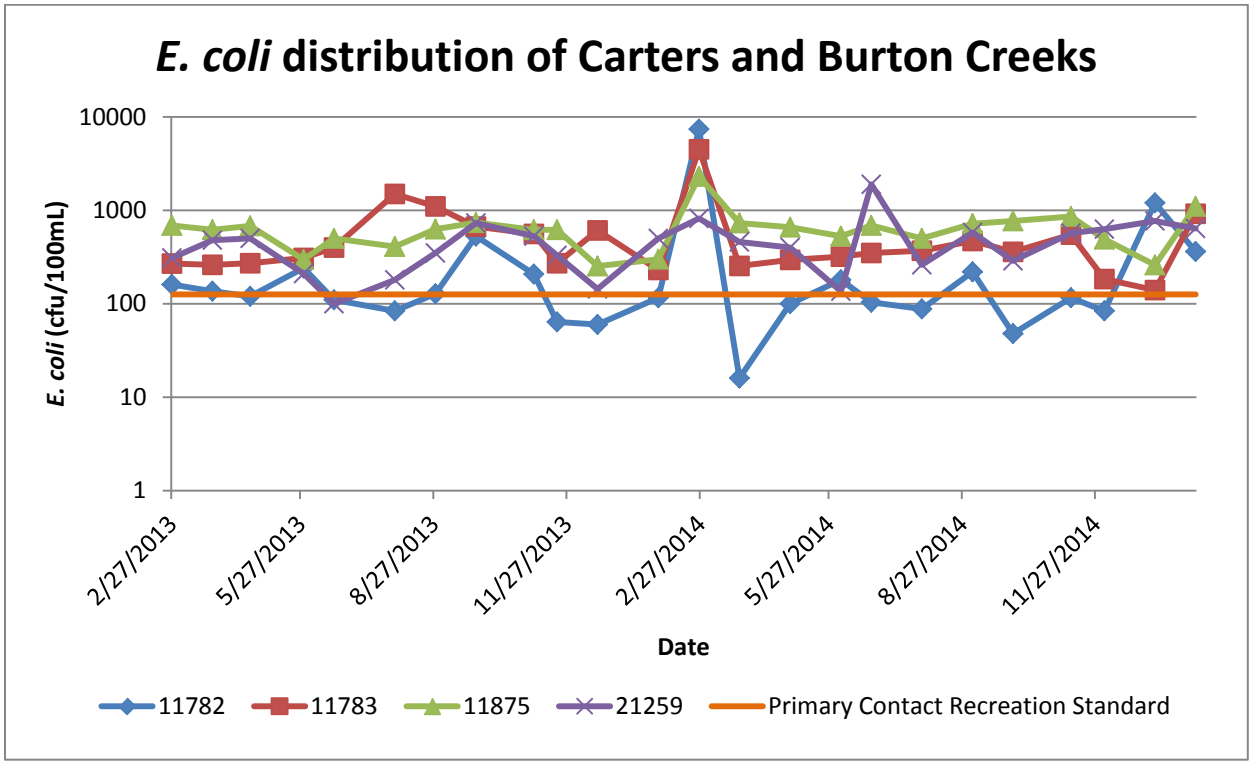


**Figure 7. *E. coli* concentration distribution for Carters and Burton Creeks**

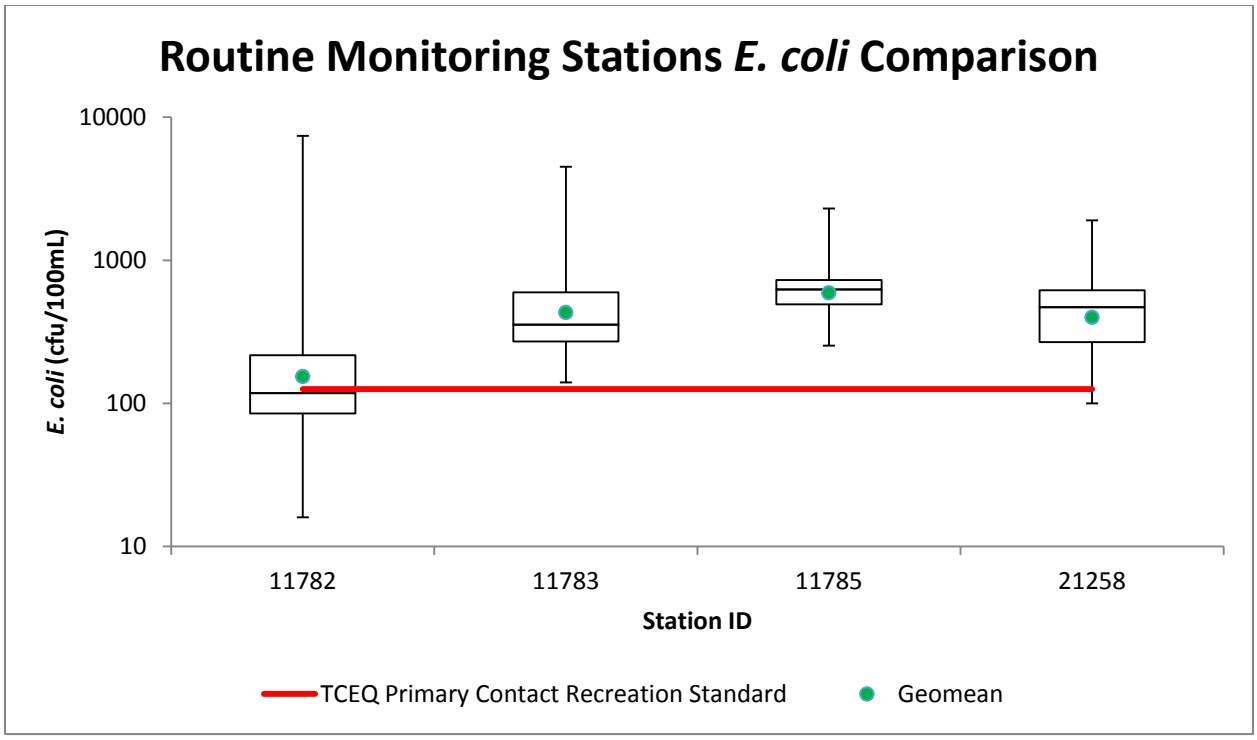


**Figure 8. Comparison of *E. coli* concentrations for the four routine monitoring stations**

**Carters Creek Downstream of Briarcrest Drive**

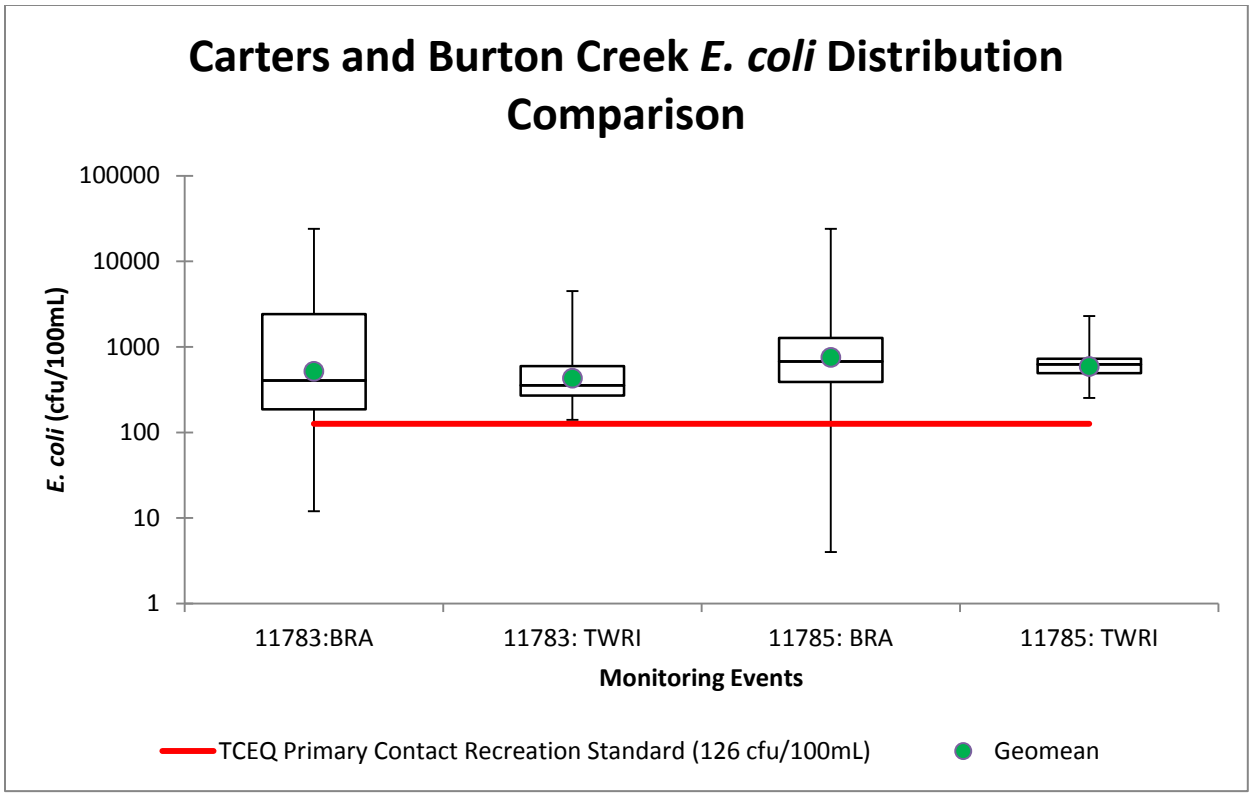


**Figure 9. *E. coli* distribution comparison of TWRI and BRA monitoring of Stations 11873 and 11875**

### Load Duration Curve Analysis

Load Duration Curve Analyses (LDC) was performed in order to assess the bacterial loading for Carters and Burton Creeks. LDCs pair streamflow and *E. coli* concentrations collected on the same date to estimate the pollutant loading reductions needed to meet EPA water quality standards (Babbar-Sebens and Karthikeyan 2009; Morrison and Bonta 2008). Initially, a flow duration curve (FDC) is developed for each selected site and compares measured stream flow values to evaluate the percentage of time the specific flow value is exceeded within the time period evaluated. Flow data must be organized from largest to smallest flow and plotted against the percent of days that the specific flow value is expected to occur. The flow duration curve can then be divided into different flow categories and typically include high flow, moist conditions, mid-range flows, dry conditions and low flows. The TMDL line or maximum allowable pollutant load is developed by multiplying the FDC by the water quality standard and an appropriate unit conversion. Monitored *E. coli* loading is approximated by plotting the associated *E.coli* data with the corresponding stream flow levels. The majority of *E.coli* data should fall below the TMDL line in waterbodies that meet water quality standards, but for impaired water bodies, the *E.coli* loading is often above the TMDL line for the majority of data points, as seen in Figures 10, 12 and 13. Necessary load reductions to

meet the water quality standard are calculated by the average difference between the TMDL and regression line plotted through the observed *E.coli* loads.

Developing LDCs also assists in determining the type of pollution contributing to the site's impairment. When *E.coli* concentrations or bacterial exceedances occur in the high flow or moist conditions portion of the graph, non-point source pollution or sediment resuspension from rain events are likely to be the primary contributing causes of pollutant loading. Exceedances in dry conditions and low flow categories indicate point source pollution, streambed disturbance and direct deposition as the primary forms of contamination at the site. While LDCs can help determine pollutant load reductions, the analysis is not able to identify specific pollution sources or timing of the pollution.

The LDC analysis presented here used all available *E. coli* and streamflow data collected by TWRI, BRA and TCEQ. Each of the four sites had sufficient paired data points to develop LDCs. The load reductions needed to meet water quality standards during each flow category are listed in Tables 12-15. *E.coli* samples taken when the water was pooled were not included in the LDC assessment.

The LDC analysis for each station indicates that non-point sources and the resuspension of *E.coli* from stream bed sediment are contributors to the overall *E. coli* load at all monitoring locations. At station 11782, the LDC (Figure 11) is above the TMDL line during high flows, moist conditions and mid-range conditions but dips below this line under dry conditions and low flows suggesting that point sources are not a sizable contributor of *E. coli* at this site. This finding is logical as no known point sources of *E. coli* exist upstream of this location. The LDC for stations 11785, 21259, and 11783 (Figures 10, 12, and 13 respectively) are above the TMDL at all points, indicating that *E. coli* concentrations are above the EPA standard during all flow conditions. In these cases, the probable pollutant loading types include non-point sources, instream sediment resuspension during high flows, point source contributions, physical streambed disturbances and direct deposition.

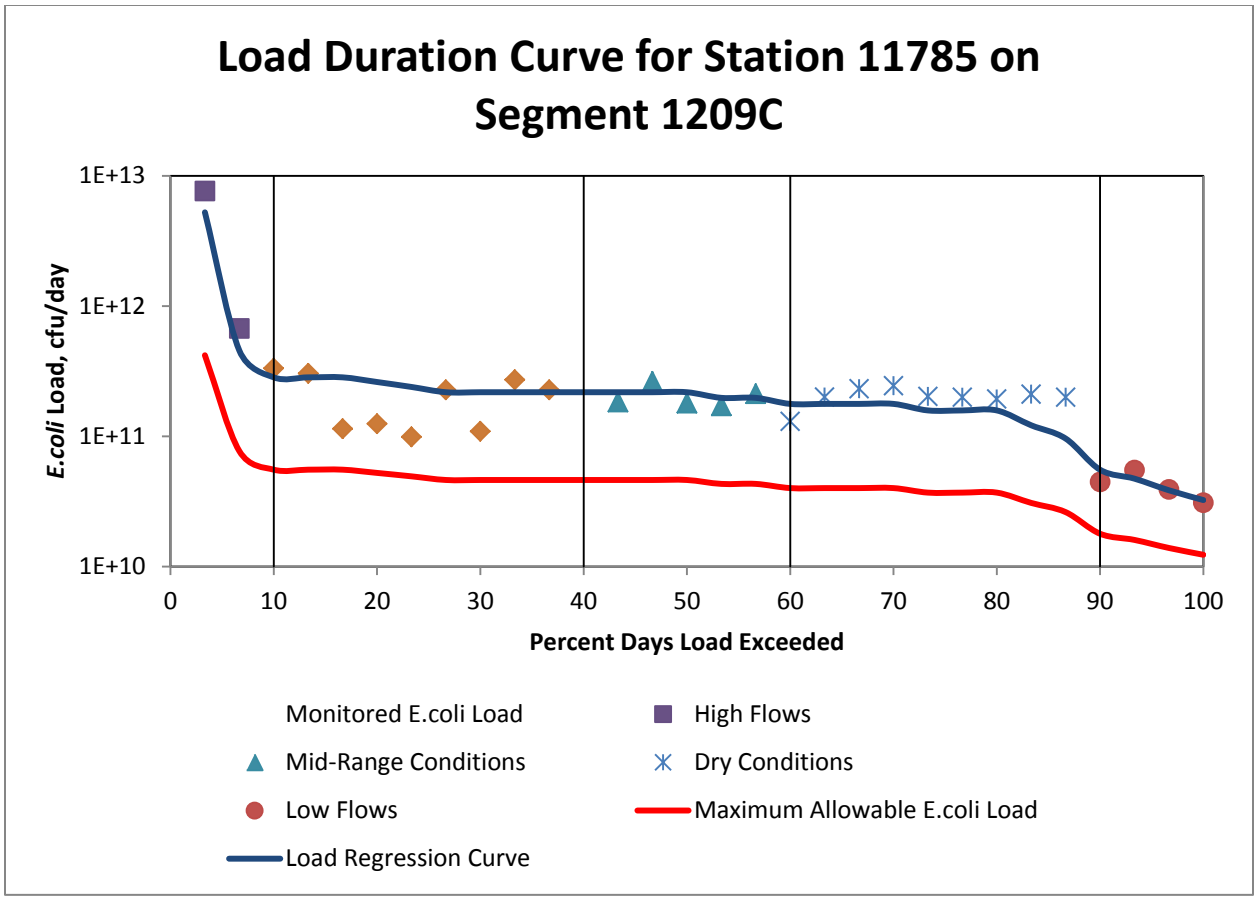


**Figure 10. Load Duration Curve for Carters Creek at Bird Pond Road, Station 11785**

**Table 8. Needed bacterial loading reductions for different flow conditions for Carters Creek at Bird Pond Road, Station 11785**

| Flow Condition | % Flow Exceedance | Percent Load Reduction | Average Annual Loading (cfu/year) |
|---|---|---|---|
| High Flow | 0-10% | 87.55 | 3.20E+04 |
| Moist Conditions | 10-40% | 79.54 | 2.90E+04 |
| Mid-Range | 40-60% | 78.58 | 2.87E+04 |
| Dry Conditions | 60-90% | 76.32 | 2.79E+04 |
| Low Flow | 90-100% | 64.94 | 2.37E+04 |

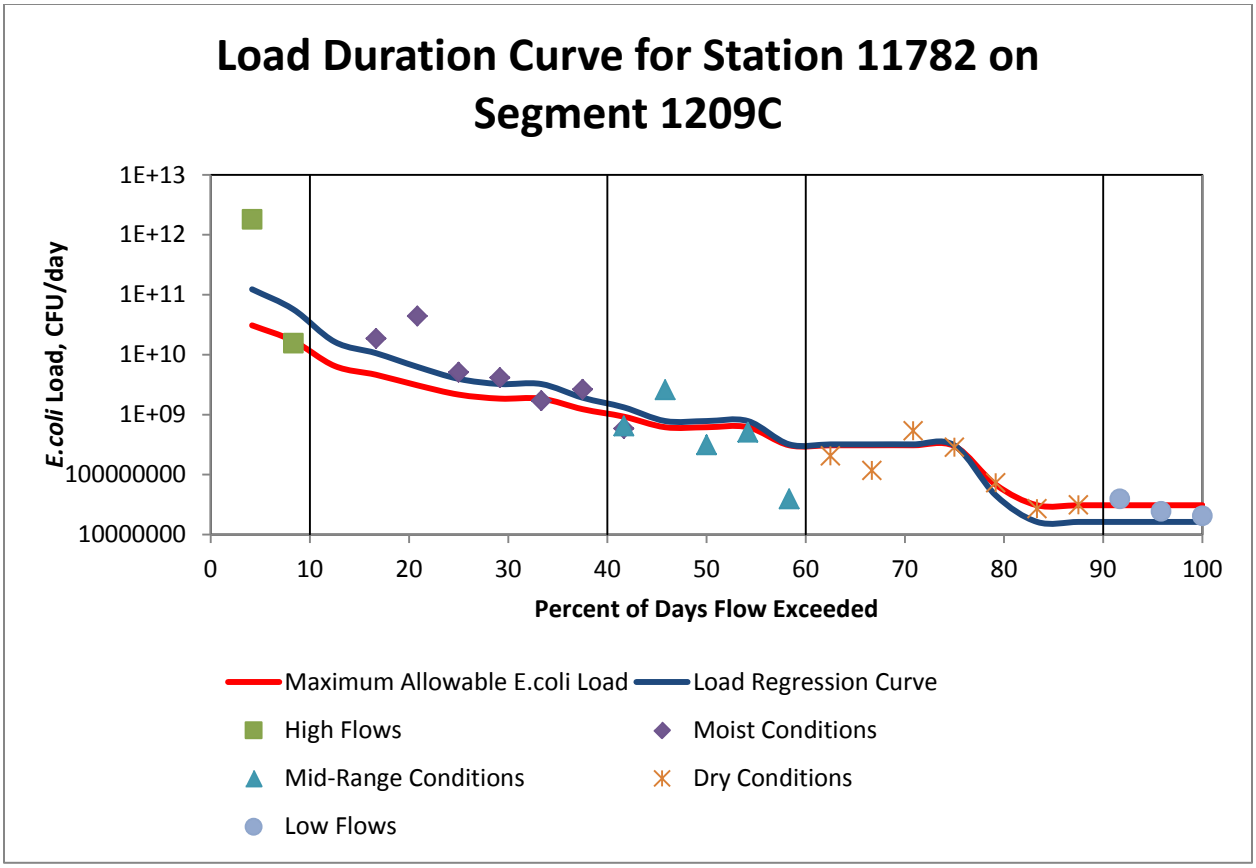


**Figure 11. Load Duration Curve for Carters Creek at SH6, Station 11782**

**Table 9. Needed bacterial loading reductions for different flow conditions for Carters Creek at SH6, Station 11782**

| Flow Condition | % Flow Exceedance | Percent Load Reduction | Average Annual Loading (cfu/year) |
|---|---|---|---|
| High Flow | 0-10% | 73.57 | 2.65E+02 |
| Moist Conditions | 10-40% | 47.77 | 1.74E+02 |
| Mid-Range | 40-60% | 19.38 | 7.08E+01 |
| Dry Conditions | 60-90% | NA | NA |
| Low Flow | 90-100% | NA | NA |

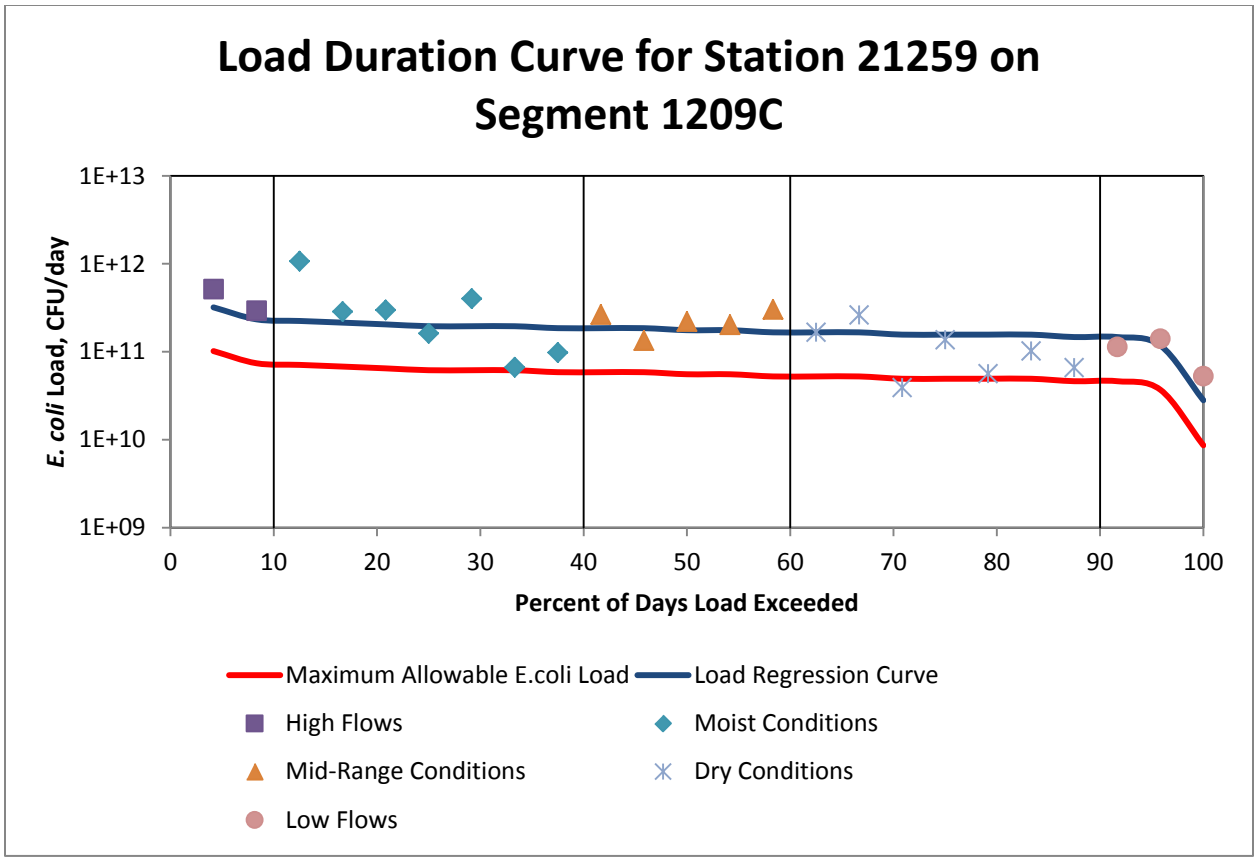


**Figure 12. Load Duration Curve for Carters Creek at William D. Fitch, Station 21259**

**Table 10. Needed bacterial loading reductions for different flow conditions for Carters Creek at William D. Fitch, Station 21259**

| Flow Condition | % Flow Exceedance | Percent Load Reduction | Average Annual Loading (cfu/year) |
|---|---|---|---|
| High Flow | 0-10% | 68.23 | 2.49E+04 |
| Moist Conditions | 10-40% | 68.37 | 2.50E+04 |
| Mid-Range | 40-60% | 68.43 | 2.50E+04 |
| Dry Conditions | 60-90% | 68.48 | 2.50E+04 |
| Low Flow | 90-100% | 68.79 | 2.51E+04 |

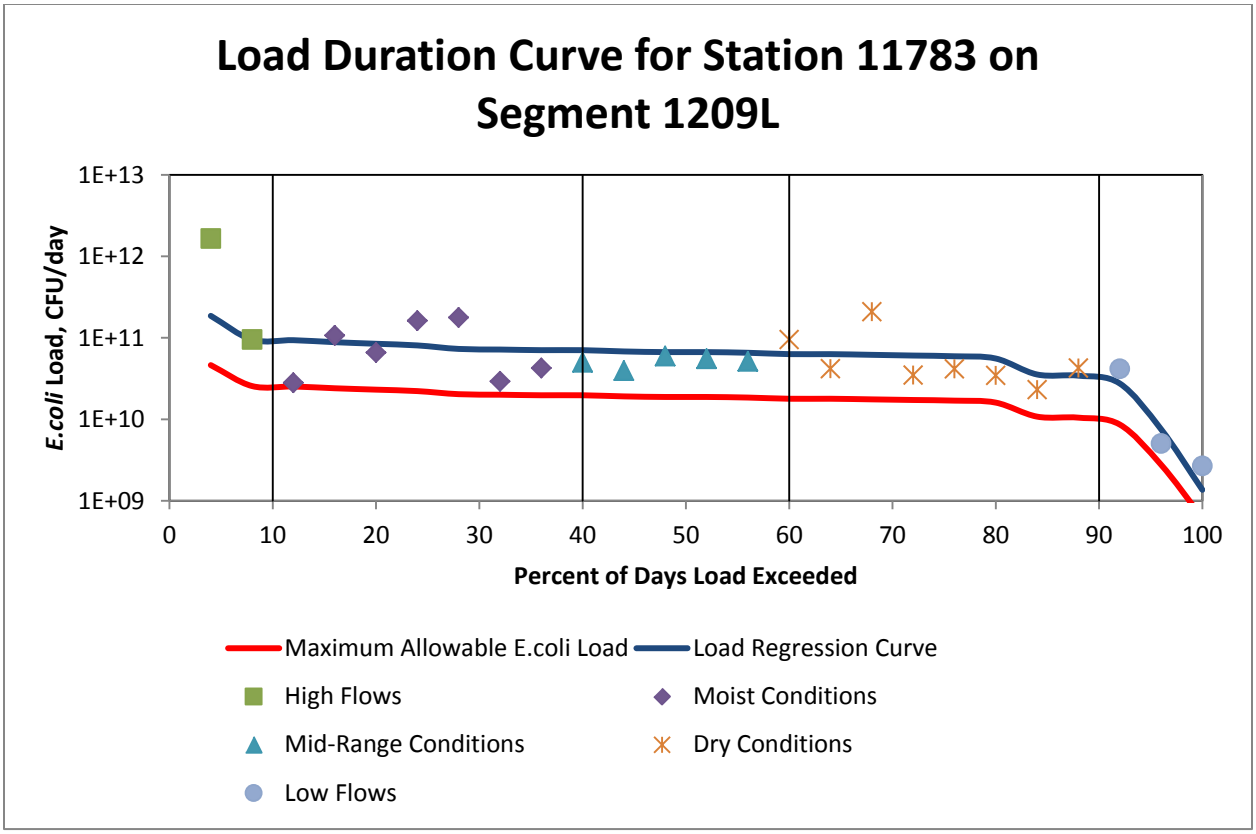


**Figure 13. Load Duration Curve for Burton Creek at SH 6, Station 11783**

**Table 11. Needed bacterial loading reductions for different flow conditions for Burton Creek at SH6, Station 11783**

| Flow Condition | % Flow Exceedance | Percent Load Reduction | Average Annual Loading (cfu/year) |
|---|---|---|---|
| High Flow | 0-10% | 74.08 | 2.70E+04 |
| Moist Conditions | 10-40% | 72.45 | 2.64E+04 |
| Mid-Range | 40-60% | 71.88 | 2.62E+04 |
| Dry Conditions | 60-90% | 71.01 | 2.59E+04 |
| Low Flow | 90-100% | 62.26 | 2.27E+04 |

## Reconnaissance Monitoring

Reconnaissance water quality monitoring events in Carters and Burton Creeks occurred monthly between February 2013 and February 2015 and were carried out by trained volunteers and TWRI staff. Data collected during these events were submitted to TST for inclusion in their statewide water quality database. Graphical representations of the water quality parameters are presented in Figures 14 through 17. Summaries of the major findings can be found in Tables 12 through Table 15. These data can also be

accessed online through TST data viewer at: https://aqua.meadowscenter.txstate.edu/. Statistical analysis for this data used a Spearman's Rho to calculate correlation.

### Dissolved Oxygen

DO concentrations varied between each TST monitoring station (Table 12, Figures 14). A small seasonal pattern appears within the data, similar to what is seen with the routine water quality data; however, the range of values observed within sampling days is larger than that seen in the routine data. This may be partly a result of the field titration method used in volunteer monitoring. No stations statistically significant correlations between DO and *E. coli* (Table 12) were observed at any TST stations.

**Table 12. Summary statistics of measured DO concentration at each reconnaissance monitoring station over the two year study**

| Site # | Summary Statistrics | | | | | Correlation to *E. coli* | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | Count | r | p-value |
| 80908 | 5.4 | 5.2 | 3.0 | 9.3 | 22 | 0.04 | 0.04 |
| 80909 | 5.1 | 4.6 | 1.2 | 14.6 | 24 | 0.29 | 0.18 |
| 80911 | 6.3 | 6.1 | 1.4 | 11.7 | 24 | -0.14 | 0.52 |
| 80912 | 6.8 | 6.2 | 2.3 | 12.1 | 22 | -0.14 | 0.55 |
| 80910 | 4.2 | 3.1 | 0.9 | 11.5 | 24 | -0.20 | 0.35 |
| 80915 | 5.2 | 4.8 | 0.5 | 12.0 | 24 | 0.31 | 0.14 |
| 80913 | 8.6 | 8.4 | 6.1 | 12.2 | 24 | -0.15 | 0.47 |
| 80916 | 9.0 | 9.3 | 4.1 | 13.6 | 24 | 0.09 | 0.66 |
| 80917 | 4.9 | 4.3 | 0.9 | 13.6 | 24 | -0.24 | 0.26 |
| 80914 | 6.6 | 7.0 | 3.4 | 11.8 | 24 | -0.17 | 0.43 |

**Carters Creek downstream of Burton Confluence**

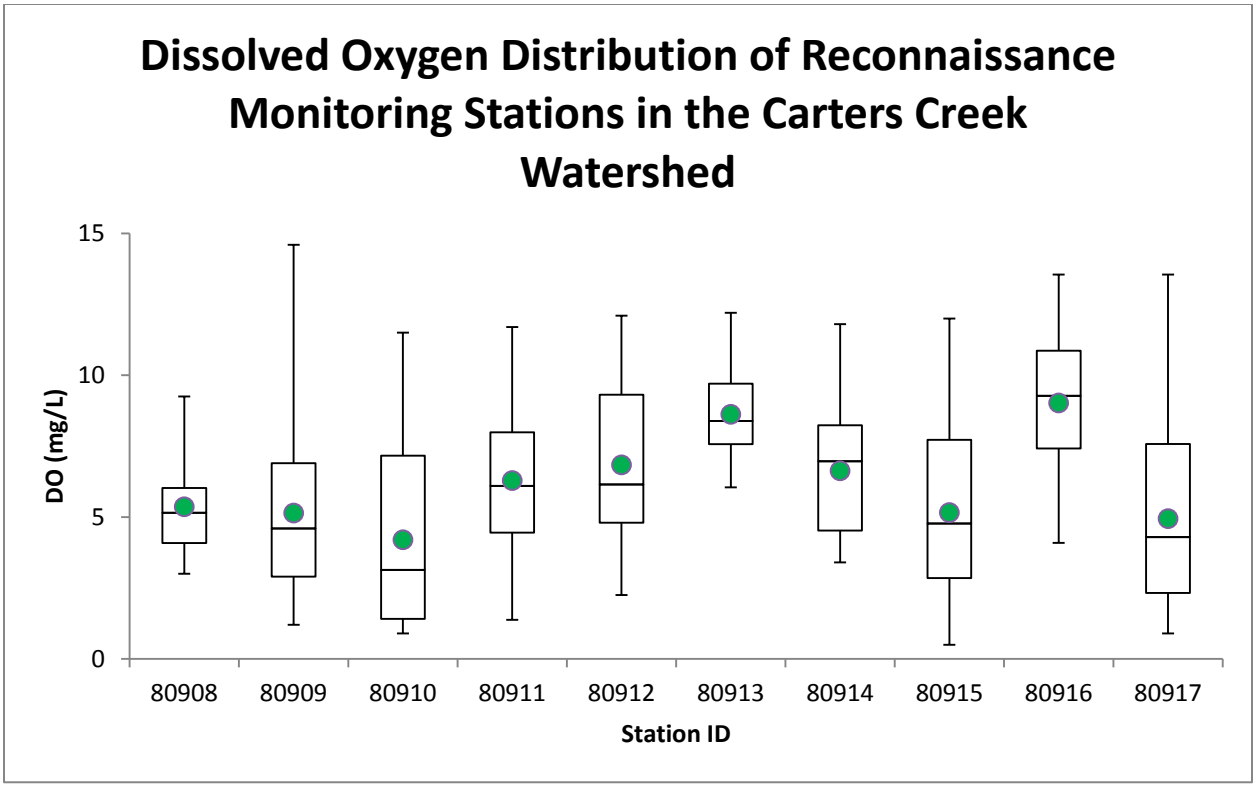


**Figure 14. Dissolved Oxygen distribution of reconnaissance monitoring stations in the Carters Creek Watershed**

### pH

Reconnaissance monitoring stations in the Upper Carters Creek watershed had similar pH values, with the exception of Station 80912 (Table 13, Figures 15) while stations in the lower watershed had more variance in range of pH values seen. The large variations of pH values seen between the monitoring stations is at least partly attributed to the use of the colorimetric method of determining pH used and the subjectivity of selecting the final pH value. Only station 80915 has a statistically significant correlation between pH and *E. coli* (Table 13).

**Table 13. Summary statistics of measured pH values at each reconnaissance monitoring station over the two year study**

| Site # | Summary Statistics | | | | | Correlation to *E. coli* | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | Count | r | p-value |
| 80908 | 7.1 | 7.0 | 7.0 | 7.8 | 24 | -0.23 | 0.27 |
| 80909 | 7.0 | 7.0 | 6.7 | 7.8 | 24 | -0.06 | 0.79 |
| 80911 | 7.3 | 7.2 | 6.9 | 8.0 | 24 | -0.08 | 0.71 |
| 80912 | 7.9 | 7.6 | 6.7 | 9.5 | 24 | -0.08 | 0.70 |
| 80910 | 7.1 | 7.0 | 6.1 | 7.7 | 24 | 0.17 | 0.44 |
| 80915 | 7.3 | 7.1 | 6.6 | 8.7 | 24 | **-0.51** | **0.01** |
| 80913 | 8.1 | 8.2 | 7.2 | 8.6 | 24 | 0.20 | 0.34 |
| 80916 | 8.3 | 8.3 | 7.5 | 8.8 | 24 | 0.05 | 0.82 |
| 80917 | 7.1 | 7.0 | 7.0 | 7.9 | 24 | -0.15 | 0.48 |
| 80914 | 7.5 | 7.5 | 6.9 | 8.4 | 24 | -0.29 | 0.18 |

*Bold values are statistically significance values (α<0.05).

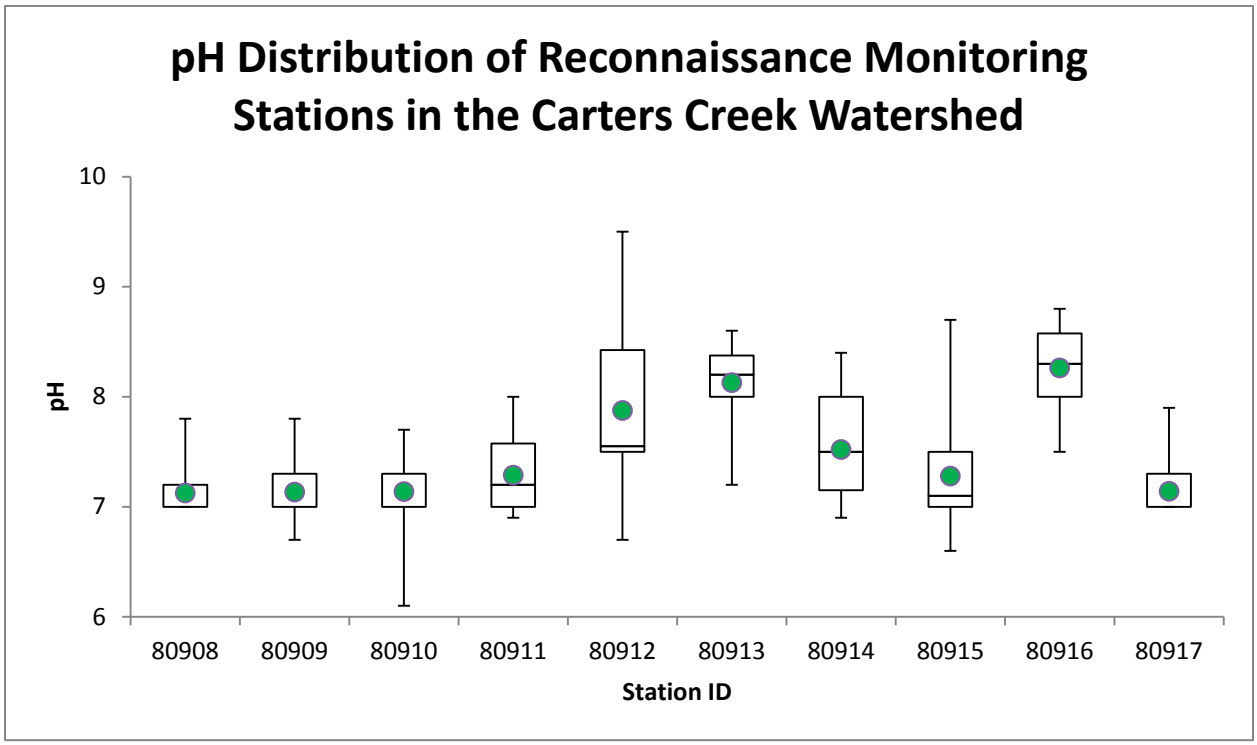


**Figure 15. pH distribution of reconnaissance monitoring stations in the Carters Creek Watershed**

## Conductivity

Conductivity varied between all reconnaissance monitoring stations with no clear trends among the data (Table 14, Figure 16). Some monitoring stations (80912, 80913, 80914, 80915, and 80916) had a small number of conductivity readings greater than 1400

µs/cm (18 out of 240). Only Station 80908 had a statistically significant correlation (r= -0.40, p= 0.05) between conductivity and *E. coli*. The remaining stations did not have any statistically significant correlation between conductivity and *E. coli* (Table 14).

**Table 14. Summary statistics of measured conductivity at each reconnaissance monitoring station over the two year study**

| Site # | Summary Statistics | | | | | Correlation to *E. coli* | |
|---|---|---|---|---|---|---|---|
| | Mean | Median | Minimum | Maximum | Count | r | p-value |
| 80908 | 1127 | 1245 | 110 | 1370 | 24 | **-0.40** | **0.05** |
| 80909 | 415 | 400 | 124 | 740 | 24 | -0.19 | 0.37 |
| 80911 | 827 | 793 | 501 | 1365 | 24 | -0.12 | 0.57 |
| 80912 | 846 | 785 | 260 | 1930 | 24 | <0.01 | 0.97 |
| 80910 | 665 | 603 | 290 | 1170 | 24 | -0.10 | 0.65 |
| 80915 | 447 | 405 | 12 | 1870 | 24 | -0.19 | 0.37 |
| 80913 | 1066 | 1079 | 173 | 1869 | 24 | 0.02 | 0.92 |
| 80916 | 1094 | 1142 | 430 | 1689 | 24 | 0.21 | 0.31 |
| 80917 | 597 | 595 | 69 | 1040 | 24 | -0.14 | 0.52 |
| 80914 | 1142 | 1183 | 15 | 2700 | 24 | <0.01 | 0.98 |

*Bold values are statistically significance values (α<0.05).

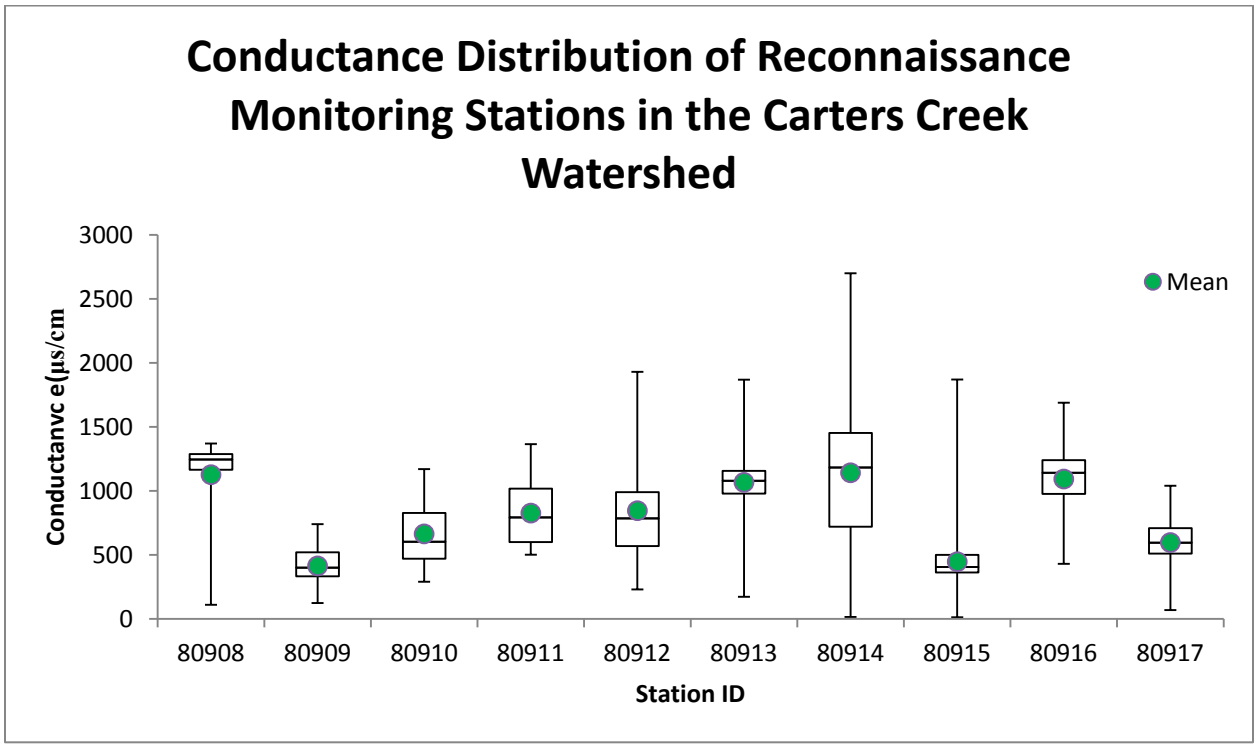


**Figure 16. Conductivity distribution of reconnaissance monitoring stations in the Carters Creek Watershed**

### *E. coli*

No apparent trends were observed in the *E. coli* data collected at the reconnaissance monitoring stations (Table 15, Figures 17). Variation in the range of individual *E. coli* concentrations was considerable and is largely due to the influence of recent rainfall during several monitoring events. Only one monitoring station (Station 80915) had a geometric mean below the TCEQ Primary Contact Recreation standard.

**Table 15. Summary statistics of measured *E. coli* concentration at each reconnaissance monitoring station over the two year study**

| Site # | Geomean | Median | Minimum | Maximum | Count |
|---|---|---|---|---|---|
| 80908 | 421 | 400 | 167 | 2420 | 24 |
| 80909 | 223 | 186 | 16 | 1986 | 24 |
| 80911 | 257 | 242 | 16 | 2420 | 24 |
| 80912 | 492 | 387 | 51 | 2420 | 24 |
| 80910 | 665 | 603 | 290 | 1170 | 24 |
| 80915 | 62 | 59 | 2 | 2420 | 24 |
| 80913 | 754 | 866 | 82 | 2420 | 24 |
| 80916 | 521 | 472 | 179 | 2420 | 24 |
| 80917 | 187 | 595 | 69 | 1040 | 24 |
| 80914 | 363 | 423 | 38 | 2420 | 24 |

**Carters Creek under bridge downstream of William D. Fitch**

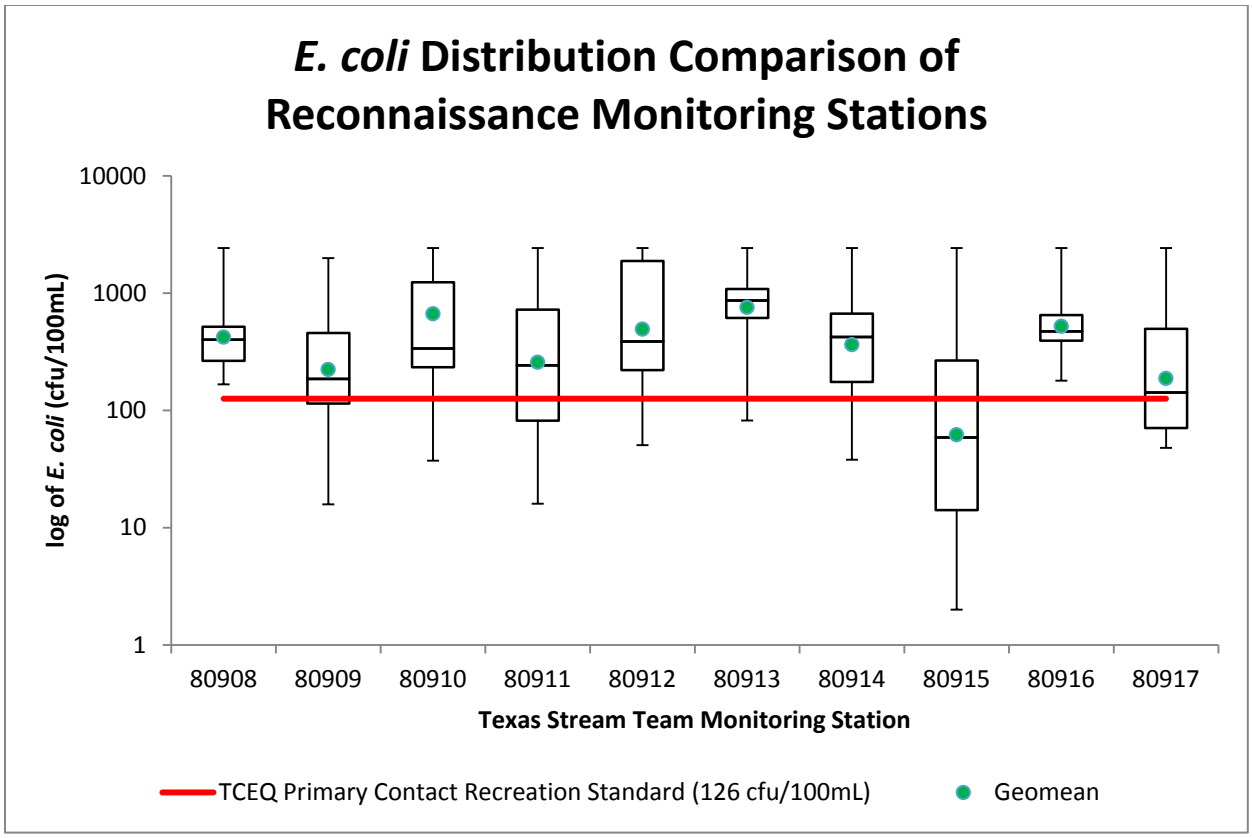


**Figure 17. *E. coli* distribution comparison of the reconnaissance monitoring stations**

## Comparison of Routine and Reconnaissance Monitoring

One routine monitoring station (Station 11783) and one reconnaissance monitoring station (Station 80908) were situated at the same location. This allows for a comparison of the data collected by both types of monitoring (Figure 22). *E. coli* concentration between the two sampling types were compared using the Wilcoxon/Kruskal-Wallis Sum-Rank Test and found no significant difference ($p=0.99$) between the two data sets. This similarity between the two sampling types allows for a comparison and further use of this data to determine locations for intensive monitoring. A Wilcoxon/Kruskal-Wallis Sum-Rank Test was performed on the two monitoring type's results for DO, pH, and conductance. Only conductivity was not statistically different ($p=0.86$) between the monitoring types, while pH ($p<0.01$) and DO ($p=0.01$) were statistically different. One explanation of these differences is the type of testing used by monitoring personnel. Reconnaissance monitoring events used more subjective tests that required personnel to use their judgement in assigning final water quality numbers while routine monitoring utilized automated instrumentation with a high level of repeatability between readings.

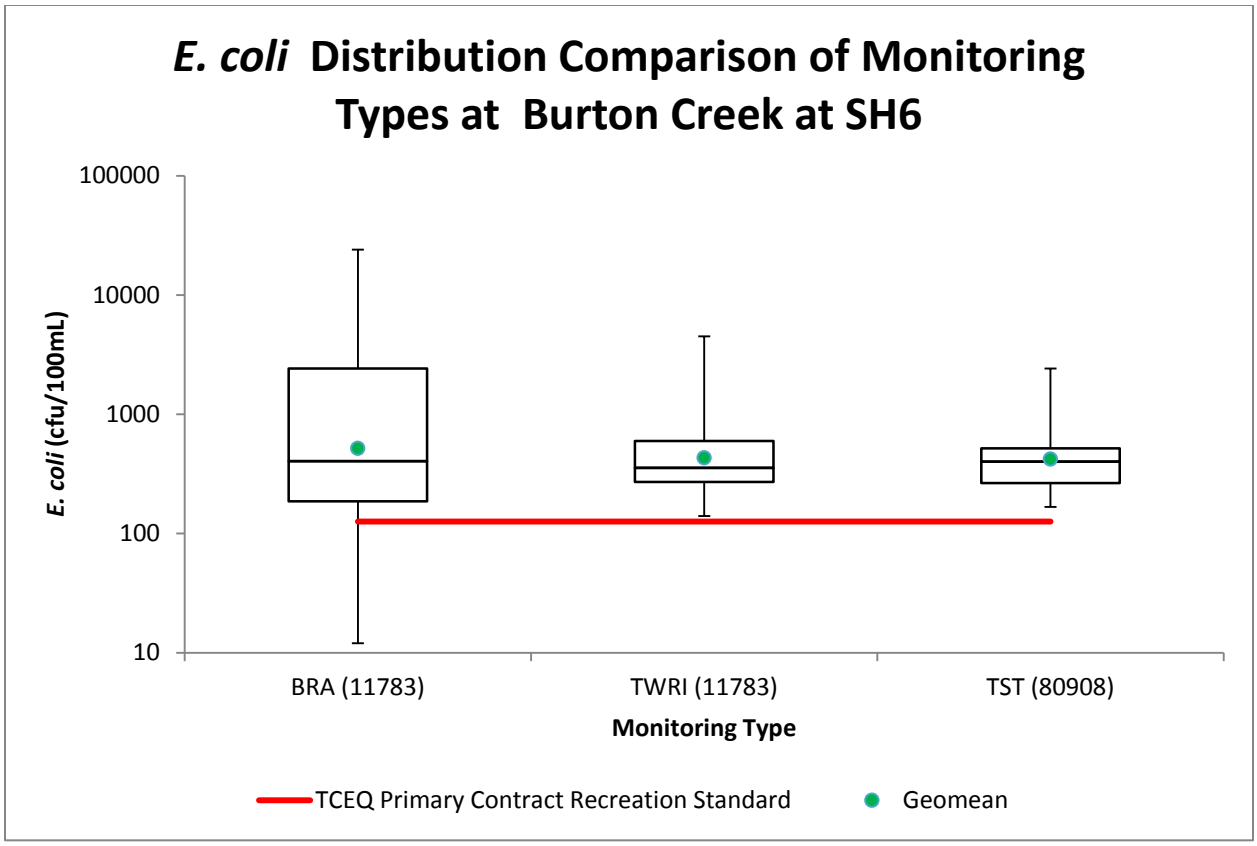


**Figure 18. Comparison of *E. coli* concentrations for the three monitoring types at Burton Creek at SH 6**

These results demonstrate that direct comparisons between routine and reconnaissance monitoring are appropriate despite the different method used to enumerate *E. coli* in each sample type. Direct comparisons of median *E. coli* concentrations were conducted using Wilcoxon statistical test to identify differences in median values. Results of this test are presented in Table 16 and demonstrate that a number of monitoring stations exhibited significantly different median *E. coli* concentrations than others. Values in bold are considered statistically different. Stations 80915 and 11782 were found to be statistically less than all but one and two other sites respectively while stations 80913 and 11785 were found to be statistically larger than all but three and four other stations respectively.

**Table 16. Results from Wilcoxon statistical analysis comparing median *E. coli* concentrations at each location to other monitoring stations**

| | 80909 | 80915 | 11782 | 80910 | 80912 | 80908 | 11783 | 80917 | 80914 | 80916 | 80913 | 80911 | 11785 | 21259 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **80909** | | **0.01** | 0.09 | 0.13 | **0.03** | **0.01** | **.02** | 0.33 | 0.09 | **<0.01** | **<0.01** | 0.91 | **<0.01** | **0.03** |
| **80915** | | | 0.06 | **<0.01** | **<0.01** | **<0.01** | **<0.01** | **0.04** | **<0.01** | **<0.01** | **<0.01** | **0.01** | **0.04** | **<0.01** |
| **11782** | | | | **0.01** | **<0.01** | **<0.01** | **<0.01** | 0.77 | **<0.01** | **<0.01** | **<0.01** | 0.19 | **<0.01** | **<0.01** |
| **80910** | | | | | 0.35 | 0.87 | 0.83 | 0.11 | 0.93 | 0.25 | **0.04** | 0.42 | 0.15 | 0.84 |
| **80912** | | | | | | 0.48 | 0.43 | **0.01** | 0.46 | 0.80 | 0.27 | 0.09 | 0.81 | 0.48 |
| **80908** | | | | | | | 0.99 | **<0.01** | 0.84 | 0.13 | **<0.01** | 0.13 | **0.01** | 0.70 |
| **11783** | | | | | | | | **<0.01** | 0.83 | 0.13 | **<0.01** | 0.14 | **0.02** | 0.82 |
| **80917** | | | | | | | | | **0.03** | **<0.01** | **<0.01** | 0.33 | **<0.01** | **0.01** |
| **80914** | | | | | | | | | | 0.23 | **<0.01** | 0.30 | **0.04** | 0.83 |
| **80916** | | | | | | | | | | | **<0.01** | **0.04** | 0.11 | 0.32 |
| **80913** | | | | | | | | | | | | **<0.01** | **0.03** | **<0.01** |
| **80911** | | | | | | | | | | | | | **0.02** | 0.16 |
| **11785** | | | | | | | | | | | | | | **0.03** |
| **21259** | | | | | | | | | | | | | | |

*Bold values are statistically significance values (α<0.05).

## Stormflow Sampling

Stormwater sampling began in October 2013 and continued through August 2014 when a sufficient number of samples were collected. Several issues plagued the sampling campaign and included damage to equipment during a major flooding event and due to vandalism. As a result, several potential storm events were not sampled. Despite these setbacks, the goal of 20 storm samples was still met through the project with 11 samples collected at station 11783 and 9 collected at station 21259.

As with other *E. coli* concentration data, the variability exhibited in the data set is considerable with measured values ranging from near the primary contact recreation water quality standard to over 350 times the standard. Figure 19 presents boxplots of the observed data at each site and illustrates the similarities between the two. Station 11783 did exhibit the wider range in observed *E. coli* concentrations and higher geometric mean than observed at station 21259. However, testing for significant differences in mean and median values using an analysis of variance (ANOVA) and Wilcoxon/Kruskal-Wallis Sum-Rank Test did not produce significant results with p-values of 0.506 and 0.305 produced respectively. No significant correlations were found between *E. coli* concentrations and total rainfall depth during storm events.

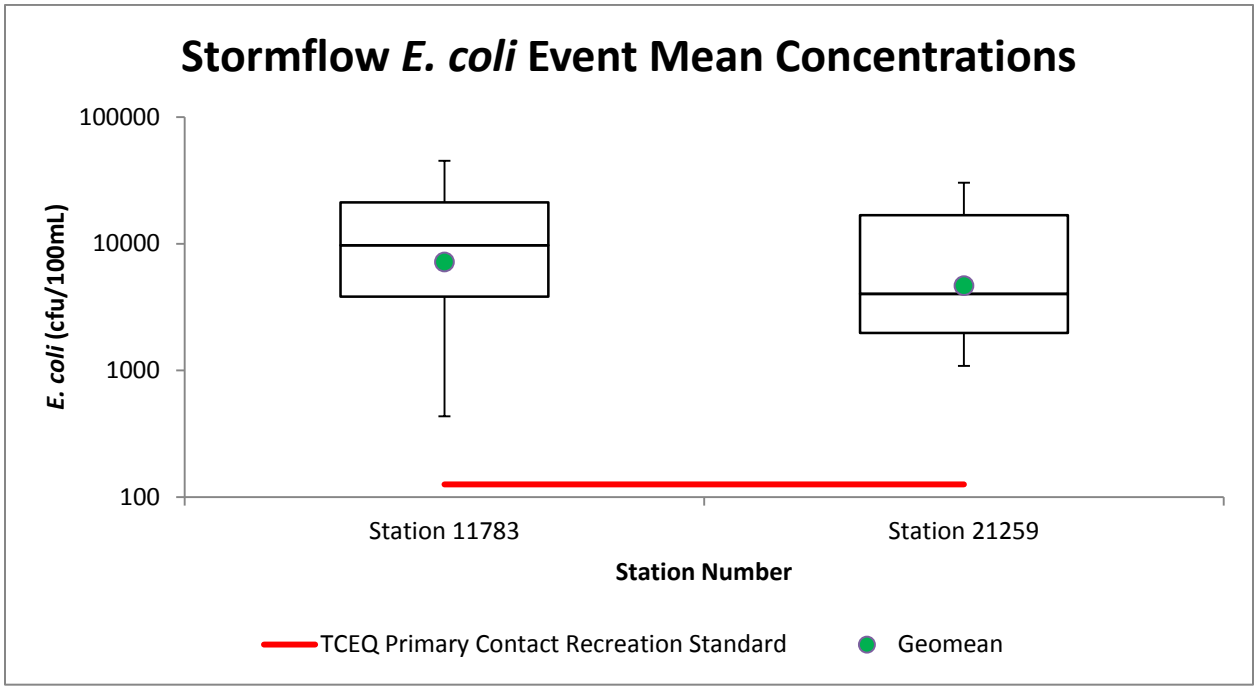


**Figure 19: *E. coli* concentrations collected during runoff events at Stations 11783 and 21259**

## Discussion and Conclusions

The goal of monitoring across the watershed was to improve and further quantify the extent of bacterial impairment across the Carters Creek watershed. Collection of bacterial data from routine, reconnaissance, and stormflow monitoring indicate that the bacteria levels in the Carters Creek watershed do not achieve water quality standards set by the state for primary contact recreation at almost all locations. Data collected also indicate that the geometric mean of *E. coli* concentrations generally increases when moving from upstream to downstream (Figure 20). There is a slight improvement in *E. coli* concentrations between the last two stations (11785 and 21259); however, the difference is not statistically significant. This improvement does illustrate the ability of the stream to naturally attenuate *E. coli* over time as is commonly seen in stream networks. Data collected during stormflow monitoring found that large rain events cause bacterial levels to increase to levels well above the Primary Contact Recreation set by TCEQ at both stations monitored. This finding is not surprising as storm events are responsible for washing non-point source pollutants into the waterbody and causing large scale sediment resuspension within the channel. Each of these occurrences is known to cause monitored *E. coli* levels to increase dramatically.

LDC analyses conducted using routine water quality monitoring sites reinforced knowledge regarding the types of *E. coli* contributions within the watershed. Non-point sources of pollution and runoff induced resuspension of sediment appear to have a slightly larger influence in instream water quality in the upstream portion of the watershed. Downstream, non-point sources, point sources and instream sources are all contributing to the observed water quality.

The upper portion of the Carters Creek watershed appears to be the area responsible for the least amount of *E. coli* loading. Sampling sites on Briar Creek (80915), Carters Creek above Burton Creek (80909 and 11782) and Hudson Creek (80917) produced the lowest geometric mean concentrations; however, large single sample *E. coli* concentrations were occasionally noted in these areas and the recorded geometric means were above the primary contact recreation standard. The lower density and relatively newer development (as compared to some other areas) are possible reasons for these relatively lower *E. coli* concentrations in these areas. In portions of the watershed where development is more dense and in some cases older, *E.coli* concentrations were typically higher. Increasing intensity of development has resulted in subsequent declines in water quality in many other watersheds (Goto and Yan2011; Mallin et al. 2000), thus this finding here is not surprising.

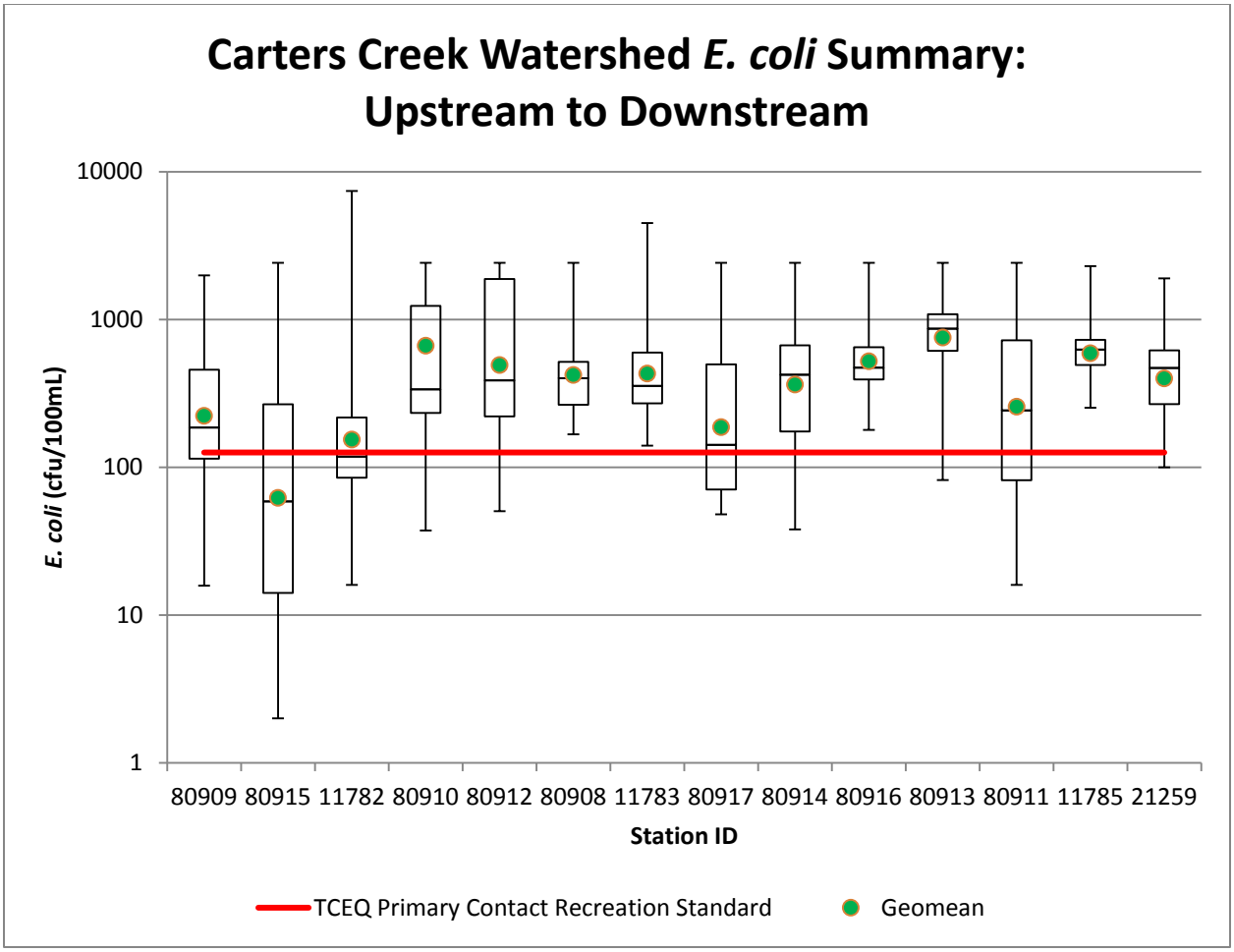


**Figure 20. Trend of *E. coli* geometric means from upstream to downstream in the Carters Creek Watershed**

Treated wastewater effluent is also discharged to several of these waterbodies. Sampling stations located upstream and downstream downstream of WWTF discharge locations were conducted to evaluate their potential influence on observed water quality. At station 80912 and 80908/11782 located approximately 1.5 miles apart and upstream and downstream of the Burton Creek WWTF respectively, a slight decrease in median *E. coli* concentrations was observed (Figure 20) over the two year monitoring period; however, these differences between sites were not significantly different (Table 16). The Carters Creek WWTF also discharges to the watershed and sites 80916 and 80913 were located upstream and downstream of the discharge point respectively with approximately 0.75 miles separating the two sites. An assessment of median *E. coli* concentrations (Figure 20) at these sites revealed a significant increase from upstream to downstream (Table 16).

Field based observations and scientific literature provide a potential explanation for the observed increase in *E. coli* near the Carters Creek WWTF. Possible causes for increases

in *E. coli* concentrations could be related to stream hydrology, the presence and influence of wildlife and/or livestock, or even potential regrowth of bacteria in the stream. Wildlife presents a plausible cause for the observed increase in this case. Ducks were routinely observed in the stream adjacent to and downstream of the monitoring station upstream of the WWTF outfall and mammal tracks were routinely observed along the banks of the creek adjacent to the downstream sampling site. A well-traveled wildlife trail also crossed the stream at this location. Stream bed sediment disturbances, which can occur as a result of mammal and waterfowl activity in a stream, have been found to significantly increase observed *E. coli* concentrations in streamflow due to the release of *E. coli* from the sediment into the water column (Muirhead et al. 2004) and could have occurred here. Also, a large pool in the creek extended upstream and downstream of the WWTF discharge point for the majority of the sampling period and may have influenced water quality observations as well. Large rain events occurring in October 2014 (4 months prior to the end of the sampling period) eroded the stream bed and caused the pool to disappear. This change in stream hydrology may have impacted downstream water quality as pooled water allows sediment and other contaminants to settle out of the water column. Downstream of a pool, the water flowing in the stream is often sediment starved which leads to increased resuspension of sediment and associated *E. coli* from the stream bed which is subsequently transported downstream (Kondolf 1997).

*E. coli* have also been demonstrated to regrow following WWTF disinfection in some cases. Potential for *E. coli* regrowth in WWTF effluent treated with chlorine (used at Burton Creek WWTF) and UV (used at Carters Creek WWTF) disinfection have been evaluated and regrowth of treated *E. coli* has been demonstrated from both by a number of research efforts (Bolster et al. 2005; Bohrerova et al. 2015). Nutrient additions to the receiving water have also been suggested as a cause for microbial regrowth (Lim and Flint 1989; Bolster et al. 2005) but limited work evaluating this in stream environments has been completed. Gregory et al. (2015) completed work using re-created stream mesocosms that evaluated the effects of a one-time addition of nutrient to unaltered water and sediment collected from Carters Creek. Through this work, no *E. coli* growth response was observed as a result of applied nutrient amendments. However, this work is not directly related as it used a one-time nutrient dose instead of a continuous source of nutrients as provided through wastewater effluent. While nutrient loading may have some influence on instream bacteria levels in some cases, evidence here does not support this as both increases and decreases in *E. coli* concentration were observed downstream of wastewater effluent discharge. Additionally, work exploring the effects of wastewater on *E. coli* regrowth in streams has not been carried out to our knowledge yet is sorely needed to better understand the potential connections between the two. Although these studies and observations provide reasonable explanations for the observed *E. coli* concentration increases, it must be noted that the sampling regime

applied could not and does not provide the type or quantity of data needed to determine the specific cause of the observed increase.

Ultimately, no obvious sources of *E. coli* loading were identified in the watershed through this monitoring approach. This is a common finding as *E. coli* sources tend to be transient in both space and time and are thus difficult to pinpoint with a routine sampling approach such as this. Taken collectively, these results highlight the need to address all sources of *E. coli* in a watershed if reductions are to be achieved. The need for targeted intensive monitoring is also illustrated as it provides a tool that is more likely to isolate a specific or much smaller area where *E. coli* loading is of concern.

## References


Babbar-Sebens, M. and R. Karthikeyan, 2009. Consideration of sample size for estimating contaminant load reductions using load duration curves. *Journal of Hydrology* 372:118-123.

Bolster, C.H., Bromley, J.M. and Jones, S.H. 2005. Recovery of Chlorine-Exposed *Eschericha coli* in Estuarine Microcosms. *Environmental Science and Technology*. (39) 3083-3089.

Bohrerova, Z., Rosenblum, J. and Linden, K.G. 2015. Importance of Recovery of *E. coli* in Water Following Ultraviolet Light Disinfection. *Journal of Environmental Engineering*. 141(6) .

Goto, D.K. and Yan, T. 2011. Effects of Land Uses on Fecal Indicator Bacteria in the Water and Soil of a Tropical Watershed. *Microbes Environment* (26) 254-260.

Gregory, L. F., R. Karthikeyan, T. J. Gentry, R. D. Harmel, J. Aitkenhead-Peterson, K. L. Wagner, and R. Lopez (2015). Bacteria Growth, Persistence, and Source Assessment in Rural Texas Landscapes and Streams. Texas Water Resources Institute. TR-489.

Kondolf, G.M. 1997. Hungry Water: Effects of Dams and Gravel Mining on River Channels. *Environmental Management*. 21(4) 533-551.

Mallin, M.A., Williams, K.E., Esham, E.C. and Lowe, R.P. 2000. Effect of Human Development on Bacteriological Water Quality in Coastal Watersheds. *Ecological Applications*. 10(4) 1047-1056.

Morrison, M.A. and J.V. Bonta. 2008. Development of Duration-Curve Based Method for Quantifying Variability and Change in Watershed Hydrology and Water Quality. U.S. EPA Office of Research and Development, National Risk Management Research Laboratory, Cincinnati, OH, EPA/600/R-08/065, May 2008.

Muirhead, R.W., Davies-Colley, R.J., Donnison, A.M. and Nagels, J.W. 2004. Faecal bacteria yields in artificial flood events: quantifying in-stream stores. *Water Research* 38:1215-1224.

TAC §307. 2013. Texas Administrative Code: Chapter 307 – Texas Surface Water Quality Standards. Available online, accessed November 2, 2015 at: http://texreg.sos.state.tx.us/public/readtac$ext.viewtac

TCEQ. 2012. 2012 Texas Integrated Report for Clean Water Act Sections 305(b) and 303(d). Available online, accessed November 2, 2015 at: http://tceq.texas.gov/waterquality/assessment/waterquality/assessment/12twqi/twqi12

TCEQ. 2012b. SWQM Procedures, Volume 1: Physical and Chemical Monitoring Methods. TCEQ, RG-415 Revised August 2012.

TCEQ. 2014. Draft 2014 Texas Integrated Report for Clean Water Act Sections 305(b) and 303(d). Available online, accessed November 2, 2015 at: https://www.tceq.texas.gov/waterquality/assessment/14twqi/14txir

TST. 2012. Texas Stream Team Water Quality Monitoring Manual: 2012. The Meadows Center for Water and the Environment. Available online, http://txstreamteam.meadowscenter.txstate.edu/resources/publications.html