Carters Creek Total Maximum Daily Load Implementation Project Final Report

Texas Water Resources Institute TR-488
February 2016

Lucas Gregory, Brian Jonescu, Jason Murray,
Cassian Schulz, Anna Gitter, Kevin Wagner

Texas Water
Resources Institute
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Carters Creek Total Maximum Daily Load Implementation Project

Final Report

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Prepared by:
Lucas Gregory, Brian Jonescu, Jason Murray, Cassian Schulz, Anna Gitter, Kevin Wagner

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List of Acronyms

COCS	City of College Station
COB	City of Bryan
GIS	Geographic Information System
IP	Implementation Plan
OSSF	On-site Sewage Facility
TAMU	Texas A&M University
TCEQ	Texas Commission on Environmental Quality
TMDL	Total Maximum Daily Load
TWRI	Texas Water Resources Institute
TxDOT	Texas Department of Transportation

Executive Summary

The "Carters Creek Total Maximum Daily Load Implementation" project was developed to provide additional information to watershed stakeholders regarding the spatial and temporal distribution of *E. coli* concentrations in water across the watershed to aid in planning future implementation efforts across the watershed. This goal was accomplished through a variety of focused tasks that collected water quality data and *E. coli* source information from across the watershed. Water quality monitoring was greatly expanded by utilizing four different monitoring approaches. Routine monthly monitoring conducted at four stations over a two-year period provided additional data for future water body assessments. Reconnaissance monitoring was conducted by volunteers on a monthly basis at 10 locations and provided water quality information in many areas of the watershed that had not been previously monitored. Stormwater sampling was conducted at two locations and demonstrated the influences of runoff events on water quality. Lastly, an intensive water quality monitoring approach was utilized to collect a large number of samples within selected creek segments on the same day to illustrate changes in water quality from upstream to downstream. This approach enabled specific areas of the watershed to be identified where *E. coli* loading is likely to occur.

Sources of *E. coli* across the watershed were also explored through this project. Physical observations were made in multiple locations across the watershed and recorded a diverse suite of *E. coli* contributors across the watershed. Pets and urban wildlife were noted in many developed locations while livestock and wildlife were noted in many of the undeveloped areas. No major influxes of *E. coli* were suspected to come from animals in any one area, but they certainly contribute to the overall *E. coli* load in the watershed. Urban infrastructure was also evaluated to identify areas where it can potentially influence water quality. A geographic information system was used to map infrastructure across the watershed and identify areas where infrastructure density or proximity to the stream suggest an increase in potential for water quality influences.

Combining water quality information with source survey results illustrated areas across the watershed where water quality observations may be at least partly explained by source survey results. These areas warrant further investigation in many cases, especially where infrastructure could be contributing to observed *E. coli* concentrations. Through this project, no simple approach to addressing *E. coli* loading in the watershed was identified. Instead, it will take a concerted effort to address many diffuse sources of *E. coli* across the watershed. Many such measures are already underway in the watershed and the entities responsible for them are addressing this challenging issue.

Introduction

In 2007, the Texas Commission on Environmental Quality's (TCEQ) Total Maximum Daily Load (TMDL) Team began the process of developing a TMDL and TMDL Implementation Plan for the Carters Creek watershed. The Carters Creek watershed is a tributary of the Navasota River and covers an area of about 56.9 square miles in Brazos County. When TMDL development began in 2007, the watershed was considered slightly more urban (57%) than rural (Figure 1). The cities of Bryan and College Station lie partly within the watershed and are drivers for development within and near the watershed.

Carters Creek drains the eastern portions of Bryan and College Station and the central portion of Brazos County before joining the Navasota River. Carters Creek, Burton Creek and Country Club Branch are all considered impaired due to elevated levels of *Escherichia coli (E. coli)*. The 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 fails to meet its Primary Contact Recreation standard of 126 colony forming units (CFU) of *E. coli* per 100 mL of water. Initial listing of these waterbodies was supported by prior monitoring conducted by TCEQ and the Brazos River Authority (BRA). In 2014, a TMDL) was completed for each creek and as a result, they are proposed for delisting in the 2014 Texas Integrated Report (TCEQ 2014).

Project Significance and Background

In association with development of the TMDL, a stakeholder group was formed to determine what strategies are appropriate and work to craft them into a TMDL Implementation Plan (I-Plan). Through a facilitated process, stakeholders provided input regarding ways to address bacteria loading in the watershed and ultimately meet the TMDL established in the watershed. A variety of management measures and control actions were included in the I-Plan to achieve this goal by addressing bacteria loading from rural and urban areas. One item that was repeatedly discussed was the need for additional information regarding the current water quality and sources of *E. coli* in the watershed. At the time, data from only four water quality monitoring stations across the watershed was available and information regarding the distribution of and level of *E. coli* across the watershed.

This project was developed to fill these information needs through enhanced water quality monitoring, conducting a watershed source survey and by relaying information gained back to watershed stakeholders. To accomplish these objectives, an extensive water quality monitoring effort throughout the watershed was conducted to quantify water quality at an increased number of stations at an increased sampling frequency. As designed, the sampling effort provided information for small sub-watersheds within the larger Carters Creek watershed. This information allowed for comparisons between sub-watersheds to be made and areas contributing more or less *E. coli* than others to be identified.

A multi-faceted watershed source survey was also conducted to support the expansion of information gathering across the watershed. Traditional, on-the-ground surveys were completed in many areas of the watershed to provide concrete evidence of watershed usage and *E. coli* sources present. Geographic information system (GIS) data were also aggregated and generated based on survey information to further identify features within the watershed that may potentially be sources of *E. coli* or influencing water quality.

Collectively, this work provides information to watershed stakeholders that will allow them to compared measured water quality to the distribution of factors that can potentially influence water quality across the watershed. Using this information, management measure implementation can be directed to specific areas within the watershed to address *E. coli* loads as efficiently as possible.

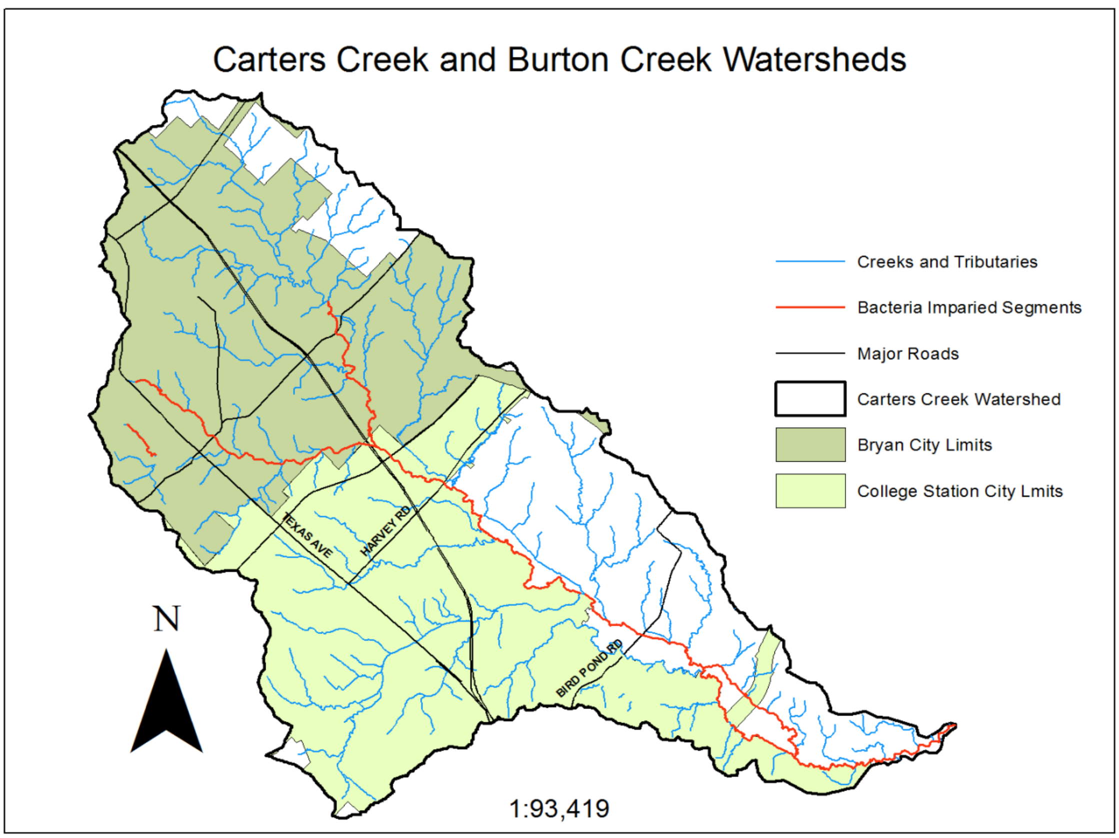

Figure 1. Carters Creek watershed and impaired segments

Methods

Water Quality Monitoring

Monitoring to improve water quality data availability and distribution across the watershed was conducted using multiple methods to accomplish separate monitoring goals. Routine monitoring was performed to provide additional data to TCEQ for use in future water body assessments. Reconnaissance monitoring focused on greatly expanding the number of locations monitored on a regular basis while automated water sampling devices collected rainfall runoff event samples. Statistical analyses conducted included 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 identify significant differences in *E. coli* concentration medians between monitoring stations. For the purposes of this report, data collected through all types of monitoring (routine, reconnaissance, storm) are evaluated collectively unless stated otherwise.

Routine Monitoring

Data collection for use in future waterbody assessments was conducted at four locations across the watershed (Table 1). Stations selection was based on two primary factors: availability of previously existing data and watershed location. In consultation with City of Bryan (COB) and City of College Station (COCS) staff and Texas A&M University (TAMU) Department of Soil and Crop Sciences (SCSC) personnel, four monitoring stations were selected. Stations 11782, 11783, and 11785 (Figure 2) were all previously monitored by the Brazos River Authority (BRA) or TCEQ and contain historical data that supplements new data collected. Station 21259 was established especially for this project to better quantify water quality near the creek's confluence with the Navasota River. Sampling at these four stations occurred monthly beginning in February 2013 and ending in February 2015 by TWRI staff.

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/Storm	30.588628	-96.224594
11783	Burton Creek @ SH6 (downstream of WWTF)	Monthly/Storm	30.644267	-96.313952

During each sampling event, stream flow volume measurements were recorded with an acoustic Doppler flow meter (SonTek FlowTracker, San Diego, CA) and were used to define *E. coli* loads transported by the creek on each sampling day. Other water quality parameters were also recorded using a handheld multi-parameter water quality sonde (YSI 556 MPS or EXO1, Yellow Springs, OH). Dissolved oxygen (DO), pH, specific conductance, and water temperature were all recorded with these devices. General observations were also made at each site and included flow severity, weather conditions, water surface conditions, the presence of odors, debris or other substances. Field notes regarding site specific occurrences and other useful information was also recorded.

Water samples were collected into pre-labeled sterile containers and transported in ice to the Soil and Aquatic Microbiology Lab (SAML) at Texas A&M University where *E. coli* concentrations were determined using the USEPA 1603 method. This method produces a direct count of *E. coli* colonies in 100 mL of water.

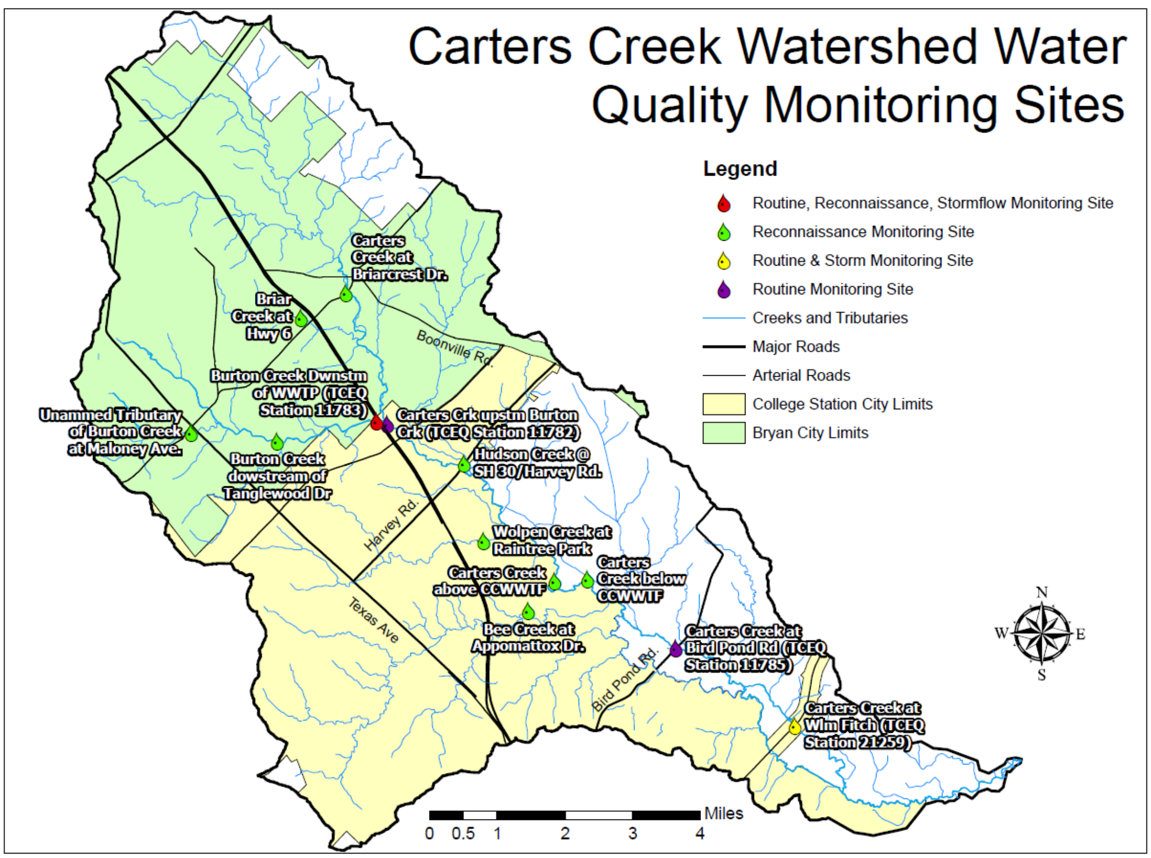

Figure 2. Monitoring locations within the Carters Creek Watershed

Reconnaissance Sampling

Reconnaissance sampling was designed to collect samples at a variety of locations across the watershed on the same dates and same general times as routine monitoring occurred. To accomplish this, up to 25 trained volunteers were utilized to collect samples and record instream water quality data. The Texas Stream Team (TST) monitoring protocol was utilized and volunteers received training prior to sampling. 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). One monitoring station (80908) was co-located with 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

Training that volunteers received consisted of four hours of hands on training that demonstrated their ability to collect water samples and perform tests in the field. In total, 76 volunteers were trained during the course of the project and a number of untrained volunteers were allowed to assist trained volunteers in the field with sampling activities. The same conditions were recorded for reconnaissance sampling as for routine sampling.

E. coli analysis for the reconnaissance samples were processed differently than routine samples. The City of Bryan Thompsons Creek Wastewater Treatment Facility (WWTF) processed samples from Bryan sub-watersheds and samples from College Station sub-watersheds were processed at the City of College Station's Carters Creek WWTF lab. *E. coli* enumeration was conducted using the IDEXX Colilert-18 method. This method produces results in a most probably number (MPN) or *E. coli* per 100 mL and is widely used for assessment purposes. These methods are considered equals by the state for assessment purposes thus justifying their use. Validation of this assumption of similar results was completed by processing water samples collected from a single site using both methods.

Storm Sampling

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 (Table 1, Figure 2), respectively to collect stormwater runoff influenced samples. These samplers were programmed to only sample after the creek sites rose to a predetermined level. Once samplers were enabled, they took flow-weighted composite samples of the runoff event and recorded water levels which were translated to stream flow volumes. This data allowed for *E. coli* loads in storm events to be calculated. Samples were processed for *E. coli* concentrations by SAML using the USEPA 1603 method. Only *E. coli* concentrations and water depth/stream flow were recorded for these sampling events.

Automated Storm Sampler at Station 21259during a runoff event

Load Duration Curves

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 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.

Watershed Survey and GIS Assessment

To better understand the sources and distribution of *E. coli* across the watershed, a physical watershed survey was conducted over the course of the project by numerous individuals. A standard field survey sheet was utilized for all surveys to standardize the type of information recorded. Surveys were conducted at numerous sites across the watershed at locations along the creek and throughout the watershed with some sites being surveyed more than once. During each survey, observations were made instream and in the adjacent watershed. Stream and watershed characteristics were recorded to identify potential water quality influences. Observations included garbage presence and abundance, presence or absence of surface runoff, presence of fecal contamination, storm drain presence and functional status, evidence of disturbed soil, animal observations, and notation of the days since the rainfall occurred. Stream characteristics focused on flow status and stream type, riparian zone and substrate material information, people seen at stream section, and any significant pools in the stream at the site. These detailed data improved the understanding of each location surveyed throughout the watershed and the distribution of potential water quality stressors.

Geographic information systems (GIS) data was also aggregated to further the understanding of the watershed as it relates to potential *E. coli* loading. The goal of the GIS was to aggregate information across the watershed so that it can be utilized to compare watershed characteristics with water quality and explore potential relationships with observed water quality. Available layers from local entities including Brazos County, COB, COCS, TAMU, and TxDOT were acquired and integrated with statewide and national datasets were also acquired from entities including TCEQ, TxDOT, the US Geologic Survey, the US Department of Agriculture (USDA) Natural Resource Conservation Service, USDA Farm Service Agency, and the Multi-Resolution Land Characteristics Consortium. New information was also created and integrated into the GIS. Watershed survey data were digitized and data layers were created that describe survey observations and depict their location across the watersheds. Water quality layers were also generated that illustrate measured water quality across the watershed.

To estimate the total number of on-site sewage facilities (OSSFs) in the watershed, data available from the Brazos County Health Department was aggregated with information regarding septage disposals made by septic pumping service companies who report the location where it originated. A method developed by Gregory et al. 2013 was also applied to identify other potential OSSFs in the watershed that may not have been noted in other data sets. Briefly, this approach combines Census data, aerial imagery and 911 address point locations to identify the number of residences in areas not serviced by centralized sewer systems. The points estimated were compared to those available from acquired data and locations where OSSFs were likely to be located but not known, were added to create an expected OSSF location layer.

Intensive Water Quality Monitoring

Tributaries of Carters and Burton Creeks routinely found with higher *E.coli* concentrations relative to other areas of the watershed with were sampled using a two-phase intensive sampling approach. The goal of this sampling type was to identify small sections of the monitored stream where *E. coli* concentrations rapidly increased. The approach utilized an initial screening sampling regime where numerous samples were taken along the stream on the same date to roughly identify areas within the stream where substantial *E. coli* concentration increases were observed. Stream reaches found to have rapid increases in *E. coli* as compared to other sampled reaches were resampled with a second intensive sampling event to further refine understanding of water quality within that reach. Results were then compared with watershed survey and GIS information to identify potential water quality stressors in that section of stream.

Results and Observations

Water Quality Monitoring

Monitoring conducted across the watershed provided an expanded understanding of water quality in the watershed. Median values of *E. coli* concentrations recorded at the paired stations (11873 and 80908) were compared using the Wilcoxon/Kruskal-Wallis Sum-Rank Test and found no significant difference (p=0.99) between the two data sets. This strongly demonstrates that the results produced under the Routine and Reconnaissance methods are statistically similar. This allows a direct comparison of all *E. coli* concentrations collected across the watershed.

E. coli concentrations recorded at all monitoring stations varied significantly throughout the project period (Figure 3). Geometric means of recorded *E. coli* concentrations were found to be over the Primary Contact Recreation standard of 126 cfu/100mL at all but one monitoring site. The monitoring station at Briar Creek upstream of the south-bound frontage road (Station 80915) was the only site with a geometric mean meeting the water quality standard. Several other monitoring stations also exhibited geometric mean *E. coli* concentrations that were near the water quality standard. In each case, these locations were in the upstream portion of the watershed.

E. coli concentrations recorded in each water sample varied significantly between sampling event and between stream sites. Minimum *E. coli* concentrations observed at each station ranged from 2 to 387 cfu/100 mL while maximum values ranged from 1986 to 7400. However, these maximum values all occurred during a sampling event conducted less than 24 hours following a runoff producing rain event. Excluding this event, maximum *E. coli* concentrations ranged from only 530 to 2420 cfu/100 mL.

E. coli concentrations were compared between monitoring stations to identify the presence of statistically significant differences in median values. The Wilcoxon statistical test was used to identify differences in median values if they existed. Results of this test are presented in Table 3 and are denoted by bold values illustrating the presence of significant differences. 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. Various other sites exhibited significant differences with each other but not obvious trends were noted. A more detailed assessment of water quality can be found in Jonescu et al. 2016.

Table 3. P-values for median comparisons between each monitoring site

	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**

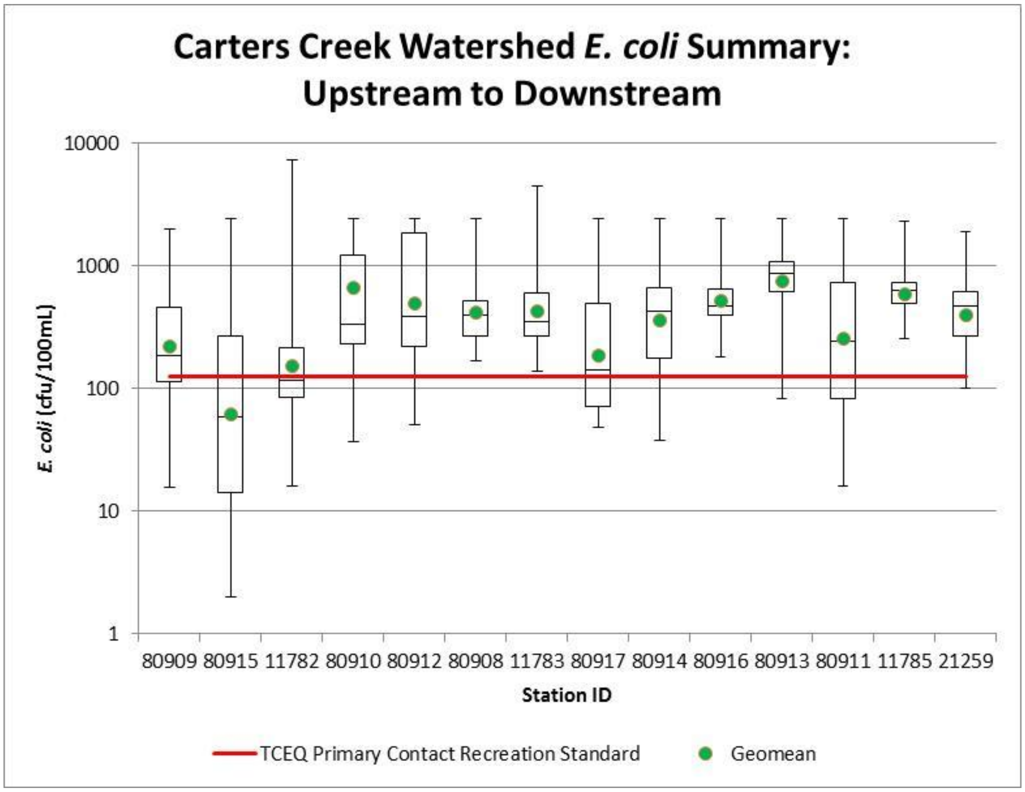

Figure 3. ***E. coli*** **concentration boxplots for each monitoring station in the Carters Creek watershed**

Load Duration Curve Analysis

LDC analysis presented used all available *E. coli* and streamflow data collected by TWRI, BRA and TCEQ. Each of the four routine monitoring sites had sufficient paired data points to develop LDCs. Streamflow measurements were not recorded at reconnaissance monitoring locations; therefore, LDCs could not be developed at these locations. Load reductions needed to meet water quality standards during each flow category are listed in Tables 4 – 7.

Results from each station indicate that non-point sources and resuspension of *E.coli* from stream bed sediment are contributors to the overall *E. coli* load at all locations. At station 11782, the LDC (Figure 4) 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 11783, 11785, and 21259 (Figures 5, 6, and 7 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.

Table 4. *E. coli* load reductions needed to meet water quality standards in Carters Creek near 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

* NA signifies that loads are within allowable limits within the flow category

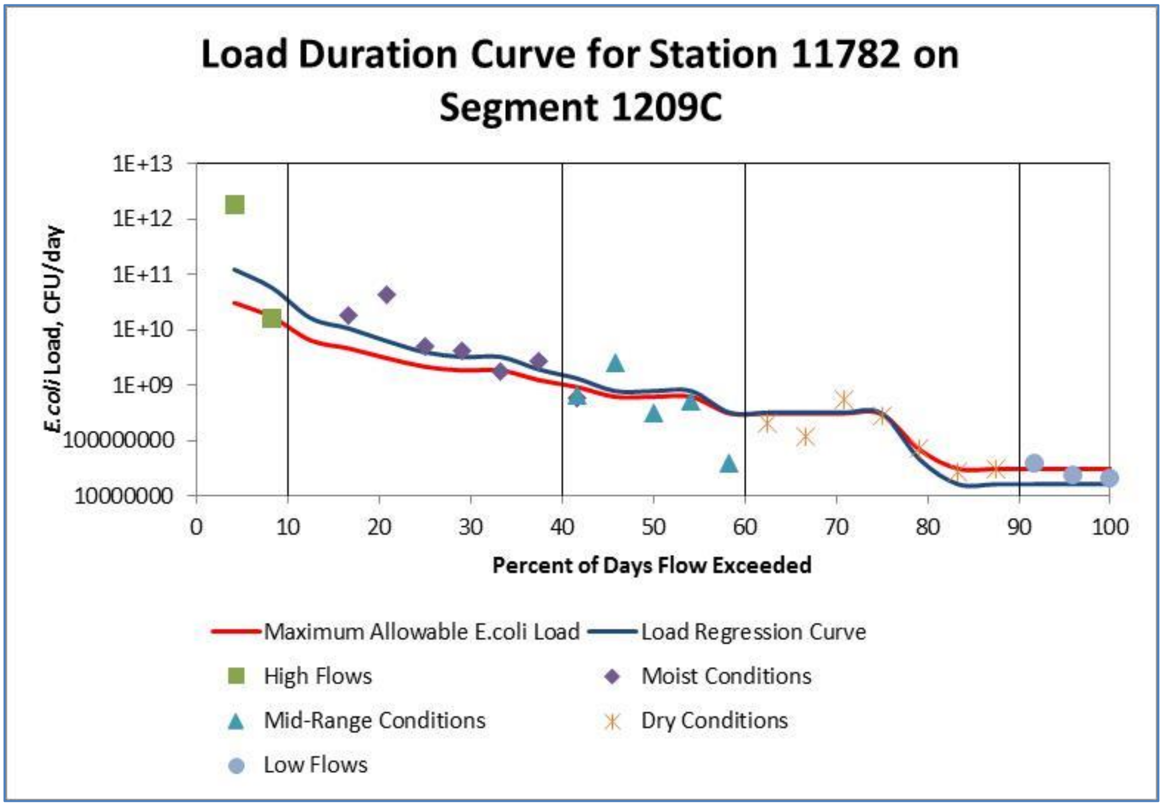

Figure 4. LDC for station 11782: Carters Creek at SH6

Table 5. *E. coli* load reductions needed to meet water quality standards in 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

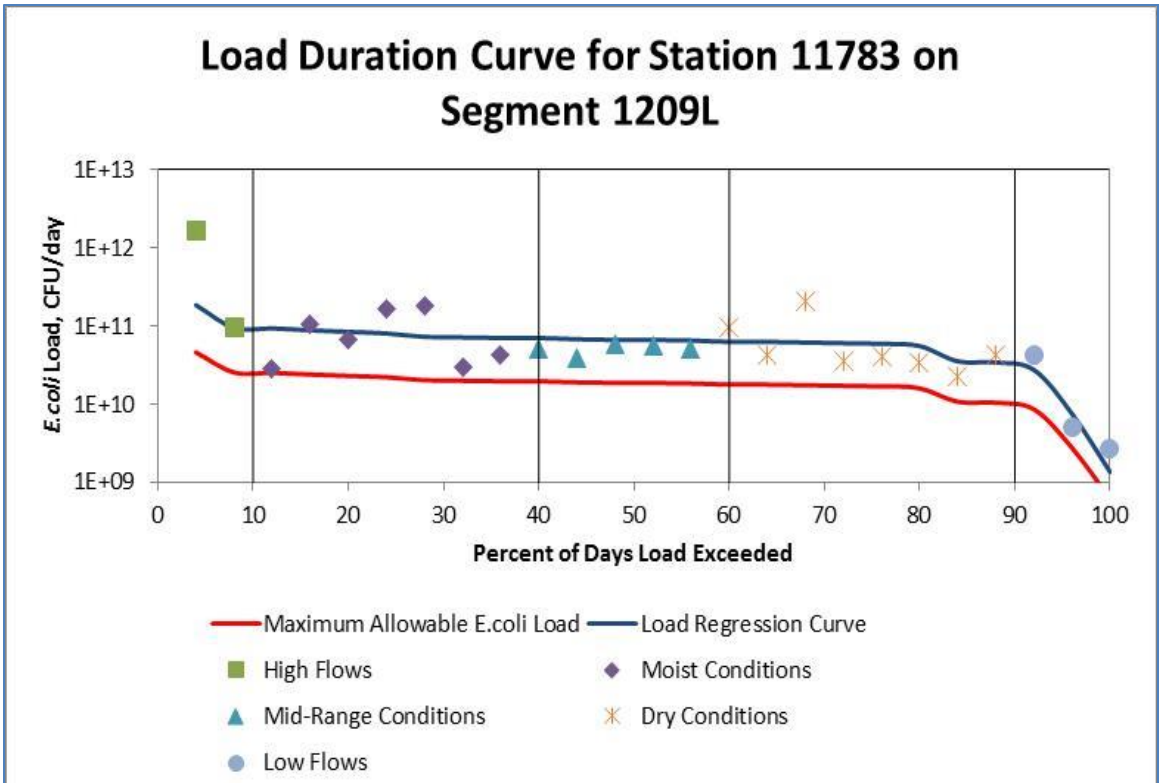

Figure 5. LDC for station 11783: Burton Creek at SH6

Table 6. *E. coli* load reductions needed to meet water quality standards in Carters Creek at Bird Pond Rd. (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

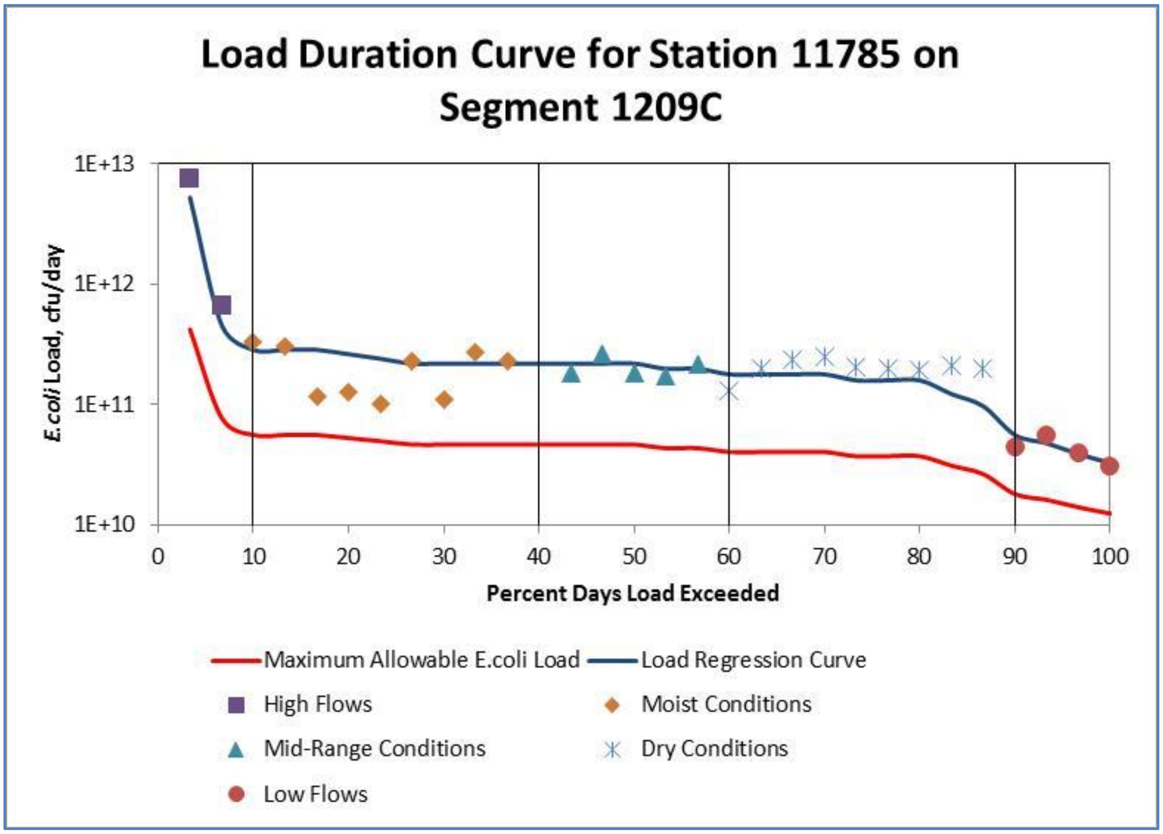

Figure 6. LDC for station 11785: Carters Creek at Bird Pond Road

Table 7. *E. coli* load reductions needed to meet water quality standards in Carters Creek at Wm 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

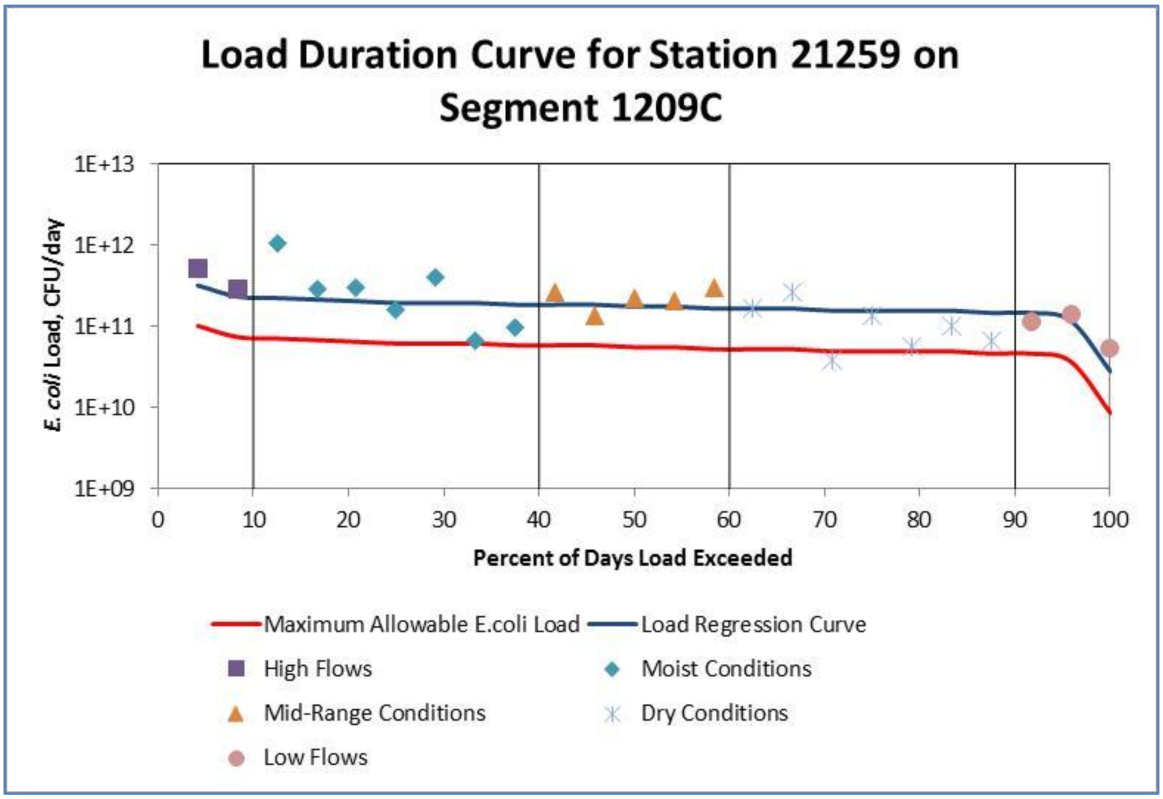

Figure 7. LDC for station 11785: Carters Creek at Wm D. Fitch

Watershed Source Survey and GIS Assessment

The watershed survey proved useful for exploring potential water quality influences of watershed attributes. A variety of potential bacteria sources occur across the watershed and a watershed survey is a good approach for aggregating information regarding each source type. Utilizing GIS also allows this information to be easily visualized in many cases. Availability of GIS data supported efforts to identify areas of the watershed where water quality may be adversely impacted by allowing for rapid visualization of potential water quality stressors and their proximity to local waterbodies.

Animal sources of *E. coli* were widely documented across the watershed as expected. Birds, dogs, and feral hogs or their evidence was most commonly observed and many other species were noted as well but at less frequent intervals. Garbage was also routinely observed across the watershed in a number of locations. Locations where observations were made are included in Figure 8. These maps do not depict the full extent of fecal loading from animals across the watershed.

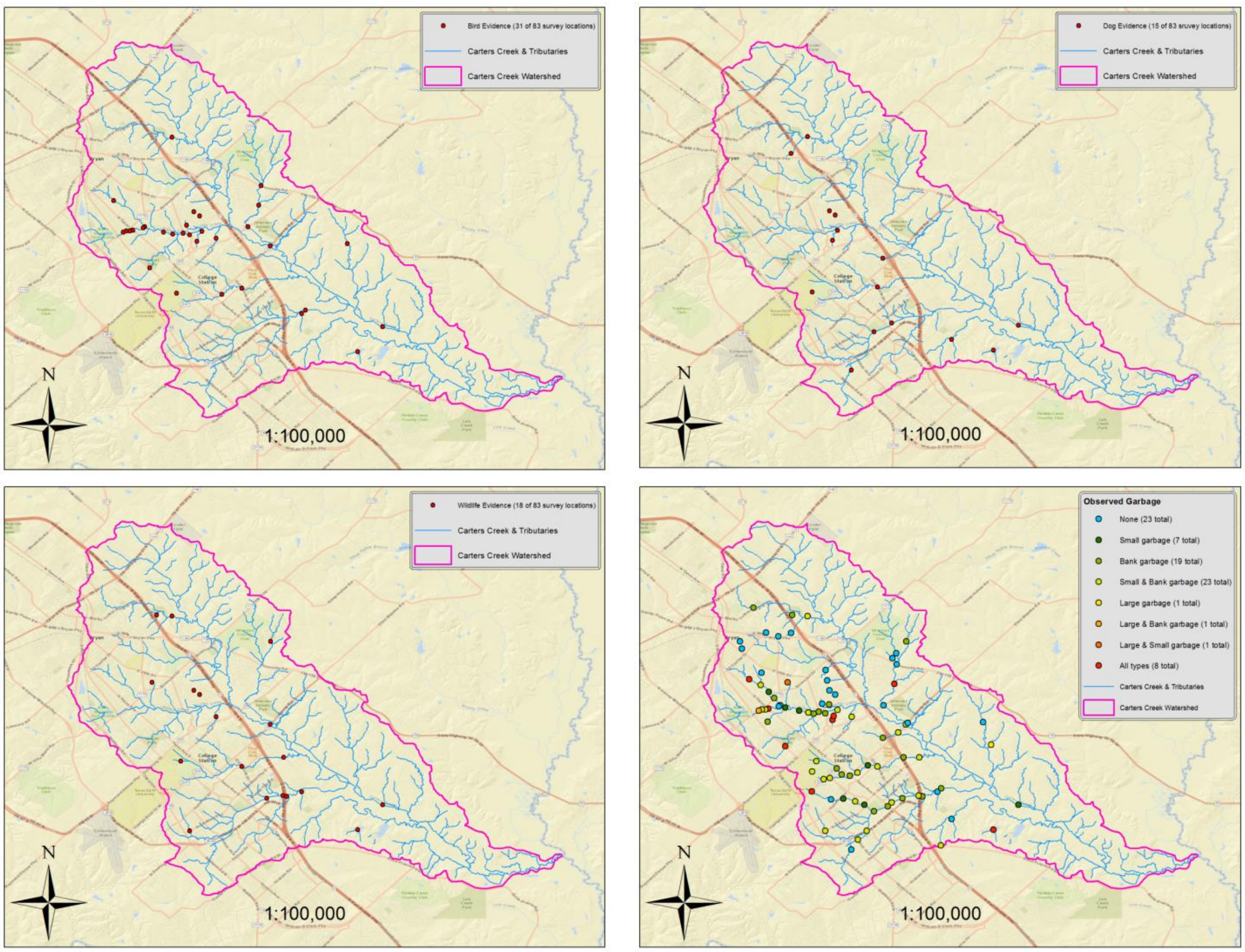

Figure 8. Locations were potential *E. coli* sources were observed in the watershed. Clockwise from top left: Birds, Dogs, Garbage, Wildlife

Infrastructure was also evaluated as a potential influence to water quality. Stormwater conveyances, wastewater conveyances, and streets can all have influences on water quality; particularly if system failures occur. Using GIS data provided by the entities within the watershed, cohesive layers of each infrastructure system was developed.

These layers were overlaid on the stream network within the watershed to identify areas where intersections occurred or high densities of a particular feature were noted. Locations where infrastructure intersects a stream present the highest potential for direct water quality impacts to be observed. As a result, these areas were mapped to illustrate their distribution across the watershed. Areas where infrastructure crosses can also be problematic if failures occur. For example, a broken wastewater line can leach untreated wastewater into stormwater infrastructure if it is also compromised. Throughout the watershed, there are 433 streets crossings over a defined creek channel, 713,200 feet of underground stormwater conveyance pipeline exists, 2,515,000 feet of wastewater pipeline traverse the watershed and cross a stream 468 times, and stormwater and wastewater pipelines cross over each other in 1,973 locations (Figure 9).

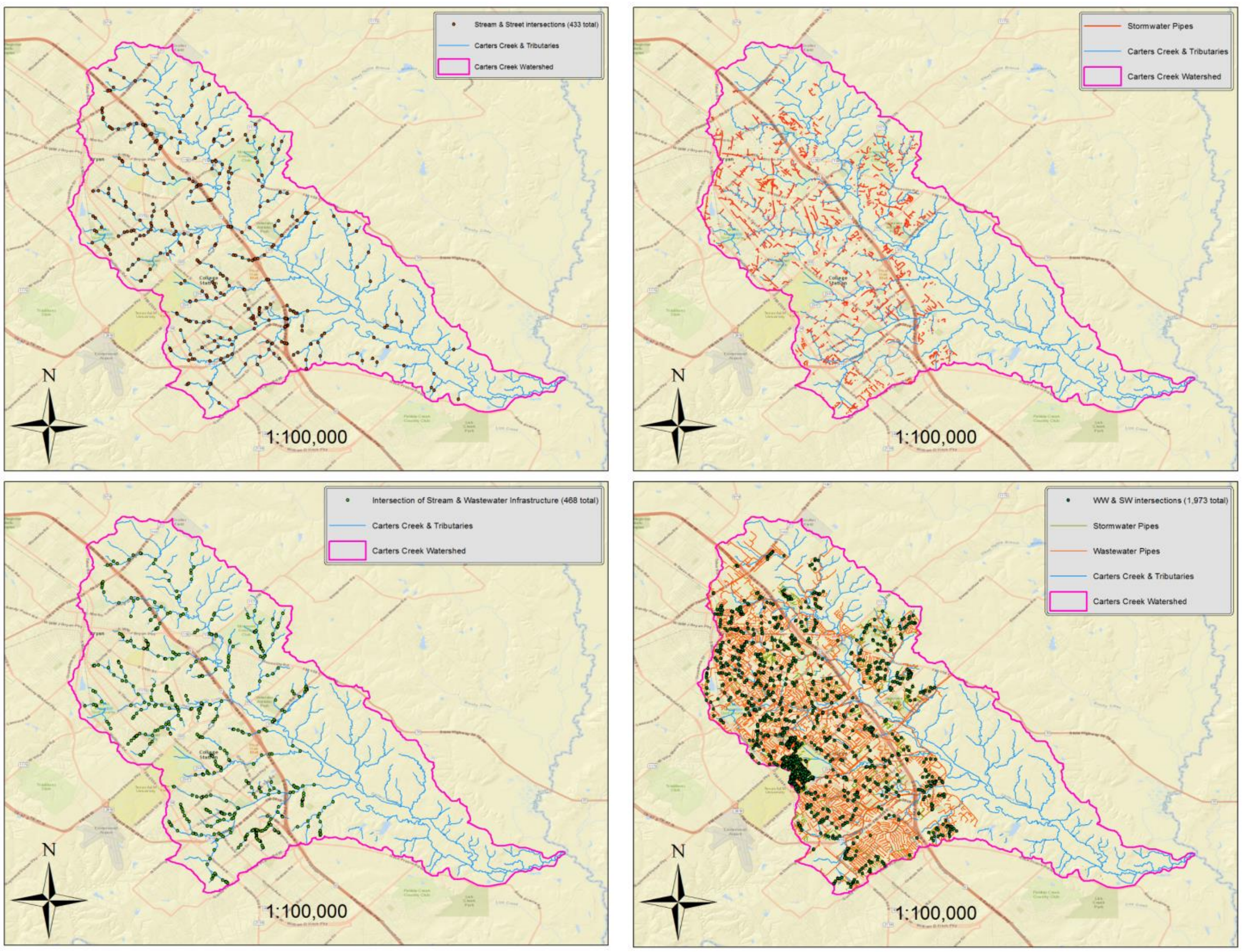

Figure 9. Locations where watershed infrastructure can influence on water quality. Clockwise from top left: Points where Streets Cross a Stream; Underground Stormwater Conveyances; Wastewater Pipeline and Stream Intersections; Stormwater and Wastewater Pipe Crossings

Although centralized wastewater systems service the majority of the watershed, the areas outside of the city limits rely heavily on on-site sewage facilities (OSSFs). When properly designed, installed, operated and maintained OSSFs provide cost effective treatment of human waste that mitigates the release of *E. coli* to the environment. As with any management system, failures can and do occur as a result of system age, improper maintenance, poor system installation or design, or system overload. Regardless of cause, failures increase the potential for wastewater to be released to the environment without proper treatment. Proximity of a failing OSSF to creeks or drainage ditches can influence the potential for improperly treated waste to make its way into downstream water bodies. In total, there are an estimated 769 OSSFs distributed across the watershed (Figure 10).

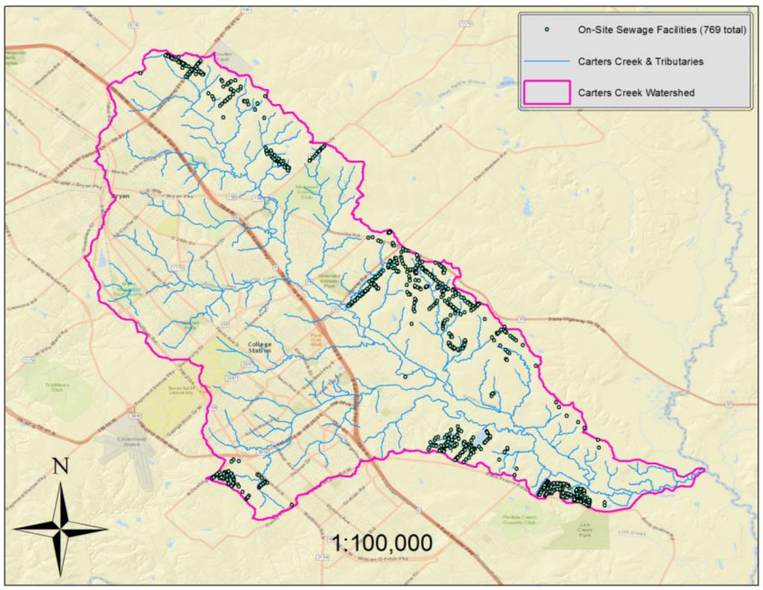

Figure 10. Estimated OSSF locations in the watershed

During the watershed survey, no obvious sources of *E. coli* loading other than fecal deposition by animals were noted and no infrastructure failures were identified.

Changes in land use and land cover were also evaluated as a potential water quality stressor. Land cover changes are often associated with changes in water quality. Generally, as the level of impervious surface increases, water quality degrades. This is due to multiple factors such as the concentration of potential pollutant sources, increased runoff production, and decreased water filtering and storage capacity of the watershed. Changes in land use and land cover in the watershed have increased considerably in recent years due to the rapid growth of Bryan and College Station and the surrounding areas. Land use and land cover layers from 2001 and 2011 were compared to quantify this level of change. This assessment demonstrated considerable loss of open space and a considerable increase in developed areas (Table 8 and Figure 11). In total, 8.5% of the watershed experienced a land use change in this 10 year assessment window. Land use losses occurred primarily in forests, shrub/scrub and in pastures while increases in developed land accounted for these losses. However, some of the development in the watershed simply moved from one development category to another. A more detailed assessment of the watershed survey and GIS is available in Gregory et al. 2016a.

Table 8. Carters Creek Land Use and Land Cover acreages and changes

Land Use and Land Cover Classification	Acreage Totals in Assessment Years		Difference between Assessment Years*
	2001	2011	
Open Water	118.5	124.8	6.2
Developed, Open Space	6,200.4	6,258.0	57.6
Developed, Low Intensity	6,131.9	6,553.1	421.2
Developed, Medium Intensity	5,125.3	6,071.4	946.1
Developed, High Intensity	1,476.5	1,898.8	422.3
Barren Land	79.2	68.9	-10.2
Deciduous Forest	3,546.3	3,035.7	-510.6
Evergreen Forest	136.8	109.2	-27.6
Mixed Forest	1,232.5	1,148.2	-84.3
Shrub/Scrub	3,026.6	2,501.5	-525.1
Grassland/Herbaceous	691.0	700.1	9.1
Pasture/Hay	6,307.6	5,686.8	-620.7
Cultivated Crops	211.9	210.8	-1.1
Woody Wetlands	2,052.3	1,957.7	-94.5
Emergent Herbaceous Wetlands	91.6	103.2	11.6
*positive values denote an increase in acreage between years and negative values denote a loss			

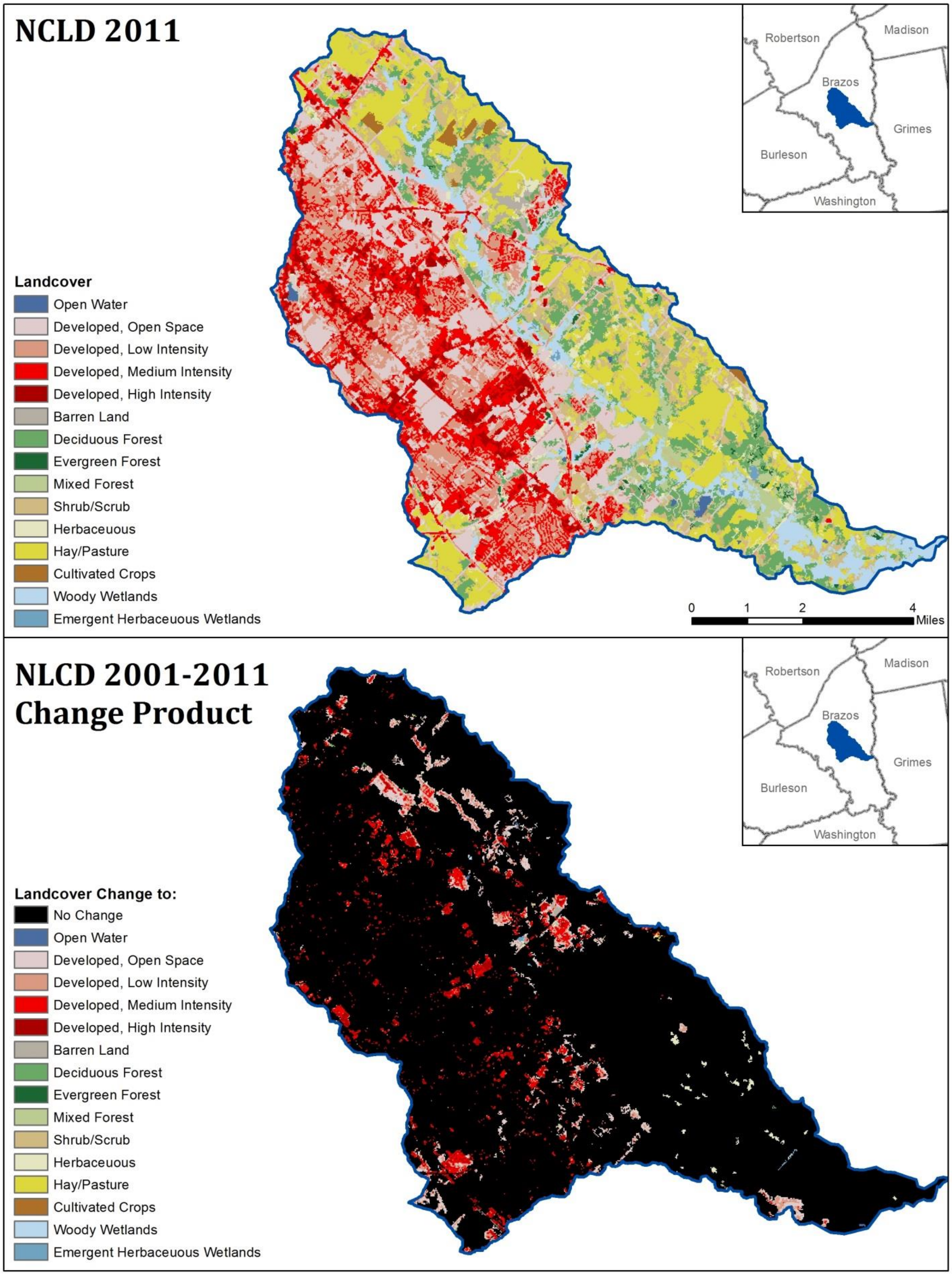

Figure 11. Land use and land cover (top) and the area where land use and land cover change occurred (bottom) in the Carters Creek watershed

Intensive Water Quality Monitoring

Intensive monitoring was conducted on 6 tributaries of Carters Creek following an assessment of the routine and reconnaissance monitoring efforts (Figure 12). Areas of the watershed that had higher *E. coli* concentrations or where not available information had been previously collected were monitored more intensively through this sampling effort. Samples were collected in a downstream to upstream fashion throughout the watershed to prevent any stream bed disturbance from influence samples collected.

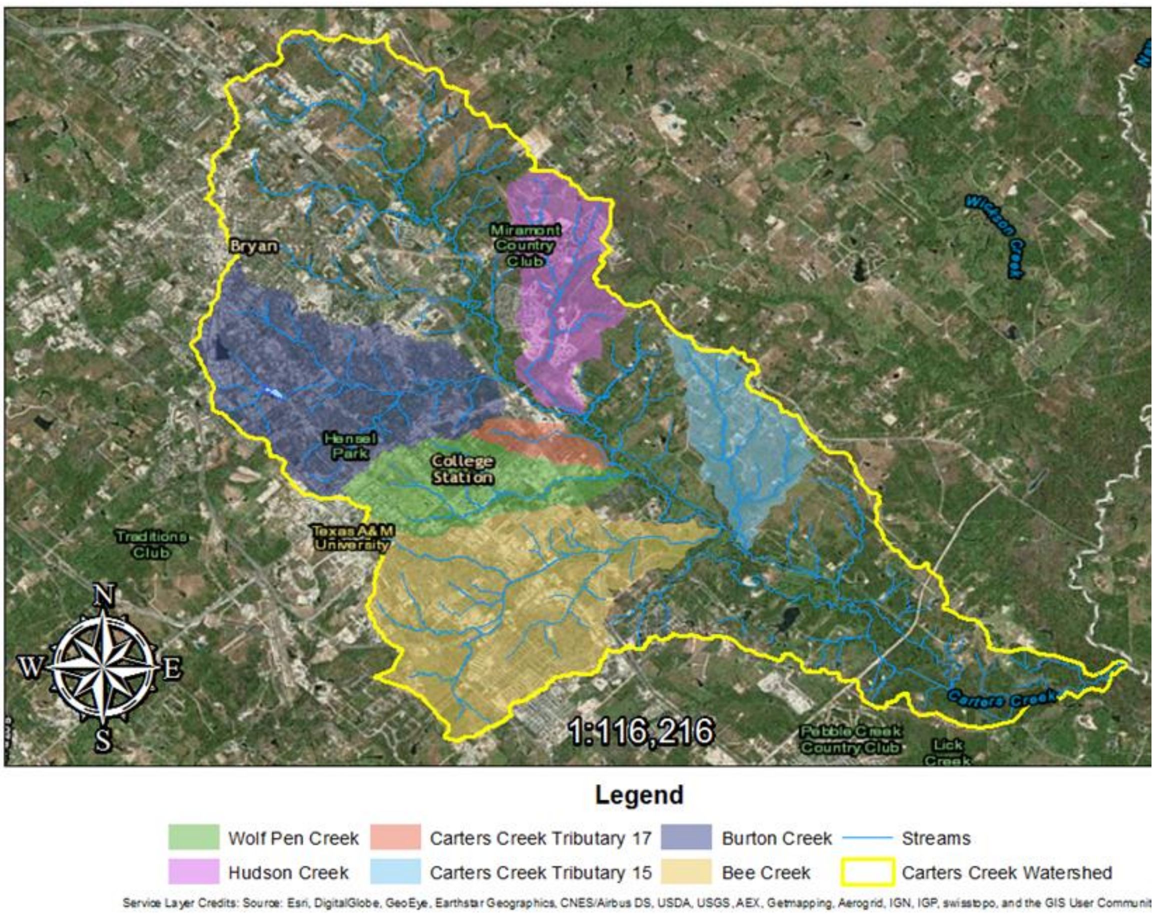

Figure 12. Sub-watersheds where intensive monitoring was completed

Sampling was attempted at a total of 69 sites across the selected sub-watersheds. Of these, 5 sites were not sampled due to lack of safe sampler access or water. *E. coli* concentrations in collected samples exhibited high variability across the watershed. Since sampling locations were selected based primarily on accessibility, the length of stream between sampling sites was divided by the difference in *E. coli* concentrations was used to find the areas with the greatest concentration increases. Areas with the most rapid rates of increase were sampled again in a subsequent round of sampling. Of the waterbodies sampled, two sections of Bee Creek and one of its tributaries; two reaches of Burton Creek and two of its tributaries; and two reaches of Wolf Pen Creek and two of its tributaries were found to have the highest rates of *E. coli* increase. Following the first round of sampling, GIS and watershed survey information were reviewed to provide information on potential *E. coli* sources which may contribute to the increases observed. These potential sources were noted and extra care was taken regarding observations during the second sampling. No obvious influences of these sources were noted; however, the entire reach of each stream segment was not surveyed.

Waterbodies exhibiting considerably larger increases in *E. coli* concentrations between sampling locations were noted during the first sampling event. Two reaches of Bee Creek and one of its tributaries; two reaches of Burton Creek and two of its tributaries; and two reaches of Wolf Pen Creek and two of its tributaries were found to have the highest rates of increase. These sites were further investigated during a second sampling event.

The second round of intensive sampling provided additional insight into the specific loading areas within the sampled reaches. As in the first round of sampling, the portion of Bee Creek immediately upstream of Texas Ave. exhibited rapid increases and decreases of *E. coli* concentrations. The most upstream portion of the creek that drains from Spence Park on the TAMU campus also exhibited a considerable increase in *E. coli* concentrations that were 2 – 3 orders of magnitude higher than the primary contact recreation standard. Several reaches within the Burton Creek watershed also showed considerable changes in *E. coli* concentration within short distances. The unnamed tributary of Burton Creek that flows from Country Club Lake across Villa Maria and Texas Ave showed a rapid increase in *E. coli* immediately upstream and downstream of Villa Maria before levels declined to near the primary contact recreation standard. In Burton Creek between Broadmoor Ave. and the downstream end of Tanglewood Park, *E. coli* also increased steadily before beginning to decline. In the Wolf Pen Creek watershed, the tributaries monitored contained the higher observed *E. coli* concentrations than the creek. These areas included the headwaters of a tributary that drain the Bonfire Memorial and an unnamed tributary that flows under Harvey Rd. from Thomas Park into the Wolf Pen Creek park greenway immediately upstream of George Bush Dr. East. A more detailed assessment of intensive monitoring results is available in Gregory et al. 2016b.

Discussion

Collection of *E. coli* data from routine, reconnaissance, stormflow and intensive monitoring indicate that bacteria levels in the Carters Creek watershed do not achieve water quality standards in most locations. Generally, the geometric mean of *E. coli* concentrations increases when moving from upstream to downstream (Figure 3) with a slight improvement observed between the last two stations (11785 and 21259). A number of monitoring stations do have significantly different median *E. coli* concentrations from other sites illustrating the presence of water quality differences across the watershed. Data collected during stormflow monitoring indicates that large rain events cause *E. coli* concentrations to increase to levels well above the Primary Contact Recreation set by TCEQ. This 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. LDC analyses conducted 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 while direct deposition, point and non-point sources all contribute to the observed water quality in downstream locations.

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. The lower density and relatively newer age of development (as compared to some other areas) are possible reasons why lower *E. coli* concentrations were observed in these areas. In portions of the watershed where development is denser 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). With the rate of land use change occurring in the watershed, this finding is not surprising.

Intensive sampling of the watershed revealed several stream segments where *E. coli* concentrations increased rapidly as compared to adjacent stream reaches. Observations made within these reaches and the presence of stormwater and wastewater infrastructure in the vicinity of these areas could potentially contribute to the observed increases; however, no concrete evidence to support this suggestion was found. Stormwater infrastructure seemingly contributed to the observed *E. coli* load in several locations. Insignificant volumes of water were present in these locations at the time of sampling and no runoff had occurred in more than two weeks; however, *E. coli* concentrations in their vicinity were still high. It is suspected that storm drains and the conveyance system may provide a suitable habitat for *E. coli* to survive in water or sediment as they have been found to in other watersheds around the world. Piping shields *E. coli* from direct sunlight and prevents the inactivation of cells through UV exposure. Additionally, stormwater infrastructure could also intercept wastewater leaking from a failing sewer line or from an illicit connection. One example of stormwater infrastructure being a suspected source of *E. coli* in the watershed is the Wolf Pen Creek tributary that is formed near the Bonfire Memorial. Water collected from this stormwater outfall had a considerably higher *E. coli* concentration than the adjacent site and downstream sites. The headwaters of Bee Creek also showed high *E. coli* concentrations where the stream drains out of Spence Park on the TAMU campus. In addition to storm water infrastructure, the ongoing renovations to Kyle Field (at the time of sampling) represent a potential influence on the elevated *E. coli* concentrations. Further sampling at this location now that the Kyle Field renovations are complete may illustrate different *E. coli* concentrations.

Waterbody shading may also influence *E. coli* concentrations observed in stream. In some cases, increases were observed where the stream flowed through predominantly shaded areas. Subsequently, when stream flowed into areas where there is limited or no shade and the stream is shallow, the *E. coli* levels begin to fall again. An example of a segment with extensive shade on the stream is the upper portion of Bee Creek between George Bush Dr. and Glade St. In this reach, *E. coli* concentrations increase rapidly before beginning to slowly decline. Other inputs of bacteria within this reach are possible and likely given the drastic increase in observed *E. coli* concentrations. Wastewater infrastructure is also a potential source at many of the observed segments; however, there was no evidence of leakage during sampling or stream surveys. Several locations had unpleasant odors, but it is unknown whether the source of these smells came from wastewater infrastructure or another source. Inspection by the appropriate wastewater personnel is recommended to further investigate potential sources *E. coli* sources in these segments.

After sampling data assessment and review, several areas should be considered for further investigation. City or TAMU personnel with knowledge of the potential sources of *E. coli* in these areas (stormwater or wastewater infrastructure) would be the ideal persons to perform these inspections as they may be able to identify problems that can be readily addressed. Also, if infrastructure smoke testing or camera inspections that are currently underway in the watershed could be applied in these areas, they too may be able to identify the underlying cause of the observed *E. coli* loading in these areas.

Summary

Efforts to improve knowledge regarding the spatial and temporal variation in *E. coli* concentrations across the Carters Creek watershed were evaluated throughout the course of this project. Water quality monitoring combined with a watershed survey and

GIS assessment improved information available and will allow watershed stakeholders to make informed decisions regarding future management to address *E. coli* loading across the watershed. Routine, reconnaissance, and storm monitoring completed over a two year period improved understanding of water quality in space and time across the watershed, but it did not provide sufficient information to pinpoint areas where significant *E. coli* loading occurred. Evaluation of watershed survey results and GIS data also provided some insight regarding potential sources of *E. coli* contributing to the watershed, but again failed to produce specific source area information. Combined, monitoring data and survey results did illustrate that some sub-watersheds have the potential to contain areas where *E. coli* concentrations increased considerably between sampling sites. Using this information, an intensive sampling campaign was planned and carried out to identify areas within selected stream segments where *E. coli* concentrations rapidly increased. Through this assessment, portions of Bee, Burton and Wolf Pen Creeks were found where measured *E. coli* concentrations increased quickly. As with other monitoring though, this sampling did not specifically identify the source of *E. coli* in these areas. Instead, areas where further investigation by entity personnel is needed were identified. Stormwater and wastewater infrastructure is present in the vicinity of these areas and should be inspected to see if they are contributing to the observed *E. coli* loads.

This project has provided many useful results that can be utilized by watershed stakeholders when planning management activities to improve local water quality. However, information included in this report is static and may already be irrelevant due to changes occurring daily across the watershed. Much of the watershed survey information documented transient water quality influences that move continually. Wild animals are the epitome of this while dogs are more readily managed. As a result, carrying out activities to address more readily managed source are likely to be most effective. Similarly, changes to watershed infrastructure are near continuous. New development is constantly extending the amount of stormwater and wastewater infrastructure in the watershed. Entities managing this infrastructure are also implementing programs to inspect or test and subsequently repair or replace infrastructure across the watershed. Thus it is very important for each entity in the watershed to utilize updated information when planning management activities in the watershed.

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