**Ozarks Environmental and Water Resources Institute (OEWRI)**
**Missouri State University (MSU)**

# Wastewater Indicators and Exfiltration Sources in Wilson Creek, Springfield, Missouri

## FINAL REPORT

**Prepared by:**

Marc R. Owen, M.S., Assistant Director
Teresa M. Carroll, Ph.D., Research Specialist
Robert T. Pavlowsky, Ph.D., Director

Field work completed by:
Nick Bradley, Ellie Bradley, Kayla Geier, Matt Thies, Nicole Weedman,
Josh Voss, and Joe Nash, Graduate Assistants

Laboratory work completed by
Megan Hente, Graduate Assistant and Kelly Rose, Undergraduate Research Assistant

Prepared for:
The City of Springfield
840 Boonville Ave.
Springfield, MO 65802

January 27, 2017

**OEWRI EDR-17-001**

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# EXECUTIVE SUMMARY

Wastewater infrastructure deterioration is common problem for many municipalities throughout the nation. Exfiltrating wastewater, or leakage from faulty systems can be a major source of contamination creating water quality problems in receiving streams, can pollute the groundwater, and pose health risks for people living in the surrounding community. Therefore, understanding how aging sewer lines are influencing local stream and identifying specific sources of sewer exfiltration is important for improving water quality in an urban area.

Wilson Creek in the City of Springfield, Missouri is listed on the 303(d) impaired water body list for bacterial contamination for consistently exceeding Missouri Department of Natural Resources water quality standards for Whole Body Contact Recreation (WBCR) Class-B designation of 206 MPN/100 mL (GAP, 2007). To better understand the influence of exfiltrating wastewater on Wilson Creek and to identify areas within the sewer system that may need maintenance, the City of Springfield, Missouri contracted with the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University to perform a pilot study to determine if water quality trends could be used to locate points of exfiltration of sewage from leaking sewer lines. The purpose of this study is to quantify variations in wastewater-specific indicators at base flow along a 5.7 km segment of Wilson Creek.

This study used analyses of closely-spaced field samples to rank and prioritize source points based on the degree to which water pollutants increased in concentration over upstream background levels at expected source locations. Of the six sewer crossings identified, two are considered very high risk for source pollution, three moderate risks, and one a low risk. Following this rationale, a preliminary comparison of average pollutant concentrations detected in the segment, including all samples, with approximate background levels suggests that exfiltration inputs have increased pollutant loads from 6-49% during base flow conditions in Wilson Creek. Therefore, repairing leaking pipelines may also help meet broader water quality goals for Springfield. However, more study of how fluctuations in exfiltration indicators relate to point and nonpoint loadings is needed.

## SCOPE AND OBJECTIVES

Sanitary sewer systems are constructed to transport wastewater from institutions, commercial facilities, residences, and industrial plants to treatment facilities. Infrastructure deterioration of these systems, however, is a common phenomenon for many municipalities throughout the U.S. (Amick and Burgess, 2000). Exfiltrating wastewater, or leakage from faulty systems can be a major source of groundwater contamination (Hornef, 1983; Bishop et al., 1998). Studies have reported sewer leakage rates can vary from 1 to 61 $m^3$/km/year and represent as much as 13% of collection volume of the plant during dry-weather flow days (Decker and Risse, 1993; Lerner *et al*., 1994; Ellis and Revitt, 2002; Fenz et al., 2005; Rutsch et al., 2008; Musolff et al., 2010). Several investigations have found that the impact of sewage exfiltration on urban groundwater is also highly variable. This is due to the fact that many wastewater constituents biodegrade while in the vadose or unsaturated zone (Vollertsen et al., 2002). This results in a greater risk potential for wastewater pollution on shallow groundwater stores, rather than in deep groundwater zones (Ellis & Revitt, 2002). However, sewage-derived pollutants have been detected from as much as 60 m below the surface due to fissured passageways in underlying aquifers (Dizer and Hagendorf, 1991; Morris et al., 2005). This puts groundwater stores in areas characterized by karst topography at high risk of contamination from wastewater inputs. This is concerning given that sewage exfiltrate often contains high levels of toxic compounds, pathogenic microorganisms, petroleum products, and nutrients (Amick and Burgess, 2000). These and other organic and inorganic pollutants create water quality problems in receiving streams, can be a major source of groundwater contamination, and subsequently pose health risks for people living in the surrounding community (Bishop et al., 1998). Therefore, understanding how aging sewer lines are influencing local stream and identifying specific sources of sewer exfiltration is important for improving water quality in an urban area.

There are several physical and biological parameters that can be considered as indicators of cumulative wastewater exfiltration. Chloride (Cl) is a good indicator of wastewater input, and is often used in conjunction with specific conductivity (SC) because SC is an indirect measure of the presence of dissolved solids such as salt, Cl, and other ionic solutes (Amick and Burgess, 2000; Huggins et al., 2005). Examination of the relationship between Cl and nitrogen is also instructive in exfiltration assessment because these parameters have been found to travel together as indicators of fecal pollution (Amick and Burgess, 2000). While nutrients such as total nitrogen (TN) and total phosphorous (TP) are found in relatively high concentrations in biological tissues and water, Cl is added to municipal water supplies during treatment. Phosphorous is also used as a fecal indicator because natural levels of phosphorus in surface waters are very low (0.01 mg/L) except in streams affected by human activity (Allen, 1999; Barr and Davis, 2010). Escherichia coli (*E. coli)* and total coliforms are commonly used indicators of the possible presence of sewage exfiltrate because it can be released directly into the stream via faulty underground wastewater collection systems (Tiefenthaler, Stein, and Lyon, 2009; Dove et al., 2015). Therefore extensive water quality monitoring of fecal indicators can be used to identify critical zones of exfiltration along an urban waterway (Sercu et al., 2011; Guérineau et al., 2014).

Wilson Creek drains the City of Springfield, Missouri and portions of unincorporated Greene County, is listed on the 303(d) impaired water body list for bacterial contamination for consistently exceeding Missouri Department of Natural Resources water quality standards for Whole Body Contact Recreation (WBCR) Class-B designation of 206 MPN/100 mL (GAP, 2007). Further, Wilson Creek and the James River located downstream are included in a total maximum daily load (TMDL) for nutrients; which can also be influenced by exfiltrating wastewater (MDNR 2001). To better understand the influence of exfiltrating wastewater on Wilson Creek and to identify areas within the sewer system that may need maintenance, the City of Springfield, Missouri contracted with the Ozarks Environmental and Water Resources Institute (OEWRI) at Missouri State University to perform a pilot study to determine if water quality trends could be used to locate points of exfiltration of sewage from leaking sewer lines. The purpose of this study is to quantify variations in wastewater-specific indicators at base flow along a 5.7 km segment of Wilson Creek beginning at the West Farm Road 150 going upstream to the confluence of Jordan and Fassnight Creeks.

The specific objectives of this assessment are to:

1. Use a rapid field-based screening protocol that collects information at closely spaced intervals using a multi-parameter probe to access the variability in temperature (T), SC, pH, dissolved oxygen (DO), and Cl to identify potential exfiltration locations.
2. Collect water quality grab samples to be analyzed in the laboratory for TP, TN, Cl, and *E. coli* concentrations at stream locations where initial screening indicated high concentrations of exfiltration indicators to verify and more clearly identify specific wastewater input locations,.
3. Make specific recommendations to the City of Springfield and its engineers regarding site prioritization based on results from this exfiltration risk assessment.

The procedures and approach described here can be used to develop ambient and site-specific sampling protocols for identifying possible exfiltration sites in Wilson Creek and other areas of the city to support continued targeted water quality monitoring.

## STUDY AREA

The Wilson Creek watershed drains approximately 218 $km^2$ of the central and western areas of the City of Springfield in Greene County flowing south to its confluence with the James River in Christian County (Figure 1). Wilson Creek is a fifth order stream that resides within the Ozark Plateau physiographic region of Missouri, and is a major tributary to the James River. This portion of Wilson Creek is within the 12-digit Hydrologic Unit Code (HUC) 110100020303S

(130.4 km$^2$) referred to as "Headwaters Wilson Creek". The underlying geology of the area is the Burlington-Keokuk limestone of Mississippian age within which is formed a karst landscape where sinkholes, losing streams, and springs are common (Vineyard and Feder, 1982). Limestone bluffs are also common where the stream meets the valley margin and bedrock is often exposed in the bed of the stream. Numerous facture zones in the bedrock create pathways for flow of groundwater and pollutants.

The study segment is 5.7 km long beginning at West Farm Road 150 (river kilometer (R-km) 0.0) upstream to the confluence of Jordan and Fassnight Creeks at R-km 5.7 (Figure 2). The North Branch of Wilson Creek enters the main channel between R-km 2.7 and 2.8 and is the only major tributary in the study segment. Wilson Creek has both losing and gaining sections within the study segment. Wilson Creek loses from R-km 0-2.5 and is a gaining stream from R-km 2.5-5.7. Additionally, all of the tributaries entering the main channel below R-km 3.0 are also classified as losing. The upstream land use is predominantly urban with some forest and pasture along the riparian cooridor within the study segment (Figure 3). There is a United States Geological Survey (USGS) gaging station, Wilsons Creek near Springfield (07052000) located at R-km 5.2 that has been in constituent operation since 1998 and is used to account for hydrological variability during the study (Table 1).

Floodplain soils along the study area are the Lanton silt loam at upstream sites and the Hunington Silt Loam further downstream with both having relatively deep accumulations of alluvium (Hughes, 1982). Both series consist of silty over bank deposits over buried channel deposits with 35-80% chert fragments. Both series are moderately permeable, but surface runoff is much slower in Lanton, indicating a greater proportion of clay in this soil. Terrace soils typically consist of a Hepler silt loam (upstream) and a Pembrook silt loam (downstream) that lie over weathered silty clay subsoils containing 5-55% chert fragments. These soils have high water capacity, but permeability is considerably lower in Hepler. Goss-Gasconade bluffs line the ridges along the stream in some locations.

## METHODS

### Source Risk Assessment & Infrastructure Identification

Prior to sampling, a source risk assessment was conducted to identify factors likely to contribute to exfiltration in this watershed such as: locations of sewage line crossings, inflowing tributaries, local springs, faults and other geologic features, soil types, and land use practices. This was accomplished by using geospatial data from online sources such as the USGS and Missouri Spatial Data Information Service (MSDIS). The City of Springfield provided the sewer infrastructure data required for this assessment.

**Field Sampling**

All sampling occurred during fair-weather, base flow conditions because both E.coli transport and storm water derived E. coli sources are highly variable at higher flows. Elevated levels under these conditions are indicative of a nearby upstream source whereas collection of samples during runoff events are more likely to be affected by dilution or transport from distant sources; making it difficult to determine points of origin (Dove et al., 2015). Field sampling events were conducted in summer 2016 on August 2nd, August 17th, and August 29th. Each monitoring event involved two teams with each team sampling half of the study segment between 11:00 am and 2:30 pm in the afternoon. Field workers walked upstream to ensure that each measure was taken above the previous sampling site. Care was taken to insure that bottom sediment was not disturbed during measurement collection or sampling.

In Situ Measurements

In situ field measurements of SC, pH, DO, Cl, and T were collected using a YSI multiprobe environmental meter (Pro Plus Model; YSI, Inc. Yellow Springs, OH, USA) (OEWRI, 2015). During the initial screening phase, a total of three measurements were collected at left, center, and right channel locations at each site to verify variability across the channel. Instrument accuracy was maintained by using the auto-calibration procedure before each sampling day and by re-conditioning and manually calibrating each sensor prior to each sampling day.

Water Sample Collection

Surface water grab samples were collected laboratory analysis of TP, TN, and Cl using 500 mL polypropylene (Nalgene$^{TM}$) open-mouth bottles (OEWRI, 2007a). Additional surface water grab samples were collected in pre-sterilized 100 mL bottles and analyzed for *E.coli* bacteria (OEWRI, 2013). Water quality samples were always collected in the thalweg. Water depths ranged from 0.07 m to greater than 1 m along the study segment. Sample bottles were triple rinsed with ambient water prior to sampling. Samples were collected by inverting the bottle to approximately 0.6 of the water depth and then turning up the opening to allow water to enter. Care was taken to insure that bottom sediment was not disturbed by sampling activity, and sampling occurred upstream of the technician. Upon collection, samples were transported on ice and delivered to the laboratory using chain of custody procedures (OEWRI, 2006). At the laboratory each 500 mL sample was split into two 250 mL samples. One 250 mL sample was preserved for nutrient analysis by adding 1 ml of concentrated sulfuric acid ($H_2SO_4$) to lower the pH below 2 standard units to stop all biological processes and preserve nutrient concentrations. The remaining 250 mL was used for Cl analysis and was not preserved. All samples were stored at ~ 4°C prior to further analysis.

Hydrological Monitoring

The USGS gaging station #07052000 located at R-km 5.2 was used to monitor flow conditions before and during sampling days. Hydrologic conditions were compared for both the previous year and over the entire day of record (17 years) at the gage using a flow duration curve. Additional, discharge measurements were collected at five locations along the study segment using a SonTek FlowTracker Acoustic Doppler velocity meter to verify downstream variability of flow (OEWRI 2007b). Flow data assisted in analysis and interpretation of the effects of losing/gaining flow and pollutant assimilation on water quality trends.

**Laboratory Analysis**

Sample processing and analysis was performed at OEWRI's Water Quality Laboratory located on the campus of Missouri State University. Surface water grab samples were analyzed for TN and TP using a Genesys 10S UV-Vis Spectrophotometer using EPA standard method 365.2 and methods outlined by Crumpton et al. (1992) (OEWRI 2010a, OEWRI 2010b). Laboratory Cl was measured using an Accumet Excel XL25 Dual Channel pH/Ion Meter (OEWRI, 2009). As determined by in-house QA/QC procedures, acceptable detection limits for these procedures are ≤ 0.1 mg/L TN, ≤ 0.005 mg/L TP, and 0.1 mg/L $Cl^-$ with all accuracy and precision checks within the range of + or – 20%. Samples were analyzed for the presence of *E. coli* using the IDEXX Colilert® and Quanti-Tray® method for detection and enumeration (OEWRI, 2013). The detection limit of this method is 1 MPN/100 mL with accuracy of + or – 20%. IDEXX MPN Generator 3.2 software was used for confirming MPN of sample results, as well as calculation of 95% confidence intervals.

**Quality Assurance/Quality Control**

Field duplicates and field blanks were collected for each batch for quality assurance (QA) and quality control (QC) purposes (OEWRI, 2007a). The duplicate sample was collected at different sampling sites each time. De-ionized (DI) water was transferred to a 500 ml sample bottle in the field for each blank. The field duplicates and field blanks were preserved and processed in the same manner as other samples. Following these field QA/QC protocols ensured that field equipment was free from contamination and that sample collection procedures accurately reflected actual field conditions. Laboratory quality control procedures included preparation of laboratory duplicates, reagent blanks, spiked samples, digestion efficiency checks and laboratory control checks. Field and laboratory duplicate samples were deemed acceptable if the relative percent difference (RPD) was less than 20 %.

Where:

$$RPD = \frac{|O - D| \times 100}{(O + D) / 2}$$

*O* = original sample
*D* = duplicate sample

Laboratory QA/QC also required the use of acid-cleaned sample bottles for all sample collection to avoid cross-contamination. Additionally, all sample bottles were labeled with date, event, site and project to ensure that proper laboratory results were attributed to the appropriate field site.

Field duplicate relative percent differences (RPD) for all in situ field measurements ranged from 0.0% to 13.3% among all parameters. This range was acceptable (< 20%) and indicated that sample collection procedures accurately reflected actual field conditions. Grab sample field blank values were reported as less than 1 mg/L or less than 1 MPN/100 mL. No *E.coli* colonies were detected in any of the blank samples. Field and lab duplicates RPD for TP, TN, Cl, and *E. coli* was 0.0% - 16.2% among each monitoring site and sampling date. The only exceptions to this were August 17th field duplicates for TN at R-km 1.8 and 2.8 which were 25.0% and 24.6%, respectively, and August 29th field duplicate for *E. coli* at R-km 2.5 which was 24.3%. All laboratory and quality control checks met acceptable performance standards. The results of the analysis of these QA/QC products show that laboratory results for nutrients, Cl and *E. coli* analysis (other than those mentioned above) could be accepted.

**Effect Magnitude Ratios of Sewage Source Indicators**

Sewage source indicators (SSI) used in this study include Cl, SC, TP, TN, and *E. coli* bacteria which have all been identified as constituents in wastewater that can be tracked in streams (Amick and Burgess, 2000; Huggins et al., 2005; Allen, 1999; Barr & Davis, 2010). Sewage Source Indicator levels were further quantified by calculating an Effect Ratio (ER) for individual peaks in SSI concentrations. Effect Ratios compared peaks in concentrations of SSI's to upstream background concentrations. These ratios defined the magnitude of the peak, distance (km) between predicted exfiltration source points, and the downstream peak was also evaluated. The combination of magnitude and distance can link all potential source points to SSI responses during each phase of the study.

## RESULTS AND DISCUSSION

**Source Assessment**

The source assessment identified a total of nine potential exfiltration source locations along the Wilson Creek study segment including six sewer crossings, a fault, and a major tributary. A mapped fault line crosses the stream at two locations, between R-km 2.2 and 2.3 and again at R-km 3.6 (Figure 4; Table 2). Sewer lines cross Wilson Creek at six points along the study segment, with a main line running down the valley near the midpoint of the study segment. Crossing points identified include: R-km 0.6, between R-km 2.0 and 2.1, between R-km 3.0 and 3.1, and at R-km 4.6, 5.4, and 5.6. Additionally, the North Branch tributary of Wilson Creek enters the study segment between R-km 2.7 and 2.8.

Permitted point source discharge locations in the Wilson Creek Watershed above the study segment were also identified. There were a total of eight permitted point sources within the upstream drainage area and the majority were classified as either "Non-Domestic Process Water" or "Noncontact Cooling Water" (Table 3). Most of the discharge sites are located from 2.8 km to 7.5 km upstream of the study sites and given the distance from the study site, we did not believe they would have an influence on the results of the pilot study (Figure 4). The exception to this was discharge site number 1 which is located at the most upstream sampling site (R-km 5.7). This company's discharge waste is non-contact cooling water discharged into a holding tank on property before being released into Jordan Creek and was not evaluated in this assessment.

**Hydrology**

Discharge records from the USGS gaging station indicated that the monitoring year was wetter than normal based on comparison of discharge records for water year 2016 versus the entire gage record. Examination of flow duration analysis showed a higher percentage of flow exceedance for sample data discharges for the 2016 water year compared to the 17 year gage record. For example the discharge during the August 2$^{nd}$ sample date was exceeded 60% of the time over the 2016 water year, but only 55% of the time over the entire gage record (Table 4). Similar exceedance differences were evident for discharge during the other two sampling dates on August 17th and August 29th. Additional downstream discharge measurements were collected and confirmed findings from an earlier report, that Wilson Creek loses at points between R-km 2.5 and 1.6 as discharge decreased between these two sites, but returned to upstream levels at points further downstream (EPA, 2011) (Table 5; Figure 2).

**Field Sampling**

A total of 271 in situ probe measurements and 174 water samples were collected along the Wilson Creek study segment in three sampling periods over course of the pilot study. The GPS coordinates and elevations of each study site are presented in Appendix A. Complete records for each sample site and date, including water quality parameters and concentrations of nutrients are included in Appendix B-D.

<u>Initial Field-Based Screening (August 2, 2016)</u>

For the initial screening assessment on August 2nd, in situ field measurements were collected every 100 m along the 5.7 km study reach. To better understand how T, SC, DO, pH, and Cl varied at a site, three readings were collected and the variability between readings was accessed. With the acceptation of DO, the average variability of the measured parameters was less than 1% across the channel. Average across channel variability for DO was still relatively low at 6.6%. Due to the lack of across channel variability, it was determined a single measurement in the thalweg was sufficient. Therefore, in subsequent sampling events a single reading was collected at each site. Additionally, in the discussion of the initial screening results below the average of the three readings was used to analyze trends.

For the initial screening phase, temperature, SC, and pH varied very little (less than 10%) among sites while DO and Cl had greater than 10% variability. Discharge at the USGS gage did not vary over the initial screening sampling period staying at 0.167 $m^3/s$ from 11:00 am to 2:00 pm, and 60% of all flows exceed that value in water year 2016 (Figure 5). Temperature readings ranged from 23.9 °C to 26.3 °C with an average of 25.2 °C and a coefficient of variation (cv% = standard deviation/mean x 100) of 2.5% (Table 6). The range in pH readings was 7.5 to 7.8 standard units with a mean of 7.6 standard units and a cv% of 1.0%. Specific conductivity values ranged from 448 µS/cm to 580 µS/cm with an average of 521 µS/cm for a cv% of 6.2%. Mean DO concentration was 7.4 mg/L with a range of 4.4 mg/L to 10.3 mg/L for a cv% of 15.4%. Chloride concentrations ranged from 48.8 mg/L to 73.0 mg/L with an average of 60.1 mg/L and a cv% of 13.0%. OEWRI performed tests on the city of Springfield's tap water on July 24, 2014. Results show that average Cl concentration is 23.8 mg/L, SC is 379 µS/cm, and pH is 7.3 standard units, which are lower than observed measurements in the stream. This suggests tap water from leaking water lines would actually dilute any sewer exfiltration signal found during sampling.

For the purposes of this study, SC and Cl are used as an indicator of sewer source indicator (SSI). Both SC and chloride exhibited a consistent pattern of decrease from upstream to downstream through the study segment (Figure 6). Average SC concentration was 556 µS/cm (range = 543-580 µS/cm) in the upstream quarter of study sites (n = 16) versus 473 µS/cm in the downstream quarter of study sites (range = 448-488 µS/cm), representing a downstream decrease of 132 µS/cm between the highest upstream and lowest downstream concentration. Chloride exhibited a similar pattern with a downstream decrease of 24 mg/L between the highest upstream and lowest downstream concentration. Average Cl concentration was 70.2 mg/L (range = 66.7-73.0 mg/L) in the upstream quarter of study sites, compared to 50.6 mg/L in the downstream quarter of study sites (range = 49.2-53.0 mg/L). Hence, Cl and SC were strongly correlated ($R = 0.94$) and both decreased significantly downstream ($p < 0.001$).

Similarly, fluctuations in these two parameters occurred at similar points along the Wilson Creek study segment. Both Cl and SC were highest approximately 200 m downstream of the two sewer crossings at R-km 5.4 and 5.6 with values of 71.9 mg/L and 561 µS/cm, respectively. Peaks in concentrations of both parameters were also recorded near the point where the North Branch tributary of Wilson Creek enters the study segment (R-km 2.8), and just downstream of the sewer main at R-km 3.1. Given the similarity in peak trends for SC and Cl and the downstream trend of decrease for both of these parameters, the entire 5.7 km segment was targeted for additional water quality sampling during the next phase of the study.

Water Quality Sampling (August 17, 2016)

A targeted water quality sampling assessment was conducted on August 17th where 29 in-situ field measurements were collected at pre-selected points along the study reach focusing on the critical zones identified in the screening phase. Discharge at the USGS gage did vary over this sampling period decreasing from 0.20 $m^3$/s at 11:00 am to 0.159 $m^3$/s at 2:00 pm indicating there was an unknown release of water upstream during sampling (Figure 7). Average discharge over the sampling period was 0.180 $m^3$/s and that flow was exceeded 57% of the time during water year 2016. However, variability among parameters was lower for this sampling than the initial screening. Specific conductivity values ranged from 477 µS/cm to 548 µS/cm with an average of 514 µS/cm for a cv% of 4.9% (Table 7). In situ chloride concentrations ranged from 52.2 mg/L to 63.3 mg/L with an average of 56.9 mg/L and a cv% of 5.6%. Summary statistics for T, pH, and DO for this sampling period are also shown in Table 7.

A total of 29 water quality samples were collected for the water quality sampling portion of this project in conjunction with the in situ measurements that included laboratory analysis of chloride, TN, TP, and *E. Coli*. Chloride concentrations were similar to the in-situ measurements ranging from 48.7-63.0 mg/L with a mean of 55.8 mg/L and a cv% of 5.7% (Table 7). The average TN concentration was 1.63 mg/L ranging from 1.46 to 2.09 mg/L with a cv% of 7.0%. Total phosphorous concentrations ranged from 0.027 to 0.062 mg/L with a mean of 0.034 mg/L and had higher variability with a cv% of 24.3%. Springfield's tap water had average TP and TN concentrations are 0.013 mg/L and 0.78 mg/L, respectively. Again, this suggests tap water from leaking water lines would actually dilute any sewer exfiltration signal found during sampling. The average E. coli concentration was 125 MPN/100 mL ranging from 26-378 MPN/100 mL among sampling sites with relatively high variability where the cv% was 72%.

Nutrients, Cl, and E. coli grab samples collected on August 17 provided further evidence for the locations of possible exfiltration risk sites along Wilson Creek. All predicted source points showed evidence of pollution from sewage exfiltration except the fault line at R-km 2.3 and the fault line at R-km 3.6. The most dramatic peaks in TP concentration (TP; 0.061 mg/L) occurred at R-km 5.2 just downstream of the sewer line crossings at R-km 5.4 and 5.6 as well as at the sewer crossing at R-km 0.6 (TP; 0.062 mg/L) (Figure 8). The effect ratio (ER) or magnitude of these peaks in TP concentration was two times that of upstream background concentrations (Table 9).

Elevated concentrations of Cl and TN were observed at similar points along the study segment. Peaks in Cl and TN levels were recorded just downstream of the sewer line crossings at R-km 5.4 and 5.6 (Cl: 60.5mg/L; TN: 1.77 mg/L), downstream of the sewer line crossing at R-km 4.6 (Cl: 57.6 mg/L; TN: 1.69 mg/L), and at the fault line at R-km 3.6 (Cl: 54.6mg/L; TN: 1.65 mg/L) (Figure 9). A relatively large peak in Cl concentration (60.9 mg/L), occurred at R-km 1.6, just downstream of the sewer crossing at R-km 2.1. The magnitude of each of these peaks in Cl concentration, however, was only slightly greater than that of the upstream background concentrations. The largest peak in TN concentration (2.09 mg/L) was at R-km 1.8 just below the sewer line at R-km 2.0. Concentrations at this site were 1.3 times higher compared to upstream concentrations. The most elevated Cl concentration (63.0 mg/L) was recorded at R-km 2.4, 300 m downstream of the North Branch, with an ER of 1.2.

E. coli concentrations increased steadily and significantly ($p < 0.001$) over the study segment. E. coli concentrations in 48% of sites sampled were at or above the 126 MPN/100mL (WBCR) Class A water quality criteria for the state of Missouri (MDNR, 2014, Figure 10). Of the 48% of sites above the 126 MPN/100mL Class A criteria, four were above the Class B criteria of 206 MPN/100mL. The four sites included two (R-km 5.4 and 5.2) at or just below the sewer crossings at R-km 5.4 and 5.6, as well as two sites just below the sewer crossing at 4.6 (R-km 4.2 and 4.4). Concentrations at this site were 2.0 times higher compared to upstream concentrations (Table 8). Sites that exceeded the Class A criterion, but not class B included the site at R-km 0.4 (just below the sewer line crossing at R-km 0.6), sites at R-km 2.6 and 2.8 at, or just below the North Branch and the sewer main at R-km 3.1, sites R-km 4.0 and 4.6 at or just downstream of the sewer crossing at R-km 4.6, and the site at R-km 4.8 downstream of the sewer crossing at R-km 5.4. Concentrations at R-km 2.6 and 2.8 were two times that of upstream concentrations. The peak at R-km 0.4 was five and a half times that of upstream concentrations.

Using the E.coli results, four sub-sections of the Wilson Creek study segment were designated for more targeted detailed sampling (Figure 10). Sub-section I captured the area of peak upstream and downstream of the sewer line crossing at R-km 0.6. Sub-section II captured the area surrounding the peak in E. coli concentration surrounding the main sewer line crossing between R-km 3.0 and 3.1, and sub-section III addressed risk areas around sewer crossings further upstream (5.4 and 5.6). Sub-section IV was added to address the plateau seen in between sub-sections I and II.

<u>Targeted Water Quality Sampling (August 29, 2016)</u>
For the targeted water quality assessment, 48 in situ field measurements were collected every 100 m along the study reach downstream of the 4 sub-sections designated in the water quality sampling phase on August 17$^{th}$. Sampling was again completed between 11:00 am and 2:00 pm and discharge at the USGS gage did not vary over the sampling period staying at 0.09 $m^3/s$ over that time, which was exceeded 87% of the time in water year 2016 (Figure 11). Specific conductivity values were elevated compared to the previous two sampling periods ranging from 585 µS/cm to 640 µS/cm with an average of 611 µS/cm for a cv% of 2.9% (Table 9). However, in situ Cl concentrations were similar to previous sampling periods ranging from 54.4 mg/L to 67.4 mg/L with an average of 60.2 mg/L and a cv% of 6.1%. Summary statistics for T, pH, and DO for this sampling period are also shown in Table 9.

A total of 48 water quality samples were collected for laboratory analysis during the targeted sampling phase of this project in conjunction with the in situ measurements. Laboratory analyzed Cl concentrations were again similar to the in-situ measurements ranging from 51.4 mg/L to 69.7 mg/L with a mean of 60.9 mg/L and a cv% of 6.7% (Table 9). The average TN concentration was 1.33 mg/L ranging from 1.04 mg/L to 1.55 mg/L with a cv% of 6.0%. Total phosphorous concentrations ranged from 0.023 mg/L to 0.071 mg/L with a mean of 0.033 mg/L and had higher variability with a cv% of 28.4%. The average E. coli concentration was 225 MPN/100 mL ranging from 80-1,011 MPN/100 mL among sampling sites with relatively high variability where the cv% was 76.7%.

All predicted source points showed evidence of pollution from sewage exfiltration. Total phosphorous concentration (TP; 0.052 mg/L) at the fault line at R-km 2.3 was two times greater than it had been on August 17th (Figure 12). Similarly, high levels of TP occurred at R-km 5.0 (0.062 mg/L) just downstream of the sewer crossing at R-km 5.4, and 4.3 (0.071 mg/L) downstream of the sewer crossing at 4.6. These concentrations were 4 and 5 times greater, respectively, than they had been on the August 17th sampling day. The ER for these peaks in TP concentration were two times greater than that of upstream background concentrations (Table 10). Another peak in TP concentration was recorded at the sewer line crossing at R-km 0.6, but the ER was lower (1.4).

Sites with elevated TN and Cl levels were similar to those of the previous sampling day and included sites at R-km 5.5 and R-km 5.4 (TN: 1.45 mg/L; Cl: 66.2 mg/L), located at or just downstream of the sewer crossing at 5.6 and 5.4 (Figure 13). Both TN and Cl were highest at R-km 5.0 (TN: 1.55 mg/L; Cl: 69.7 mg/L), downstream of the sewer crossing at R-km 5.4. Other much less sizable peaks in TN and Cl levels were recorded at R-km 2.6, and 2.8 downstream of the North Branch confluence. From that point downstream concentrations in both parameters decreased substantially. The magnitude of these concentrations, however, was only slightly greater than that of the upstream background concentration (1.1) and none exceeded 1.2 (Table 10).

E.coli concentrations among sampling sites between the second and third sampling day increased, on average, by 58%. Of the 48 sites, 85% of them had E. coli concentrations that exceeded the WBCR-Class A criterion of 126 MPN/100 mL (Figure 14). Of those sites, 37% had concentrations above the WBCR-Class B criterion of 206 MPN/100 mL. The E. coli concentrations of 27% of those sites exceeded 400 MPN/100mL. The largest peak in E. coli (1,011.3 MPN/100 mL) was at the sewer main line crossing at R-km 3.1. Concentrations at this site were 6.4 times greater than upstream concentrations (Table 10). At R-km 2.9, just downstream of the sewer crossing at R-km 3.1, concentrations were 2.6 times higher than upstream concentrations. The site at R-km 2.2, located just downstream of the fault line at R-km 2.3 and the site at R-km 3.2, just downstream of the fault line at R-km 3.6, had E. coli levels that exceeded 650 MPN/100 mL, with ER of 3.0 and 4.2, respectively. E. coli concentration at R-km 2.7, just downstream of the North Branch confluence, was 436 MPN/100mL; two times greater than values upstream. Other sites, just downstream of the North Branch that exhibited elevated E.coli levels were at R-km 2.6, 2.4, and 2.3 with ER's of 1.7, 1.2, and 1.2, respectively. Other peaks of substantial magnitude occurred at R-km 5.5 and 5.1 (downstream of the sewer crossing at R-km 5.4 and 5.6), and at R-km 4.3, 300 m downstream of the sewer line at R-km 4.6. E. coli concentrations at these sites were approximately 1.2, 1.6, and 1.5 times greater than upstream, respectively. E.coli levels at R-km 0.2 (downstream of the sewer crossing at R-km 0.6) were 2.2 times greater than upstream concentrations. E. coli levels at R-km 3.2, 3.1, and 2.2 exceeded August 17$^{th}$ sample levels for the same sites by 8-22%.

Decreased stream discharge on this sampling day could have contributed to the increase in bacteria levels due to less dilution due to low flow conditions. This is consistent with others who have shown that bacteria levels are often higher in natural streams during lower flow conditions (Tiefenthaler et al., 2009). The magnitude of increase in E. coli concentrations at potential source points supports the notion that the decrease in discharge limited bacterial transport downstream resulting in elevated E. coli concentrations at sites very near active sewage leaks (Dove et al., 2015). This is evidenced by the fact that the distance between peaks in E. coli concentrations and predicted source points was 0 for the three sites with the highest concentrations.

<u>E. coli Geometric Means for Aug. 17th and Aug 29th Sampling Dates</u>

The MDNR Methodology for 303(d) listing in Missouri recommends using a geometric mean to compute a measure of central tendency for each sampling site (MDNR 2014). This analysis allows for a comparison of results between sampling dates and confirmed that all of the potential source points showed evidence of possible pollution from sewage exfiltration except the fault line between R-km 2.2 and 2.3 (Figure 15). The highest geometric mean E. coli concentration was 392 MPN/100 mL at the R-km 5.4 sewer crossing which is also 200 m downstream of the sewer crossing at R-km 5.6. Additional analysis of geometric means showed that E. coli values exhibited a significant ($p = < 0.001$) decreasing downstream trend. Geometric means (GM) were further analyzed by calculating Effect Ratios for each of the sites with elevated GM E. coli concentrations. As illustrated in Figure 15, GM E. coli concentrations at each site were greater than 1.2 and concentrations at sites at R-km 2.7 and 2.8 (at the North Branch confluence), and 5.4 (located at below the sewer crossings at R-km 5.4 and 5.6) were two times greater than upstream concentrations.

**Effect Magnitude Ratios**

Consistent with the observations of others, *E. coli* appeared to be the strongest SSI given that ER values were consistently greater than 2.2 at nearly all potential source points during both the August 17$^{th}$ and August 29$^{th}$ sampling periods (Edberg et al., 2000). The only source point where this pattern was variable was the fault lines at R-km 2.2 and 3.6. August 17th *E. coli* analysis indicated that there was no evidence of sewage exfiltration at sites below either of these fault lines. August 29th analysis, however, showed that *E. coli* concentrations were three times higher downstream of the fault at R-km 2.0, and 4.2 times higher downstream of the fault at R-km 3.6 compared to upstream concentrations. This could be because higher discharge on the August 17th sampling date could have had a dilution effect on *E. coli* concentrations and discharge on August 29th was considerably lower. Furthermore, pollution from exfiltration sources may travel for some distance through the groundwater below the bed before coming to the surface during higher base flow. The reliability of the ER method of quantification appeared to be high for TP as well. For example, effect ratios for TP among August 17th and August 29th sampling days occurred at similar potential exfiltration source points (sewer crossings at R-km 0.6, 5.4, and 5.6) and were of similar magnitudes 1.4 to 2.4 (Table 8 and 10). The ER analysis for TN and Cl suggests that they are weaker SSI than TP or *E.coli* as effect ratios for TN and Cl were 1.2 or higher at only one potential source point on the August 17th sampling date, and never greater than 1.1 at any potential source point on the August 29th sampling date. This was while ER for *E. coli* on the August 29th sampling date were greater than 1.2 at all potential source points.

**Classification of Exfiltration Risk**

Consequently, we used TP and *E. coli* results to classify each of the potential source points as being a *very high, high, moderate, or low* sewage exfiltration risk source point. Very high exfiltration-risk source points included the sewer crossings at R-km 3.1 and 0.6 (Table 11 and Figure 16). These potential source points had high *E. coli* concentrations with ERs greater than 5.0. The fault lines at R-km 2.3 and 3.6 are classified as high risk having ER vales at or above 3.0 for E. Coli. This suggests sewer exfiltration (or other pollution source) may also be entering the stream via karst pathways from areas other than adjacent to the stream. A better understanding of the base flow hydrology (losing vs. gaining) at these locations and perhaps dye tracing would help better understand faults as a potential pollution source. The sewer line crossings at 4.6, 5.4, and 5.6 are classified as moderate risk sources, with ER values of 2.0 to 3.0 for TP and E. Coli. The North Branch at R-km 2.8 is also a moderate risk site. E. Coli ER for this site is between 2.0 and 3.0. The sewer line crossing at R-km 2.1 is a low exfiltration risk sites with an E.Coli ER value of 1.4.

**Suggestions for Further Study**

Several suggestions are presented here to help improve the design of future studies:

1. Site and reach-scale variability in *E. Coli* and TP concentrations needs to be better understood. Results from this study indicate that the best parameters for exfiltration assessment are TP and *E. coli*. However, only one sample or measurement for each parameter was taken from the thalweg at each study site. Future assessments would benefit

from taking replicate samples at each site. This would strengthen the validity of the data analysis.

2. Since sewage leachate should be able to be identified through trends in T, SC, Cl and DO, and because these water quality parameters were informative during the initial field survey, it is recommended that *in-situ* measures of these parameters continue to be taken in conjunction with SSI grab samples of TP and *E coli.* (Tiefenthaler et al., 2009).

3. Improve the understanding that an important limitation of *E. coli* is that it is not human specific (Sercu et al., 2011). Several studies have used alternative approaches to discern between human and non-human sources of *E. coli.* One such method is to pair *E. coli* monitoring with assessment of specific wastewater micropollutants such as caffeine (Gue´rineau, et al., 2014). This would be an advantageous line of study that could confirm that bacterial findings were from human rather than animal sources.

4. It is likely the sewer lines identified in this study are not leaking right at the stream crossing since the crossings are below the water table. It is more likely that the exfiltration is occurring at more elevated points in the sewage lines such as service laterals or other junctions which may exist above groundwater tables, at or near these stream crossings. Therefore, examination of the sewer system at and near high risk sites identified in this study would be required.

## CONCLUSIONS

The purpose of this study was to monitor a 5.7 km reach of Wilson Creek and determine if water quality trends could be used to locate points of exfiltration of sewage from leaking sewer lines so they could be repaired and ultimately improve water quality. A total of 271 probe measurements and 174 water samples were collected and analyzed over three sampling dates in August for this study. In situ measurements by multi-parameter probe collected measurements of T, pH, SC, DO, and Cl during all three sampling dates. Surface water grab samples were collected only during the second and third sampling dates and analyzed in the laboratory for TP, TN, Cl, and *E. coli* concentrations. The source assessment identified a total of nine potential source locations along the Wilson Creek study segment including six sewer crossings, a fault (2), and a major tributary (1). All potential source points showed evidence of possible pollution from sewage exfiltration at variable classifications of risk (major, moderate, minor). Specific locations identified by this study are detailed here:

1. **The sewer crossings at R-km 3.1 and 0.6 represent very high exfiltration risk sites where ER values greater than 5.0 for E. Coli.** During August 29th sampling, the highest peak *in*

*E. coli* concentration was at R-km 3.1 with a magnitude 6.4 times that recorded upstream During the August 17th sample date, the highest effect ratio for *E. coli* compared to upstream concentrations (5.5) was recorded at R-km 0.4. These were the highest ER values for this study.

2. **The fault line crossings at R-km 2.2 and 3.6 are classified as high exfiltration risk sites as ER values are at or above 3.0 for E. Coli.** This suggests sewer exfiltration (or other pollution source) may also be entering the stream via karst pathways from areas other than adjacent to the stream. A better understanding of the base flow hydrology (losing vs. gaining) at these locations and perhaps dye tracing would help better understand faults as a potential pollution source.

3. **The sewer line crossings at R-km 4.6, 5.4, and 5.6 are moderate exfiltration risk sites with ER values greater than 2.0 for E. Coli and TP.**
   While theses upstream sites have high raw concentrations of E. Coli, ER values are moderate due to higher upstream concentrations. Upstream influences from Fassnight or Jordan Creeks could also be contributing to the problems in these upper reaches of the study segment. These two tributaries enter Wilson Creek just above R-km 5.7, and have a long history of water quality degradation from a variety of point and nonpoint pollution sources associated with urban development (Richards and Johnson, 2002; Miller, 2006; Hutchinson, 2010).

4. **The North Branch of Wilson Creek at R-km 2.8 is also classified as moderate, with an E. Coli ER value greater than 2.0.** During August 29th sampling, peaks in *E. coli* concentrations occurred at R-km 2.8 (184 MPN/100 mL) and 2.6 (156 MPN/100 mL). The ER for both concentrations was than 2.0 to 2.3 times greater than recorded upstream.

5. **The sewer crossing at R-km 2.1 is considered a low exfiltration risk site with an ER value of less than 2.0 for E. Coli.** Small peaks in *E. coli* concentrations occurred at this site during the August $17^{th}$ sampling periods, but the ER was lower than the other sites and no ER was detected on August 29th.

Overall, this protocol has proven useful for identifying exfiltration leaks at expected source points as well as providing a better understanding of the effects of sewer exfiltration on base flow water quality in Wilson Creek. As found in other studies, TP and E. Coli were most useful in identifying source locations (Allen 1999; Barr and Davis 2010; Tiefenthaler, Stein, and Lyon 2009; Dove et al. 2015). However, TN and Cl also indicated exfiltration effects in Wilson Creek. Ultimately, this study used analyses of closely-spaced field samples to rank and prioritize source points based on the degree to which water pollutants increased in concentration over upstream background levels at expected source locations. Following this rationale, a preliminary comparison of average pollutant concentrations detected in the segment, including all samples, with approximate background levels suggests that exfiltration inputs have increased the loads of TP by 6%, TN by 8%, Cl by 8%, and E. Coli by 49% during base flow conditions in Wilson Creek. Therefore, repairing leaking pipelines may also help meet broader water quality goals for Springfield. However, more study of how fluctuations in exfiltration indicators relate to point and nonpoint loadings is needed.

## REFERENCES


Allan, J. D., 1999. Stream Ecology. Structure and Function of Running Waters. Kluwer Academic Publishers, Dordrecht.

Amick, R. S. and E. H. Burgess, 2000. Exfiltration in Sewer Systems. National Risk Management Research Laboratory. Office of Research and Development. U.S. Environmental Protection Agency. Cincinnati, OH. EPA/600/R-01/034.

Barr, M. N. & J. V. Davis, 2010. Surface-Water Quality Conditions and Long-Term Trends at Selected Sites within the Ambient Water-Quality Monitoring Network in Missouri, Water Years 1993–2008. Scientific Investigations Report 2010–5078 U.S. Geological Survey, Reston, Virginia: 2010 52 PP.

Bishop, P.K., B.D. Misstear, M. White, and N.J. Harding, 1998. Impacts of Sewers on Groundwater Quality. CIWEM 12, 216–223.

Crumpton, W.G., T.M. Isenhart, and P.D. Mitchell, 1992. Nitrate and Organic N Analysis with Second-Derivative Spectroscopy. Limnol. Oceanogr., 37(4), 907-913.

Decker, J and A. Risse, 1993. Investigations about quantitative and qualitative pollution load of subsoil, ground and surface water by leaking sewers. Marsalek, J and Torno, H (Edits): Proc 6th Int. Conf., Urban Storm Drainage, Seapoint Publishing, Victoria, British Columbia, Canada.

Dizer, H., and U. Hagendorf. 1991. Microbial contamination as an indicator of sewer leakage. Water Res. 25 (7), 791–796.

Dove, E., J. Denlinger, and A. Leipard, 2015. Technical Memorandum; Line Creek Phase II Water Quality Sampling. HDR, Inc. 17 pp.

Edberg, S.C., E. W. Rice, R. J. Karlin, and M. J. Allen, 2000. *Escherichia coli*: The Best Biological Drinking Water Indicator for Public Health Protection. J. Appl. Microbiol. 88, 106S-116S.

Ellis, J.B. and D.M. Revitt, 2002. Sewer losses and interactions with groundwater quality. Water Sci. Technol. 45 (3), 195–202.

Ellis, J.B., 2001. Sewer Infiltration/exfiltration and Interactions with Sewer Flows and Groundwater Quality. Conference Proceedings, Interactions Between Sewers, Treatment Plants and Receiving Water in Urban Areas - Interurba II, Lisbon, Portugal, 311-319.

Fenz, R., A. P. Blaschke, M. Clara, H. Kroiss, D. Mascher, and M. Zessner, 2005. Quantification of Sewer Exfiltration Using the Anti-epileptic Drug Carbamazepine as Marker Species for Wastewater. Water Sci. Technol. 52 (9), 209-217.

Gue´rineau, H., S. Dorner, A. Carrie`re, N. McQuaid, S. Sauve´, K. Aboulfadl, M. Hajj-Mohamad, M. Pre´vost , 2014. Source tracking of leaky sewers: A novel approach combining fecal indicators in water and sediments Water Research 58: 50-61.

Hornef, H., 1983. Menaces to the quality of groundwater due to leaky public sewers and house drainage systems. Korrespondenz Abwasser 12/83, 896–903.

Huggins, D.G., R.C. Everhart, D.S. Baker, and R.H. Hagen, 2005. Water Quality Analysis for the Heartland Inventory and Monitoring network (HTLN) of the US National Park Service: Ozark national Scenic Riverways. Central Plains Center for BioAssessment, Kansas Biological Survey, University of Kansas, 40 pp.

Hughes, H.E., 1982. Soil Survey of Greene and Lawrence Counties, Missouri. Washington D.C.: U.S. Government Printing Office, U.S. Department of Agriculture, Soil Conservation Service.

Hutchison, E.C.D., 2010. Mass Transport of Suspended Sediment, Dissolved Solids, Nutrients, and Anions in the James River, SW Missouri. Unpublished Masters Thesis, Department of Geography, Geology, and Planning, Missouri State University.

Lerner, D.N., D. Halliday, and J. Hoffman, 1994. The impact of sewers on groundwater quality. 64 – 75 in Wilkinson, W.B (Edit): Groundwater Problems in Urban Areas. Thomas Telford Ltd., London.

Madigan M. T., J.M. Martinko, and J. Parker, 2000. Brock biology of microorganisms, p 135–162. Prentice-Hall, Upper Saddle River, NJ.

MEC Water Resources, Inc. and Ozarks Environmental Water Resources Institute, 2007. Southwest Missouri Water Quality Improvement Project (WQIP) James River Basin Water Quality Gap Analysis.

Miller, R.B., 2006. Nutrient Loads in an Urban Ozark Watershed: Jordan, Fassnight and Upper Wilson Creeks, Springfield, Missouri. Unpublished Masters Thesis, Department of Geography, Geology, and Planning, Missouri State University.

Missouri Department of Natural Resources (MDNR), 2014. The Code of State Regulations (CSR); Division 20, Clean Water Commission. Chapter 7-Water Quality, pp 1-47.

Morris, B.L., J. Rueedi, A.A. Cronin, and E.J. Whitehead, 2005. Case Study City Doncaster: Field Investigations Final Report, AISUWRS D10-Workpackage 4.

Musolff, A., S. Leschik, F. Reinstorf, G. Strauch, and M. Schirmer, 2010. Micropollutant Loads in the Urban Water Cycle. Environ. Sci. Technol. 44 (13), 4877-4883.

OEWRI, 2015. Standard Operating Procedure for: The Measurement of Dissolved Oxygen, Temperature, Specific Conductance, pH, and Chloride using the YSI Professional Plus Handheld Multiparameter Meter. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2013. Standard Operating Procedure for: The Measurement of Escherichia coli and Total Coliform using the IDEXX Quanti-Tray/2000 System with Colilert reagent. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2010a. Standard Operating Procedure for: Total Nitrogen Analyses using Genesys 10S UV-Vis. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2010b. Standard Operating Procedure for: Total Phosphorus Analyses using Genesys 10S UV-Vis. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2009. Standard Operating Procedure for: Accumet Excel XL25 Dual Channel pH/Ion Meter for Chloride Concentration Determination. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2007a. Standard Operating Procedure for: Water Sample Collection. Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2007b. Standard Operating Procedure for: Operation of the SonTek/YSI FlowTracker

Handheld ADV (Acoustic Doppler Velocimeter). Ozarks Environmental and Water Resources Institute, Missouri State University.

OEWRI, 2006. Standard Operating Procedure for: Chain of Custody. Ozarks Environmental and Water Resources Institute, Missouri State University.

Richards, J. M. and B. T. Johnson, 2002. Water Quality, Selected Chemical Characteristics, and Toxicity of Base Flow and Urban Stormwater in the Pearson Creek and Wilsons Creek Basins, Greene County, Missouri, August 1999 to August 2000. Water-Resources Investigations Report 02-4124, United States Geological Survey.

Rodgers, W.E., 2005. Mercury Contamination of Channel and Floodplain Sediments in Wilson Creek Watershed, Southwest Missouri. Unpublished Masters Thesis, Missouri State University.

Rutsch, M., J. Rieckermann, J. Cullmann, J. B. Ellis, J. Vollertsen, and P. Krebs, 2008. Towards a Better Understanding of Sewer Exfiltration. Water Res. 42 (10-11), 2385-2394.

Sercu, B., L.C. Van De Werfhorst, J.L.S. Murray, and P.A.Holden, 2011. Sewage exfiltration as a source of storm drain contamination during dry weather in urban watersheds. Environ. Sci. Technol. 45 (17), 7151-7157.

Tiefenthaler, L.L, E.D. Stein, G.S. Lyon, 2009. Fecal indicator bacteria (FIB) levels during dry weather from Southern California reference streams. Environ Monit Assess (2009) 155:477–492.

Thomson, K. C. (1986). *Geology of Greene County, Missouri*. Watershed Management Coordinating Committee. Springfield, Missouri.

United States Environmental Protection Agency (USEPA), 2011. Total Maximum Daily Load (TMDL) For Wilson and Jordan Creeks (MO — 2375 and 3374) Christian and Greene Counties, Missouri.

Vineyard, J.D. and G.L. Feder, 1982. Springs of Missouri. Division of Geology and Land Survey, Missouri Department of Natural Resources in cooperation with the United States Geological Survey and Missouri Department of Conservation.

Vollertsen, J., Hvitved-Jacobsen, T., 2003. Exfiltration from gravity sewers: a pilot scale study. Water Sci. Technol. 47 (4), 69–76.

## TABLES

Table 1. Drainage area and discharge at USGS gaging station (R-km 5.2).

| USGS Gage ID # | Description | Period of Record | Drainage Area | Annual Mean Discharge For Period of Record | Annual Mean Discharge For WY 2016 |
|---|---|---|---|---|---|
| 07052000 | Wilson Creek at Springfield, MO | May 1932 to Nov. 1939, June 1973 to Sept. 1977, June 1998 to present | 17.8 $mi^2$ (46.1 $km^2$) | 19.2 $ft^3/s$ (0.54 $m^3/s$) | 23.1 $ft^3/s$ (0.65 $m^3/s$) |

Table 2. Potential exfiltration source points along the Wilson Creek 5.7 km study segment.

| Potential Source Point (R-km) | Type |
|---|---|
| 0.6 | Sewer line |
| 2.1 | Sewer line |
| 2.3 | Fault |
| 2.8 | North Branch Wilson Creek |
| 3.1 | Sewer line |
| 3.6 | Fault |
| 4.6 | Sewer line |
| 5.4 | Sewer line |
| 5.6 | Sewer line |

Table 3. Permitted Discharges for Wilson Creek watershed.

| Site Number | Facility Name | Easting (m)* | Northing (m)* | Type | Stream | Waste | Status | Approx. Distance Upstream (km) |
|---|---|---|---|---|---|---|---|---|
| 1 | Euticals, Inc. | 470,971.23 | 4,115,670.39 | Outfall | Jordan Creek | Noncontact Cooling Water | Expired | 0.0 |
| 2 | PAUL MUELLER COMPANY | 471,910.06 | 4,118,440.68 | Storm Water Outfall | Tributary of Jordan Creek | Nonprocess | Expired | 3.5 |
| 3 | Ozarks Regional YMCA | 474,262.93 | 4,118,161.90 | Outfall | Tributary of Jordan Creek | Non-Domestic Process Water | Effective | 5.0 |
| 4 | Kraft Foods Global | 477,197.80 | 4,116,085.65 | Outfall | Tributary of Fassnight Creek | Non-Domestic Process Water | Expired | 7.5 |
| 5 | Kraft Foods Global | 477,187.85 | 4,116,048.73 | Storm Water Outfall | Tributary of Fassnight Creek | Noncontact Cooling Water | Expired | 7.5 |
| 6 | Sherman Street Plant | 475,057.00 | 4,118,518.00 | Outfall | S. Branch Jordan Creek | Non-Domes Process/Incidental Stormwater | Effective | 5.6 |
| 7 | Sherman Street Plant | 475,177.00 | 4,118,548.00 | Outfall | S. Branch Jordan Creek | Storm water/incidental non-domes process | Effective | 5.7 |
| 8 | Conco Companies | 468,844.00 | 4,118,985.00 | Outfall | N. Branch Wilsons Creek | Non-Domes Process/Incidental Stormwater | Effective | 2.8 |

* coordinate system UTM NAD83 Zone 15 North

Table 4. Flow duration percentages for sampling date discharge from gage records.

| Monitoring Date | Mean Sample Discharge ($m^3/s$) | Daily Mean Discharge Percent Exceedance for 2016 | Daily Mean Discharge Percent Exceedance 17 Year Gage Record |
|---|---|---|---|
| August 2, 2016 | 0.16 | 60% | 54% |
| August 17, 2016 | 0.14 | 57% | 51% |
| August 29, 2016 | 0.09 | 87% | 82% |

Table 5. Record of downstream variability in discharge on August 30, 2016.

| R-km | Discharge ($m^3/s$) | Time (CST) |
|---|---|---|
| 0.4 | 0.09 | 15:10:13 |
| 1.6 | 0.06 | 16:22:07 |
| 2.9 | 0.08 | 14:02:52 |
| 4.4 | 0.08 | 15:11:35 |
| 5.2 | 0.07 | 17:47:13 |

Table 6. Summary statistics for August 2, 2016 in-situ field measurements.

| | Temp (°C) | pH (std.) | SC (µS/cm) | DO (mg/L) | Cl (mg/L) |
|---|---|---|---|---|---|
| n | 58 | 58 | 58 | 58 | 58 |
| Mean | 25.2 | 7.6 | 521 | 7.4 | 60.1 |
| Median | 25.2 | 7.6 | 529 | 7.5 | 58.8 |
| Min | 23.9 | 7.5 | 448 | 4.4 | 48.8 |
| Max | 26.3 | 7.8 | 580 | 10.3 | 73.0 |
| SD | 0.6 | 0.1 | 32 | 1.1 | 7.8 |
| CV% | 2.5 | 1.0 | 6.2 | 15.4 | 13.0 |

Table 7. Summary statistics for August 17, 2016 sampling

| | Temp (°C) | pH (std.) | SC (µS/cm) | DO (mg/L) | Cl (mg/L) | Cl (mg/L) | TN (mg/L) | TP (mg/L) | *E. coli* (MPN) |
|---|---|---|---|---|---|---|---|---|---|
| Method | In-situ | | | | | Laboratory | | | |
| n | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 | 29 |
| Mean | 22.7 | 7.8 | 514 | 8.0 | 56.9 | 55.8 | 1.63 | 0.034 | 125 |
| Median | 22.7 | 7.7 | 525 | 7.9 | 56.6 | 56.0 | 1.59 | 0.032 | 101 |
| Min | 22.0 | 7.6 | 477 | 7.1 | 52.2 | 48.7 | 1.46 | 0.027 | 26 |
| Max | 23.8 | 7.9 | 548 | 8.9 | 63.3 | 63.0 | 2.09 | 0.062 | 378 |
| SD | 0.4 | 0.1 | 25 | 0.5 | 3.2 | 3.1 | 0.11 | 0.008 | 91 |
| CV% | 1.9 | 1.3 | 4.9 | 6.4 | 5.6 | 5.7 | 7.0 | 24.3 | 72.2 |

Table 8. Summary of exfiltration source points and Effect Ratio (ER) for Aug. 17th.

| Potential Source Point | Type | Effect Ratio & Distance (km) | TP (mg/L) | TN (mg/L) | Cl (mg/L) | *E. coli* MPN (Col/100 mL) |
|---|---|---|---|---|---|---|
| 0.6 | Sewer line | Effect Ratio | 2.0 | | | 5.5 |
| | | Dist. | 0 | | | 200 |
| 2.0/2.1 | Sewer line | Effect Ratio | | 1.3 | | |
| | | Dist. | | 200 | | |
| 2.2/2.3 | Fault | Effect Ratio | | | | |
| | | Dist. | | | | |
| 2.8/2.7 | North Branch | Effect Ratio | | | 1.2 | 2.2 or 2.0 |
| | | Dist. | | | 300 | 0 or 200 |
| 3.0/3.1 | Sewer line | Effect Ratio | | | | 2.2 |
| | | Dist. | | | | 200 |
| 3.6 | Fault | Effect Ratio | | | | |
| | | Dist. | | | | |
| 4.6 | Sewer line | Effect Ratio | | | | 1.4 or 2.3 or 2.0 or 1.2 |
| | | Dist. | | | | 0 or 200 or 400 or 600 |
| 5.4 | Sewer line | Effect Ratio | 2.0 | | | 2.3 or 1.2 |
| | | Dist. | 200 | | | 200 or 600 |
| 5.6 | Sewer line | Effect Ratio | 2.0 | | | 2.4 |
| | | Dist. | 400 | | | 200 |

Effect = ratio between SSI indicator at peak and upstream background.
Distance = distance in km between source point and downstream peak.

Table 9. Summary statistics for August 29, 2016 sampling

| | Temp (°C) | pH (std.) | SC (µS/cm) | DO (mg/L) | Cl (mg/L) | Cl (mg/L) | TN (mg/L) | TP (mg/L) | *E. coli* (MPN) |
|---|---|---|---|---|---|---|---|---|---|
| Method | In-situ | | | | | Laboratory | | | |
| n | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 | 48 |
| Mean | 24.6 | 7.8 | 611 | 7.5 | 60.2 | 60.9 | 1.33 | 0.033 | 225 |
| Median | 24.7 | 7.7 | 609 | 7.4 | 59.8 | 60.3 | 1.35 | 0.031 | 170 |
| Min | 23.5 | 7.6 | 585 | 6.1 | 54.4 | 51.4 | 1.04 | 0.023 | 80 |
| Max | 25.8 | 7.9 | 640 | 8.8 | 67.4 | 69.7 | 1.55 | 0.071 | 1011 |
| SD | 0.6 | 0.1 | 18 | 0.5 | 3.7 | 4.08 | 0.09 | 0.01 | 173 |
| CV% | 2.2 | 1.3 | 2.9 | 7.2 | 6.1 | 6.7 | 6.0 | 28.4 | 76.7 |

Table 10. Summary of exfiltration source points and Effect Ratio (ER) for Aug. 29th.

| Potential Source Point | Type | Effect Ratio & Distance (km) | TP (mg/L) | TN (mg/L) | Cl (mg/L) | *E. coli* MPN (Col/100 mL) |
|---|---|---|---|---|---|---|
| 0.6 | Sewer line | Effect Ratio | 1.4 | | | 2.2 |
| | | Dist. | 0 | | | 400 |
| 2.0/2.1 | Sewer line | Effect Ratio | | | | 1.4 |
| | | Dist. | | | | 900 |
| 2.2/2.3 | Fault | Effect Ratio | 2.0 | | | 3.0 |
| | | Dist. | 0 | | | 0 |
| 2.8/2.7 | North Branch | Effect Ratio | | | | 2.0 or 2.0 or 1.2 or 1.2 |
| | | Dist. | | | | 0 or 100 or 300 or 400 |
| 3.0/3.1 | Sewer line | Effect Ratio | | | | 6.4 or 2.6 |
| | | Dist. | | | | 0 or 100 |
| 3.6 | Fault | Effect Ratio | | | | 4.2 |
| | | Dist. | | | | 400 |
| 4.6 | Sewer line | Effect Ratio | 2.4 | | | 1.5 |
| | | Dist. | 300 | | | 300 |
| 5.4 | Sewer line | Effect Ratio | 2.0 | | | 1.2 or 1.6 |
| | | Dist. | 400 | | | 0 or 300 |
| 5.6 | Sewer line | Effect Ratio | | | | 1.2 |
| | | Dist. | | | | 100 |

Effect = ratio between SSI indicator at peak and upstream background.
Distance = distance in km between source point and downstream peak.

Table 11. Summary of findings by source location.

| **Potential Source Point (R-km)** | **Type** | **Parameter and Effect Ratio** | **Classification** |
|---|---|---|---|
| 0.6 | Sewer line | TP = 1.4-2.0<br>E. Coli = 2.2-5.5 | Very High |
| 2.1 | Sewer line | TN = 1.3<br>E. Coli = 1.4 | Low |
| 2.3 | Fault | TP = 2.0<br>E. Coli = 3.0 | High |
| 2.8 | North Branch Wilson Creek | Cl = 1.2<br>E. Coli = 1.2-2.2 | Moderate |
| 3.1 | Sewer line | E. Coli = 2.2-6.4 | Very High |
| 3.6 | Fault | E. Coli = 4.2 | High |
| 4.6 | Sewer line | TP = 2.4<br>E. Coli = 1.2-2.3 | Moderate |
| 5.4 | Sewer line | TP = 2.0<br>E. Coli = 1.2-2.3 | Moderate |
| 5.6 | Sewer line | TP = 2.0<br>E. Coli = 1.2-2.4 | Moderate |

## FIGURES

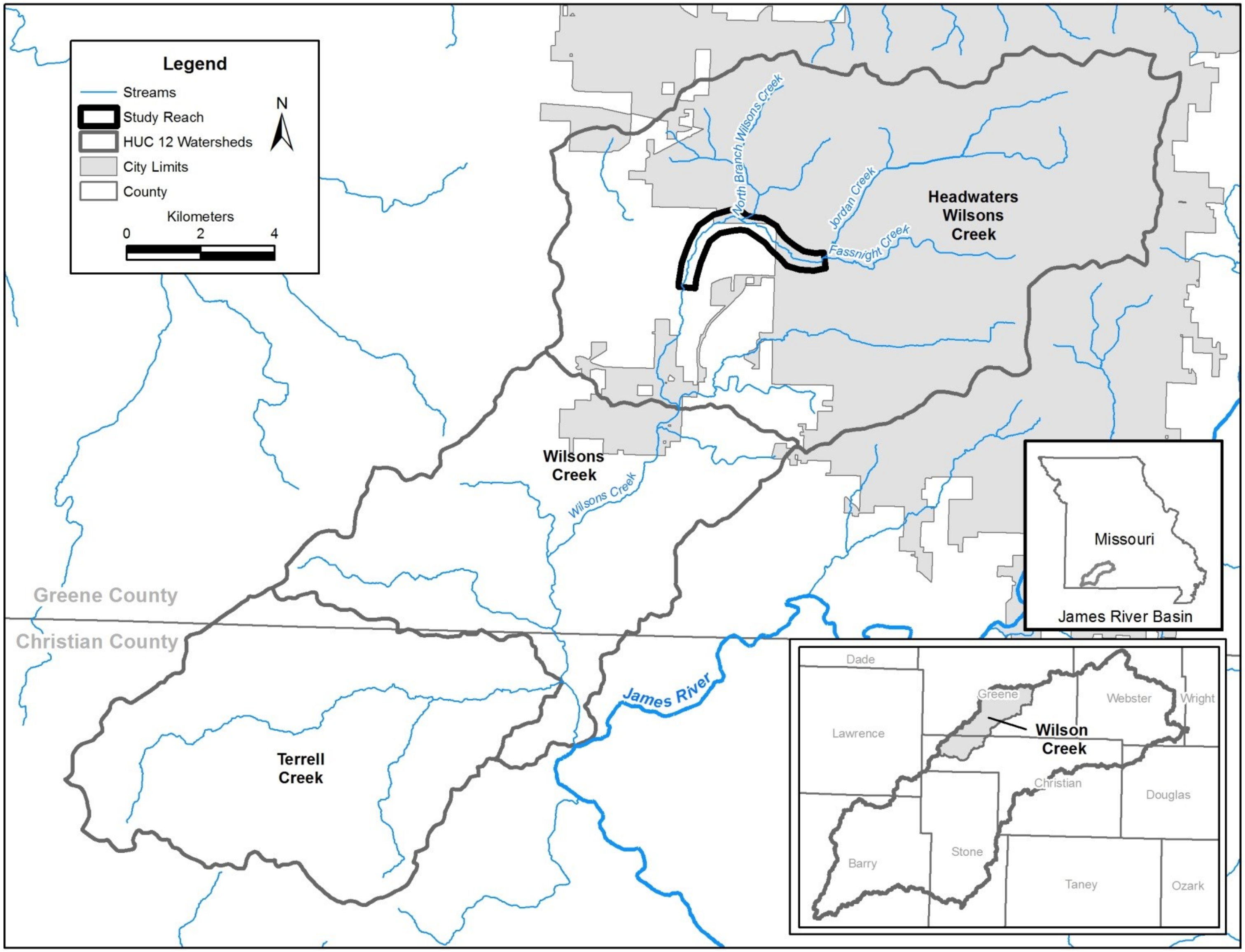



Figure 1. Wilson Creek location within the James River Basin.

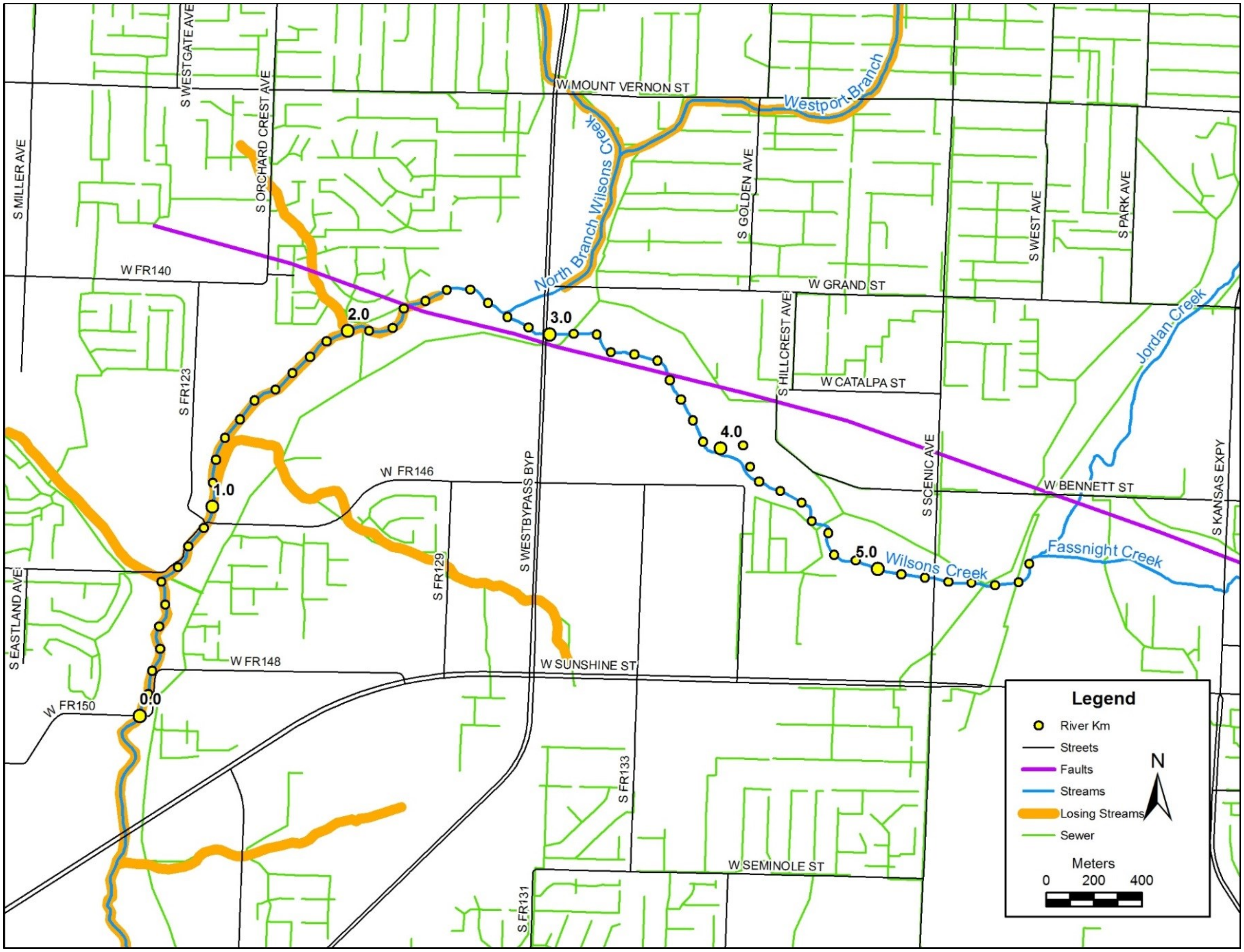


Figure 2. Wilson Creek location within the James River Basin.

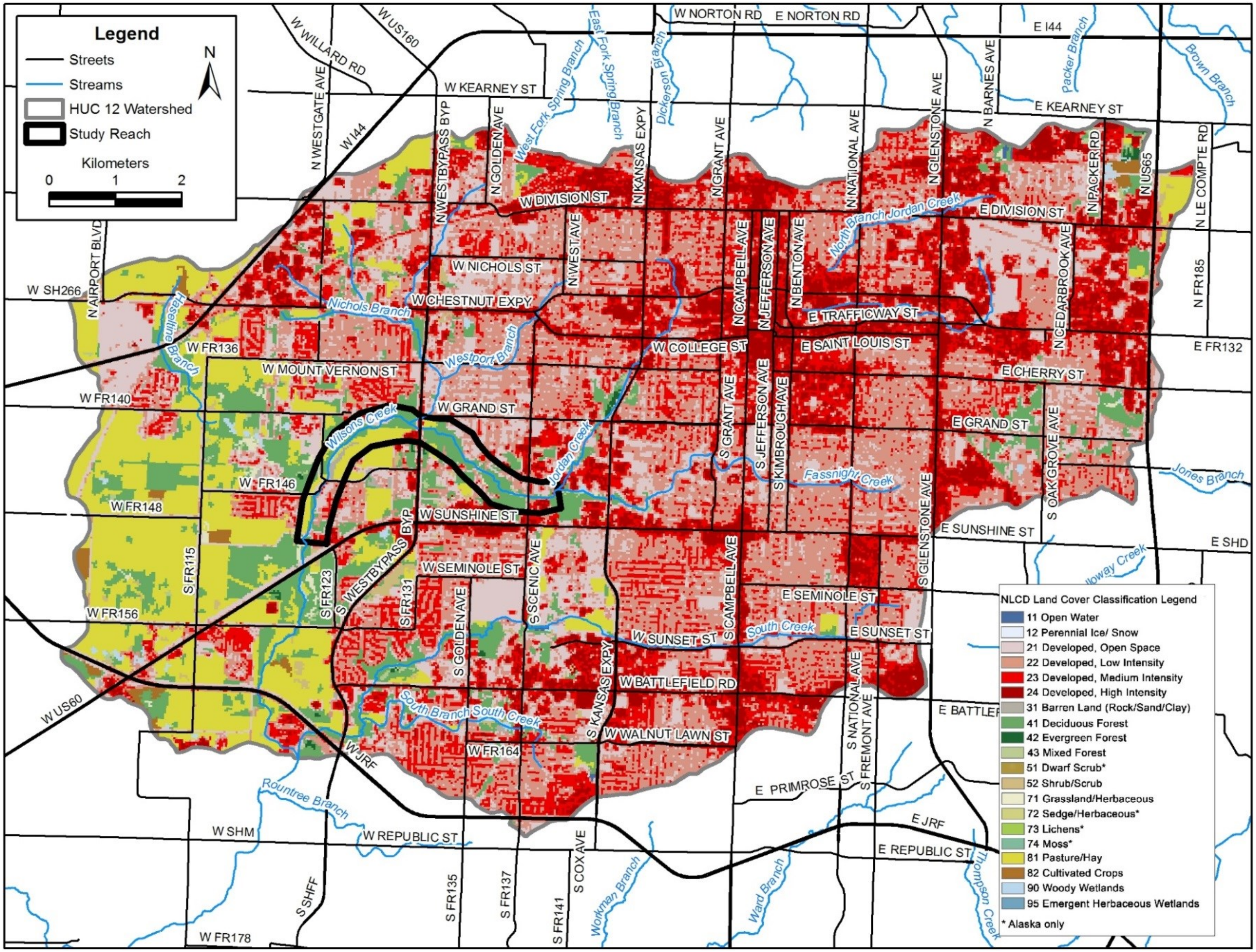



Figure 3. Land use in the Wilson Creek Watershed.

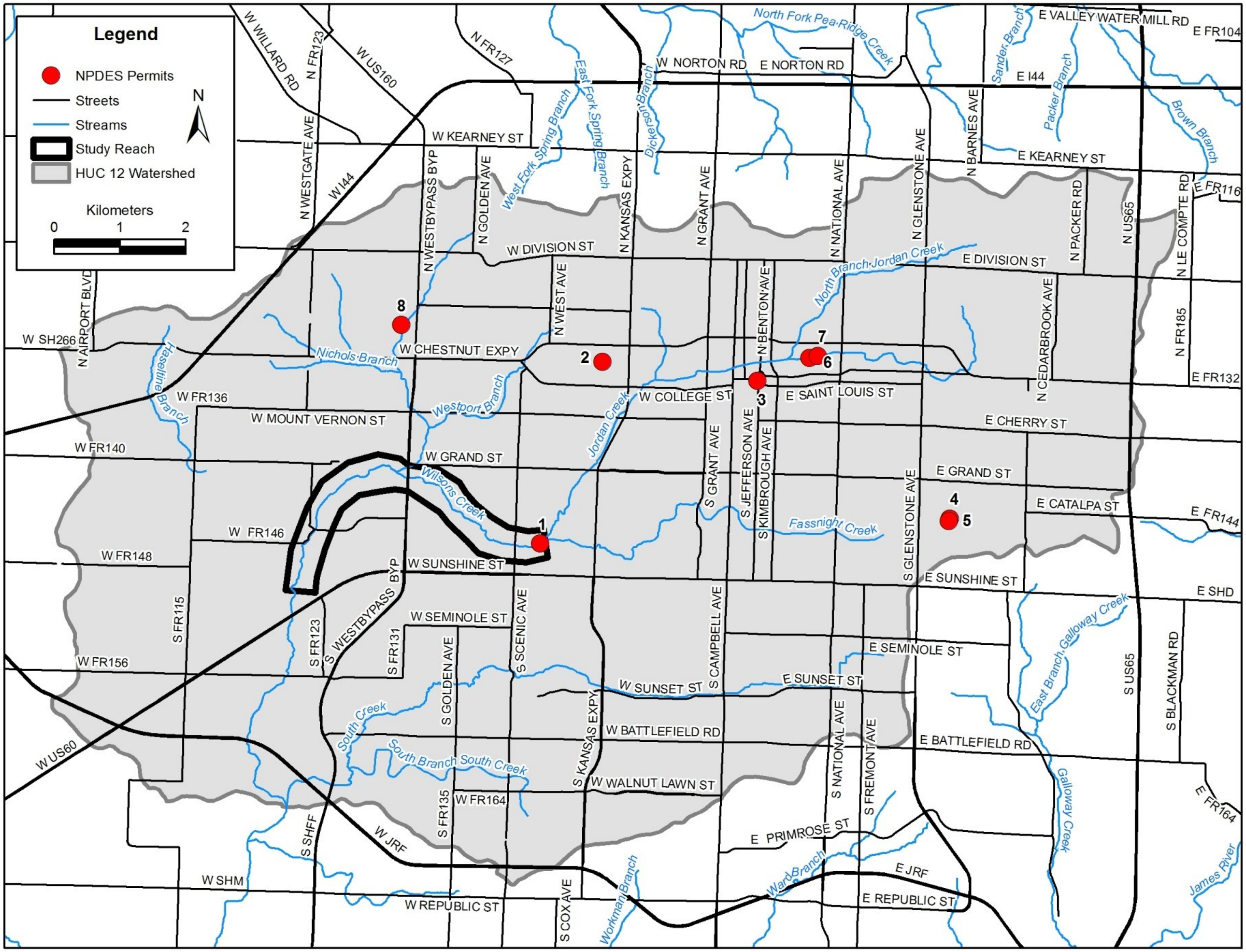
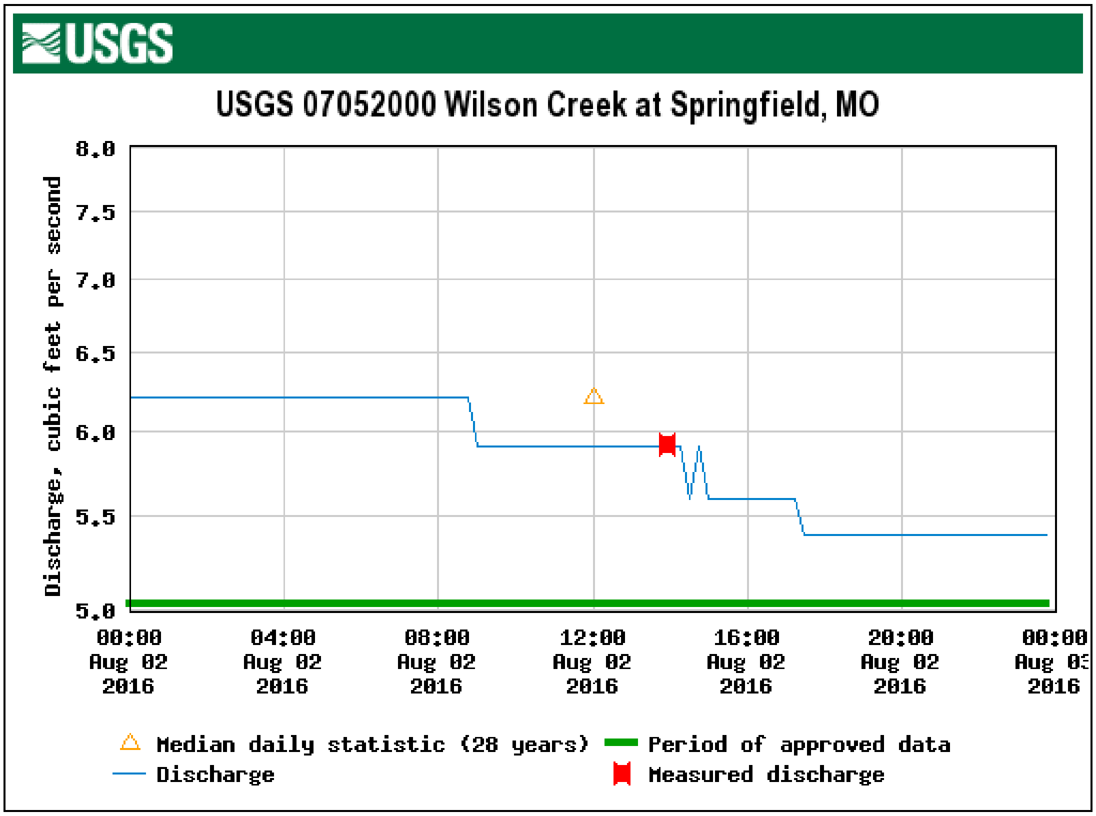



Figure 4. Locations of Permitted Discharges in the Wilson Creek Watershed.



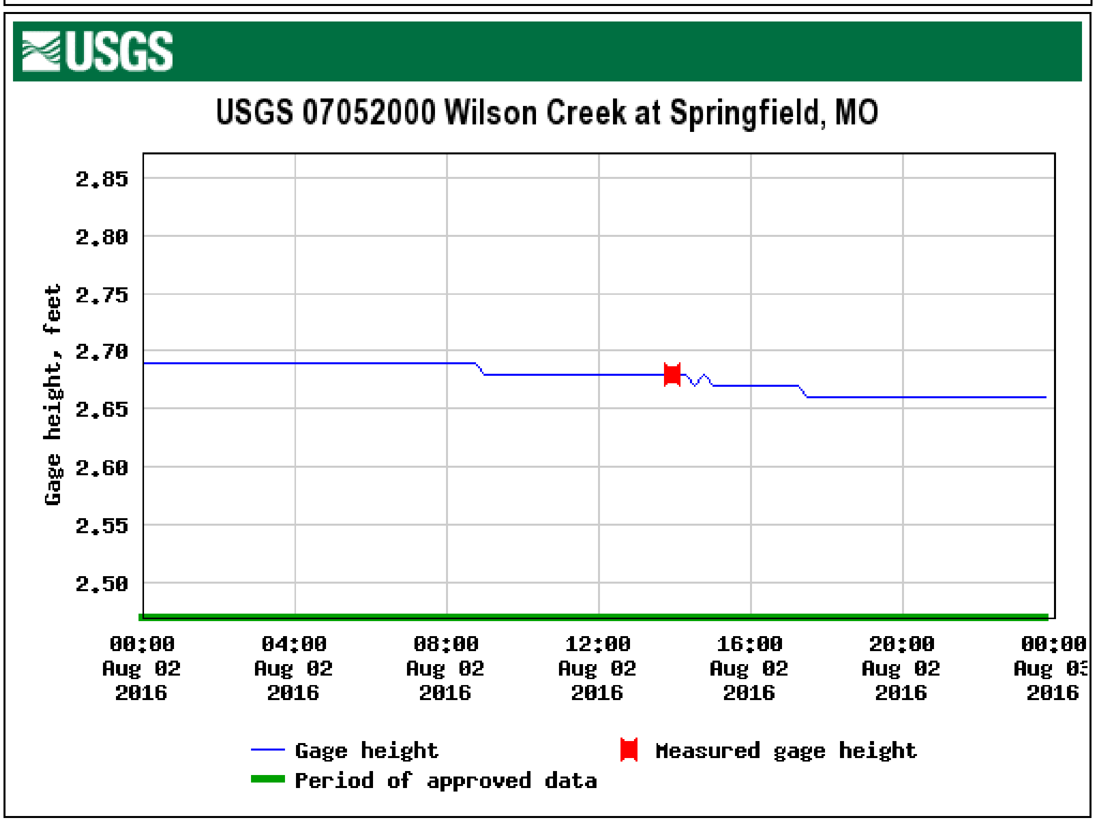




Figure 5. Discharge and gage height on August 2, 2016.

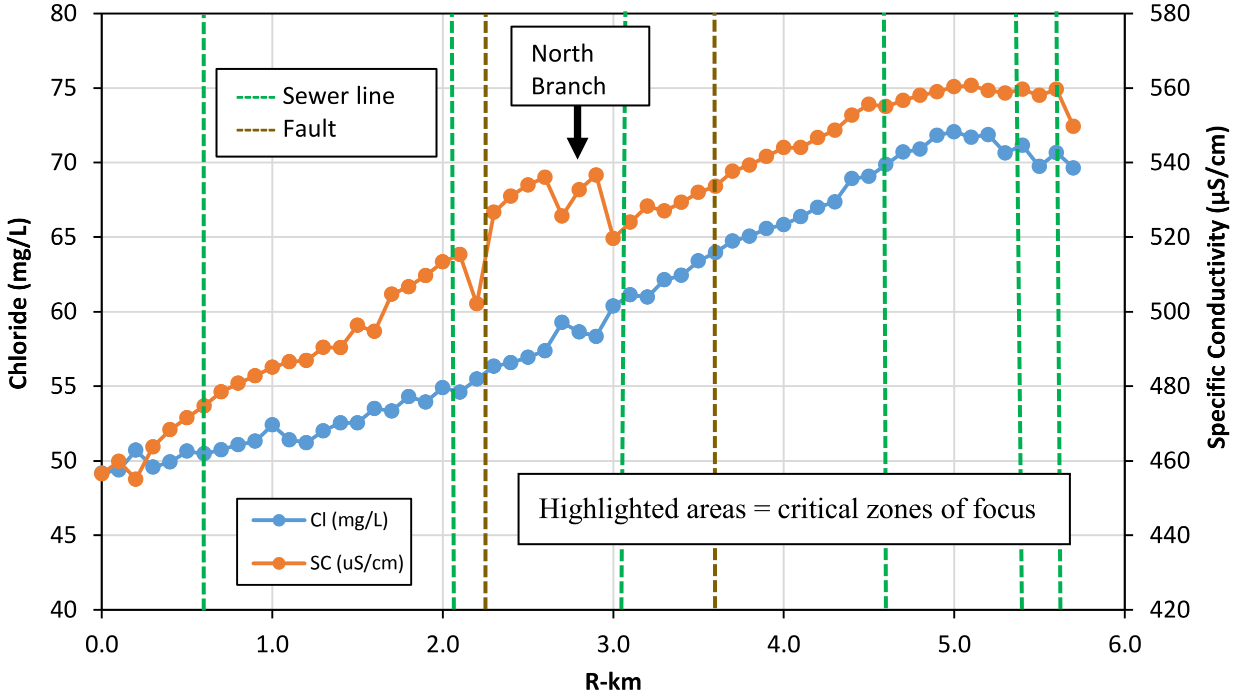


Figure 6. Chloride and specific conductivity trends.

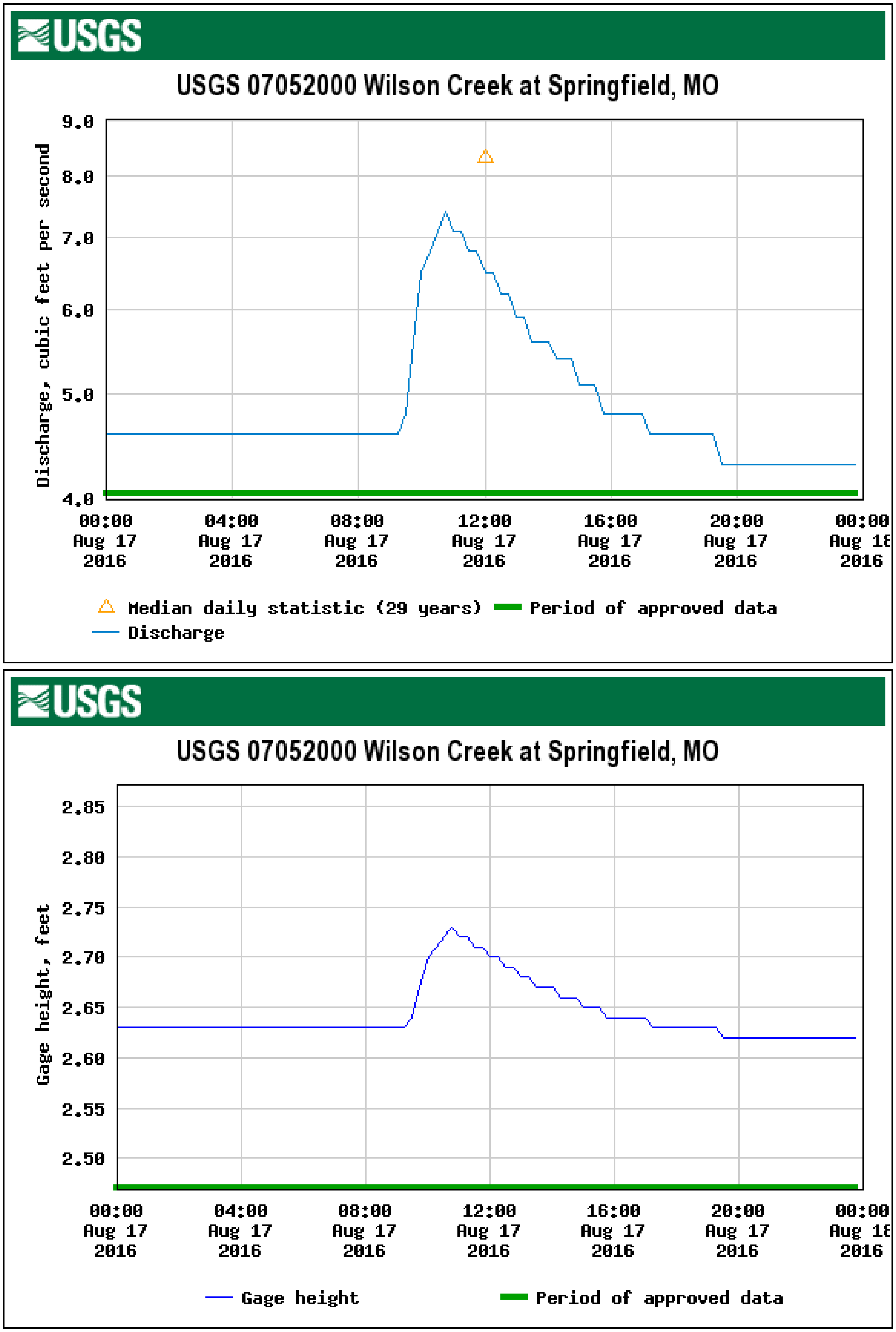


Figure 7. Discharge and gage height for August 17, 2016.

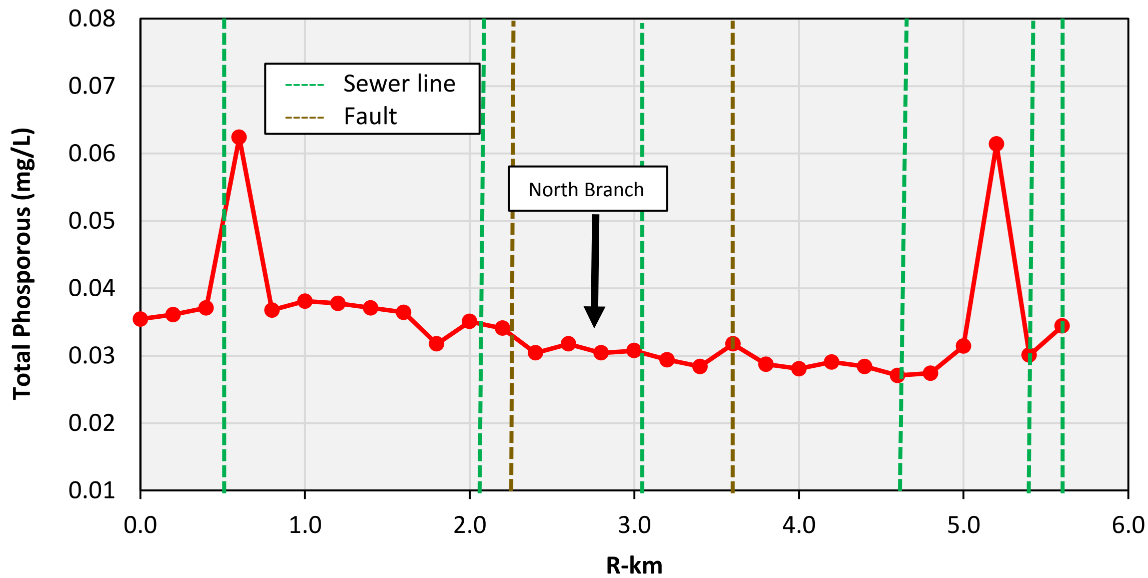



Figure 8. Downstream TP trends for August 17th

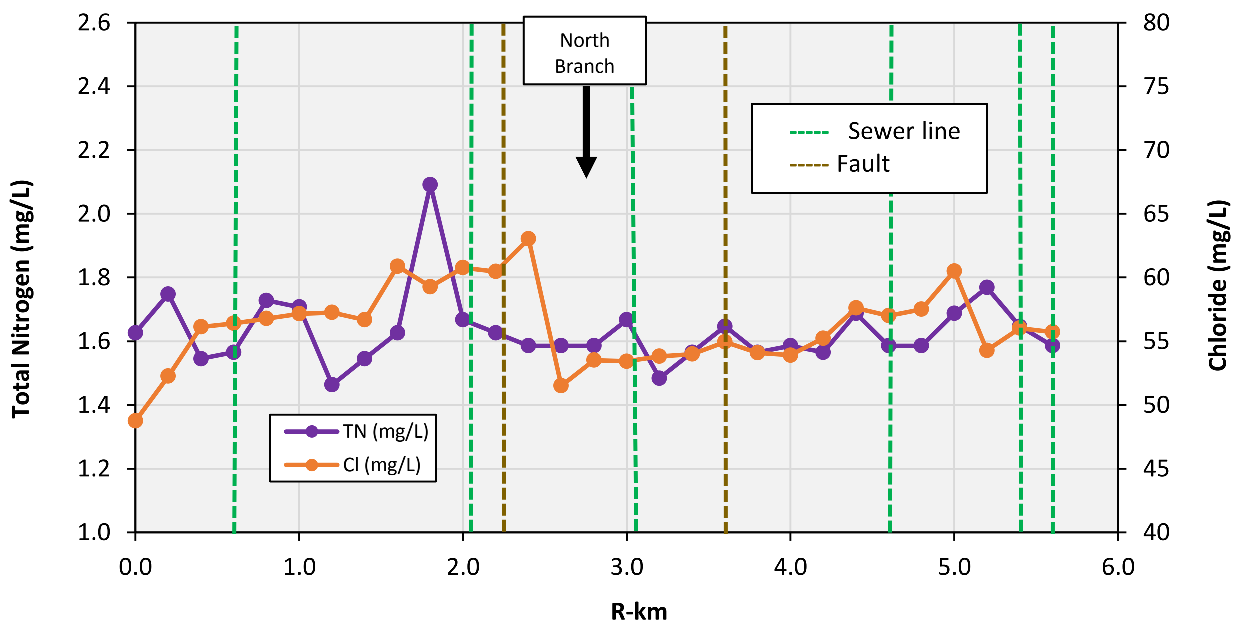



Figure 9. Downstream TN and Cl trends for August 17th

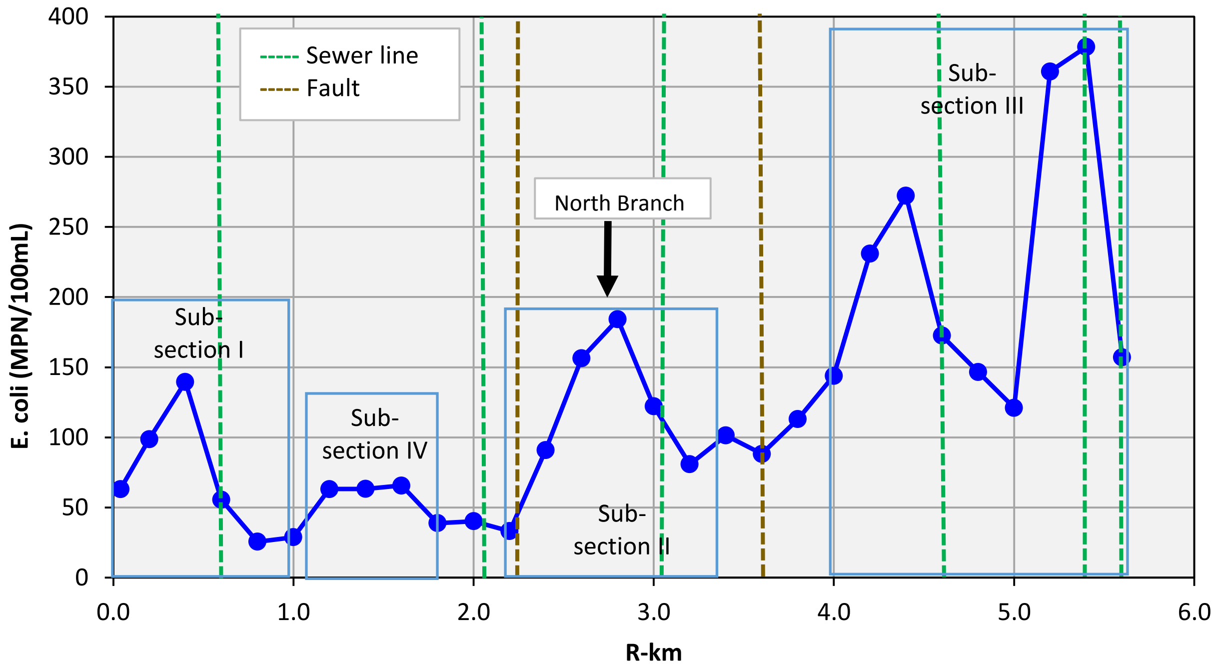
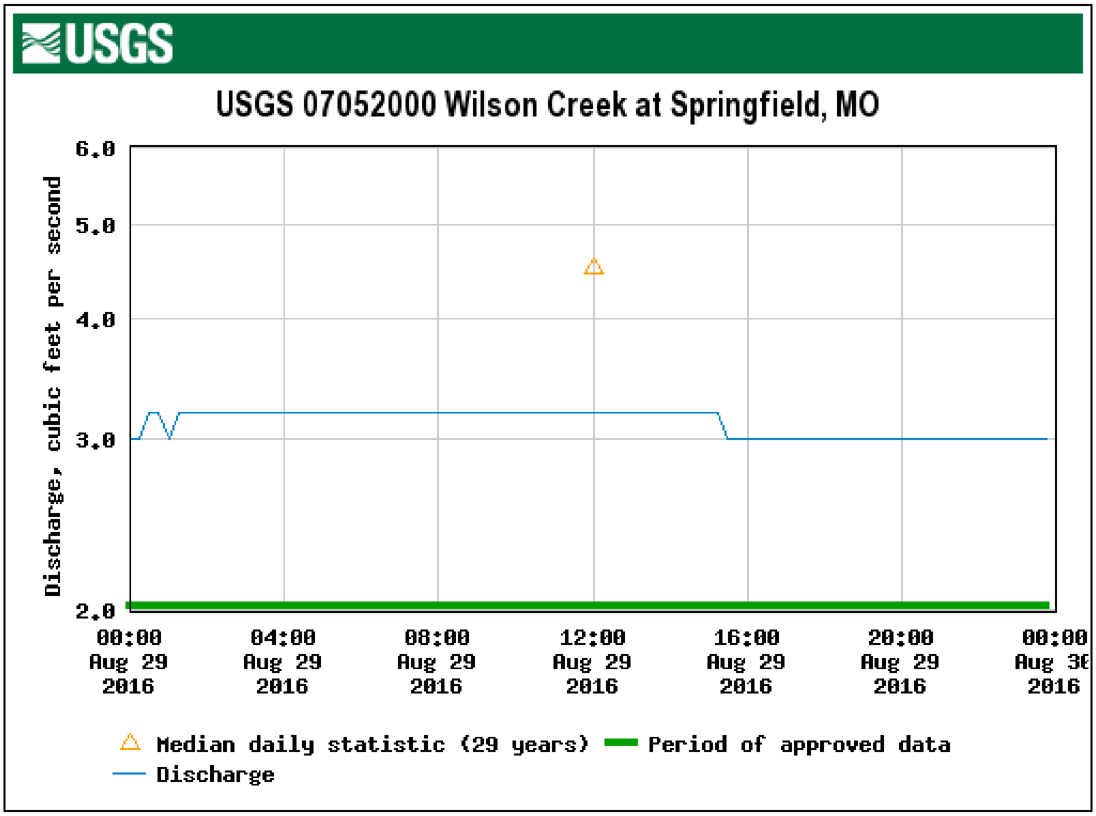



Figure 10. Downstream E. Coli trends for August 17th



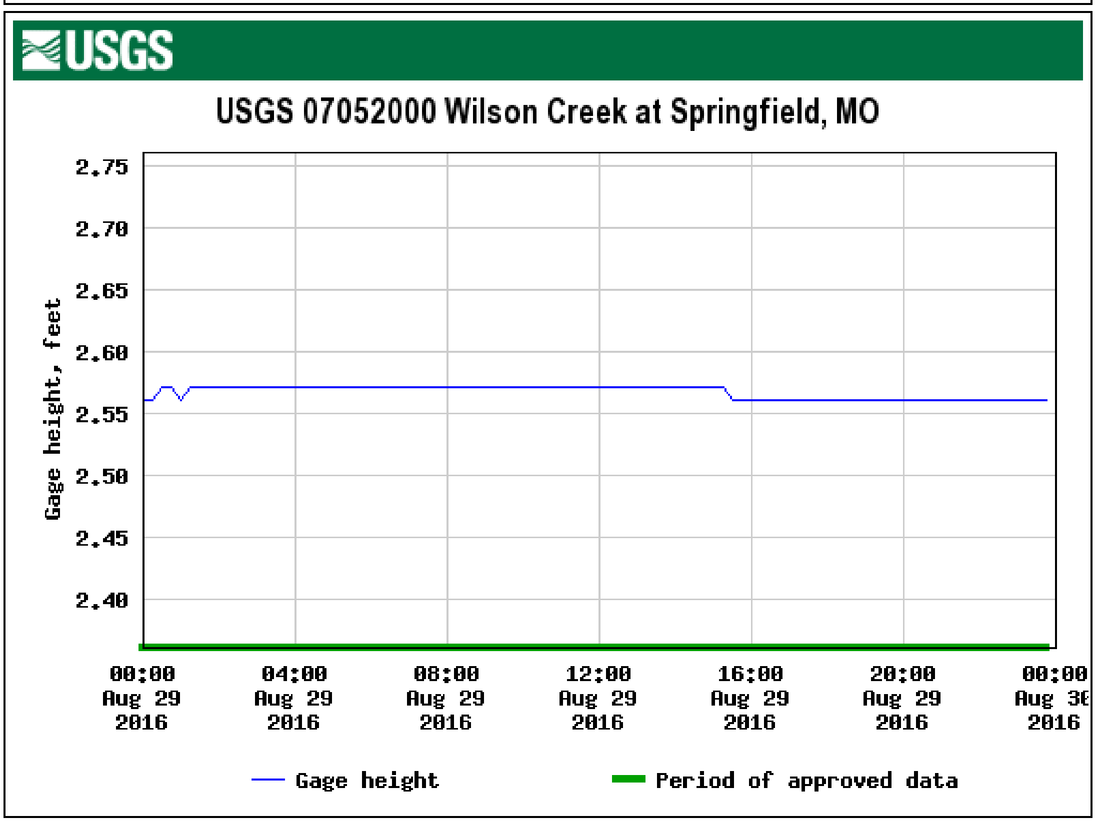




Figure 11. Discharge and gage height for August 29, 2016.

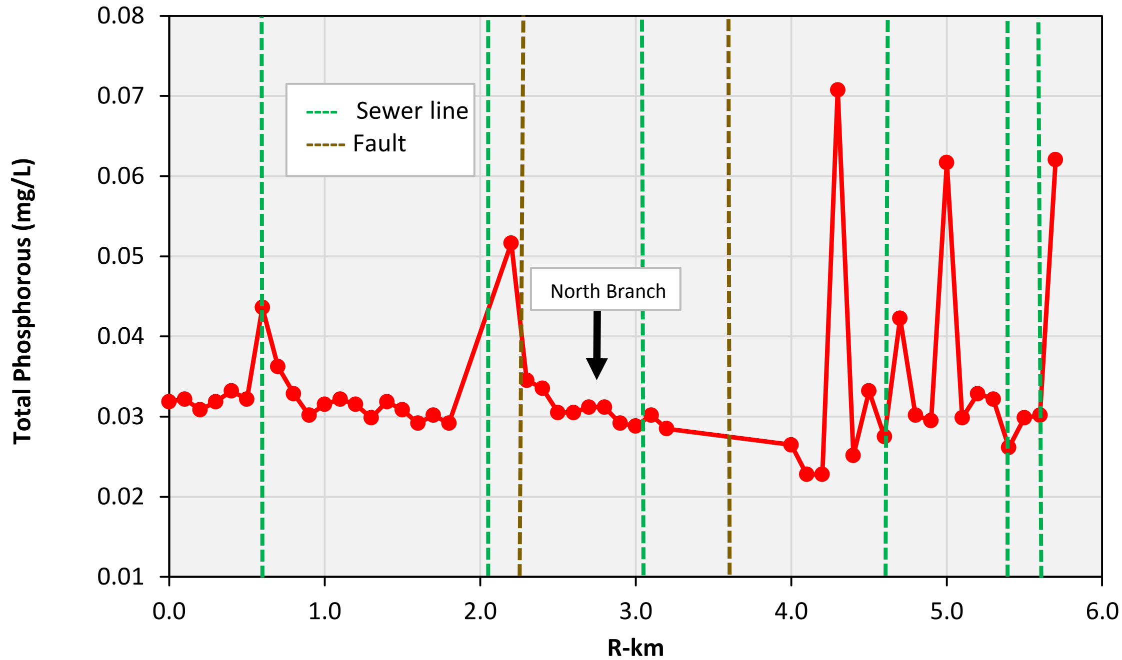



Figure 12. Downstream TP trends for August 29th.

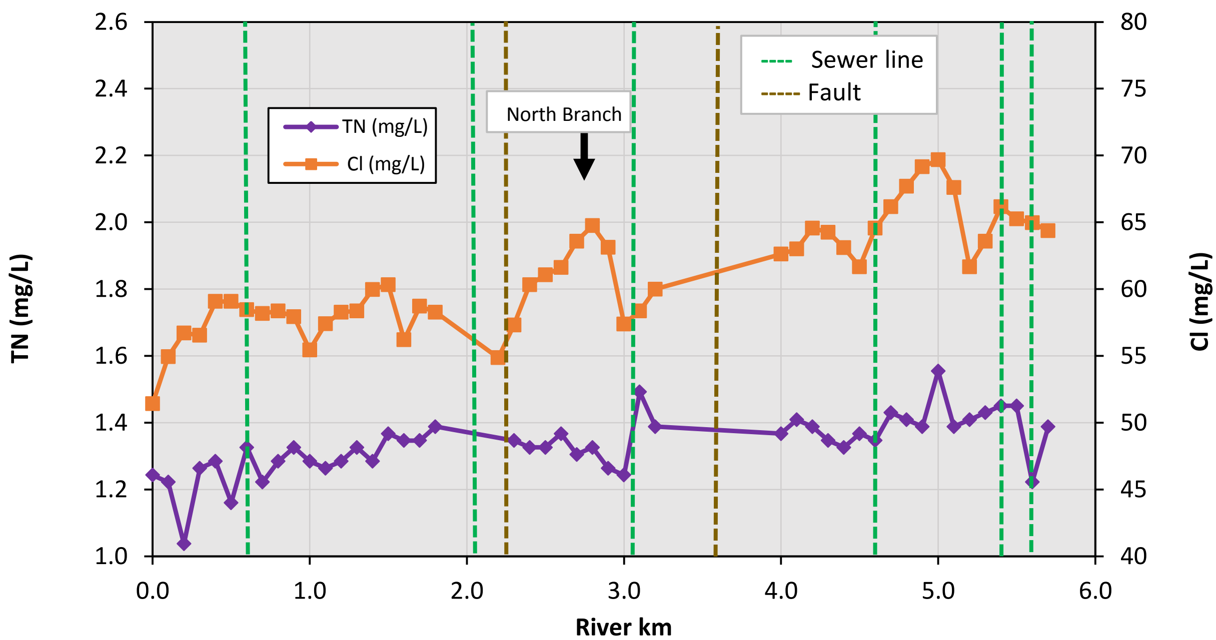



Figure 13. Downstream TN and Cl trends for August 29th.

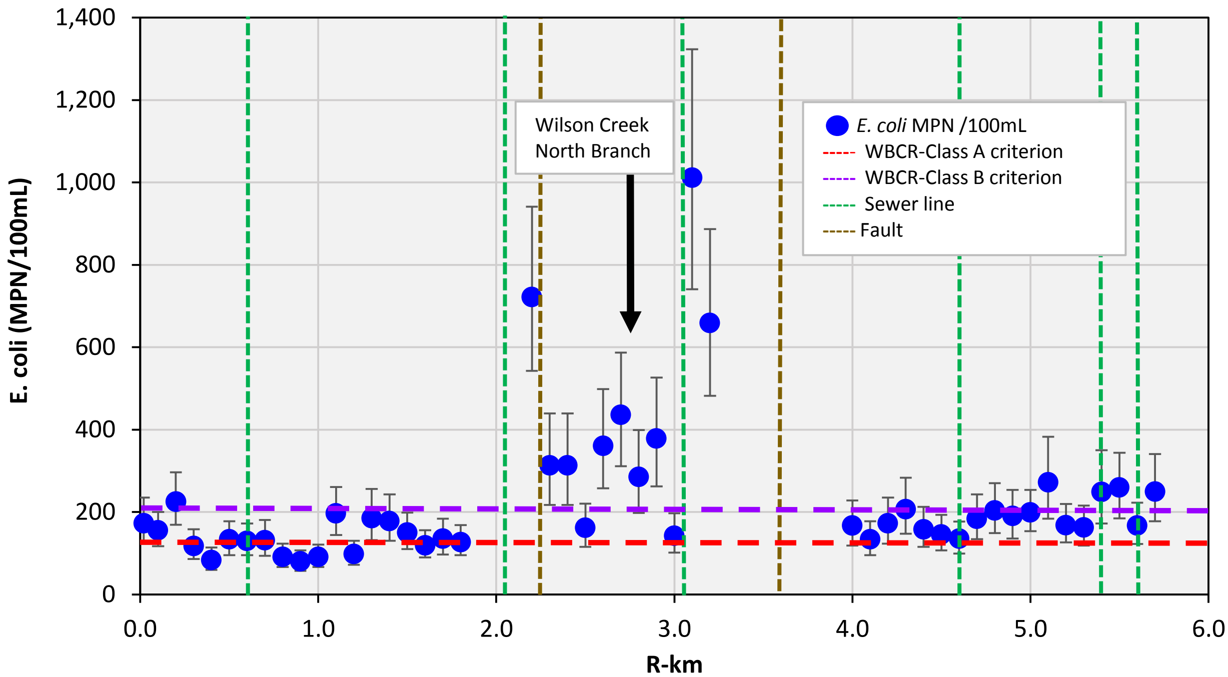


Figure 14. Downstream variability in E. Coli with 95% confidence limits for August 29th.

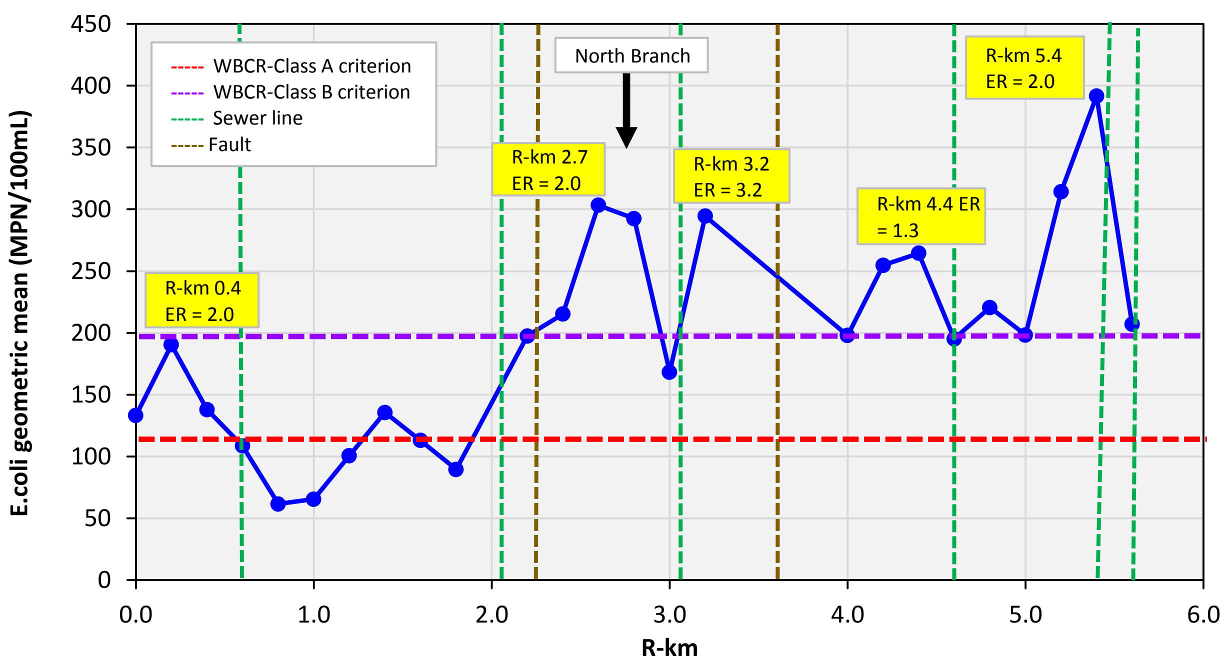


Figure 15. Downstream geometric mean E. Coli trends for Aug. 17th and Aug. 29th.

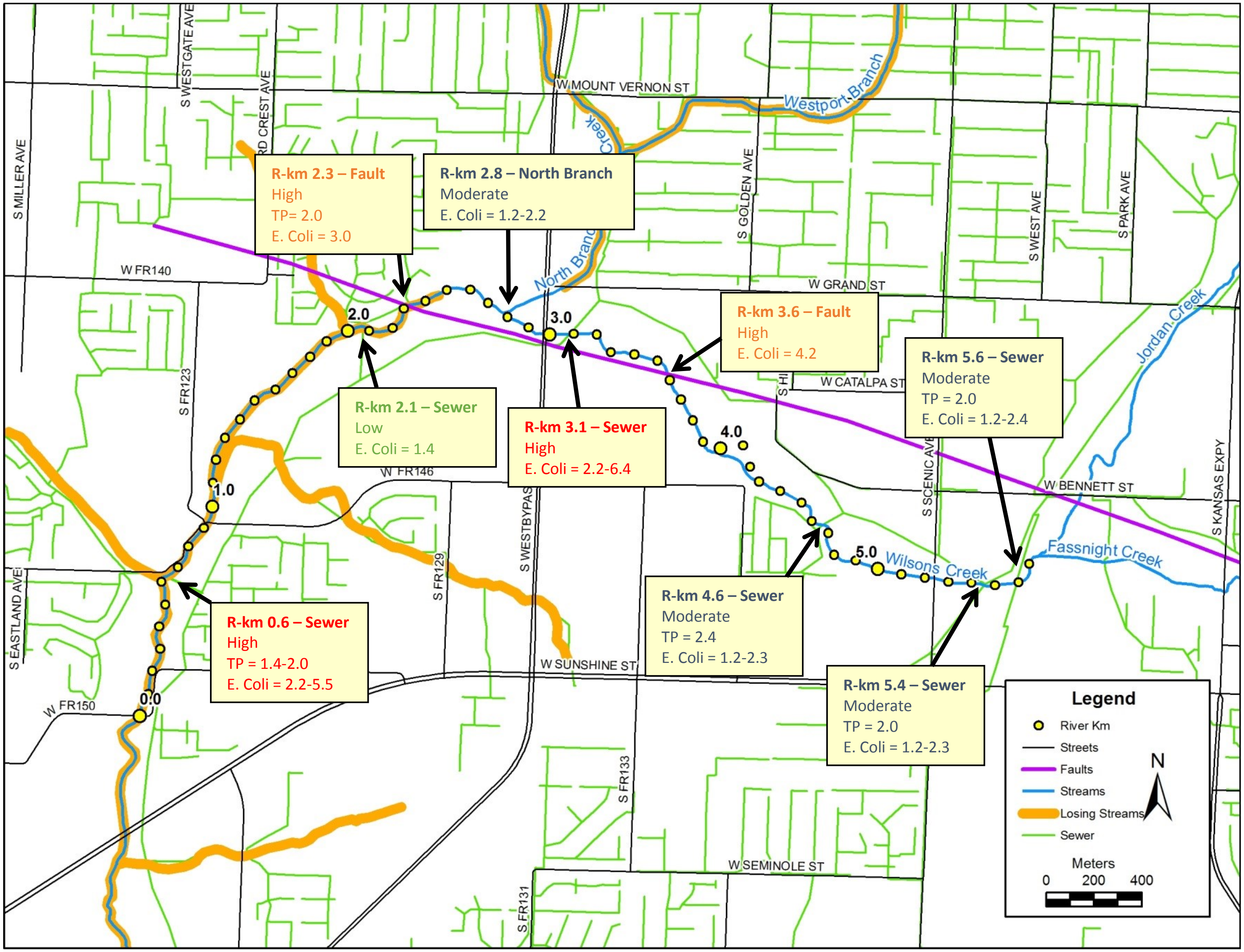



Figure 16. Wilson Creek Exfiltration Source Points and Selected SSI Responses.

APPENDIX A. Study Sample Sites.

| Site/R-km | Latitude (°N) | Longitude (°W) | Elevation (m) |
|---|---|---|---|
| 0.0 | 37.18127496 | -93.36886799 | 354.96 |
| 0.1 | 37.18212888 | -93.36847326 | 355.69 |
| 0.2 | 37.18301269 | -93.3683424 | 355.77 |
| 0.3 | 37.18383445 | -93.36800753 | 356.21 |
| 0.4 | 37.18469861 | -93.36779019 | 356.79 |
| 0.5 | 37.18550304 | -93.36765419 | 356.47 |
| 0.6 | 37.18638269 | -93.36783267 | 356.78 |
| 0.7 | 37.18694223 | -93.36706432 | 357.02 |
| 0.8 | 37.18775642 | -93.36658964 | 357.28 |
| 0.9 | 37.18840693 | -93.36583465 | 357.54 |
| 1.0 | 37.18923268 | -93.3656007 | 358.15 |
| 1.1 | 37.19012642 | -93.36537886 | 358.04 |
| 1.2 | 37.19099787 | -93.36527508 | 358.24 |
| 1.3 | 37.19185915 | -93.36467568 | 358.92 |
| 1.4 | 37.19252955 | -93.36420174 | 358.91 |
| 1.5 | 37.19316298 | -93.36335201 | 359.24 |
| 1.6 | 37.19367016 | -93.36253205 | 359.33 |
| 1.7 | 37.19429447 | -93.36174942 | 359.51 |
| 1.8 | 37.19491292 | -93.36092913 | 359.66 |
| 1.9 | 37.1954459 | -93.36009494 | 359.67 |
| 2.0 | 37.19587323 | -93.35910865 | 359.81 |
| 2.1 | 37.19607976 | -93.35805477 | 360.88 |
| 2.2 | 37.19647652 | -93.35708628 | 362.30 |
| 2.3 | 37.19677334 | -93.35650116 | 360.43 |
| 2.4 | 37.19708255 | -93.3553608 | 360.63 |
| 2.5 | 37.19745397 | -93.35448891 | 360.72 |
| 2.6 | 37.19747662 | -93.35334786 | 360.98 |
| 2.7 | 37.19697691 | -93.35247327 | 361.25 |
| 2.8 | 37.19656188 | -93.35148305 | 361.54 |
| 2.9 | 37.19590613 | -93.35061285 | 362.02 |
| 3.0 | 37.19575197 | -93.34960863 | 362.09 |
| 3.1 | 37.19580224 | -93.3484645 | 362.57 |
| 3.2 | 37.19586255 | -93.34733531 | 362.18 |
| 3.3 | 37.19516292 | -93.34665602 | 362.36 |
| 3.4 | 37.19516667 | -93.34546965 | 362.71 |
| 3.5 | 37.1948686 | -93.34459411 | 362.67 |
| 3.6 | 37.19419976 | -93.34402154 | 363.17 |
| 3.7 | 37.19339795 | -93.34338634 | 363.64 |
| 3.8 | 37.19268696 | -93.34284986 | 363.41 |
| 3.9 | 37.19182964 | -93.34229994 | 363.86 |
| 4.0 | 37.1916014 | -93.34148542 | 364.38 |
| 4.1 | 37.19154269 | -93.34044945 | 364.81 |
| 4.2 | 37.19086935 | -93.33988428 | 365.48 |
| 4.3 | 37.19038087 | -93.33962272 | 365.37 |
| 4.4 | 37.19002767 | -93.33875167 | 365.66 |
| 4.5 | 37.18966874 | -93.33763382 | 365.76 |
| 4.6 | 37.18891023 | -93.337185 | 366.65 |
| 4.7 | 37.18844282 | -93.33647852 | 366.57 |
| 4.8 | 37.18762899 | -93.33615138 | 367.26 |
| 4.9 | 37.18735258 | -93.33511956 | 366.42 |
| 5.0 | 37.187126 | -93.33409883 | 368.00 |
| 5.1 | 37.18690878 | -93.33297592 | 366.50 |
| 5.2 | 37.18683101 | -93.33177649 | 367.21 |
| 5.3 | 37.18656254 | -93.33074791 | 369.01 |
| 5.4 | 37.18658526 | -93.32964054 | 367.79 |
| 5.7 | 37.18654338 | -93.32858048 | 368.41 |
| 5.6 | 37.18660907 | -93.32756055 | 369.11 |
| 5.7 | 37.18685846 | -93.32685162 | 369.21 |

APPENDIX B. August 2nd Sample Data.

| | Temp (°C) | | | pH (std. units) | | | SC (µS/cm) | | | DO (mg/L) | | | Cl (mg/L) | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| R-km | L | C | R | L | C | R | L | C | R | L | C | R | L | C | R |
| 0.0 | 24.4 | 24.3 | 24.2 | 7.8 | 7.8 | 7.8 | 457 | 457 | 455 | 7.5 | 7.4 | 7.0 | 49.4 | 49.2 | 48.8 |
| 0.1 | 24.3 | 24.3 | 24.3 | 7.8 | 7.8 | 7.8 | 460 | 460 | 460 | 7.5 | 7.3 | 7.4 | 49.2 | 49.4 | 49.4 |
| 0.2 | 24.5 | 24.5 | 24.4 | 7.8 | 7.8 | 7.8 | 448 | 455 | 463 | 7.8 | 7.6 | 7.7 | 50.6 | 50.1 | 51.3 |
| 0.3 | 25.2 | 24.7 | 25.4 | 7.8 | 7.8 | 7.8 | 464 | 466 | 462 | 8.2 | 7.7 | 6.9 | 49.5 | 49.8 | 49.3 |
| 0.4 | 25.1 | 24.8 | 24.7 | 7.8 | 7.8 | 7.8 | 467 | 469 | 469 | 7.8 | 7.7 | 7.0 | 49.9 | 50.5 | 49.2 |
| 0.5 | 24.9 | 24.7 | 24.6 | 7.8 | 7.7 | 7.7 | 470 | 472 | 472 | 7.4 | 7.5 | 7.1 | 51.0 | 50.5 | 50.3 |
| 0.6 | 24.7 | 24.6 | 24.5 | 7.7 | 7.7 | 7.7 | 474 | 476 | 475 | 7.0 | 7.0 | 6.7 | 50.4 | 50.2 | 50.7 |
| 0.7 | 24.8 | 24.9 | 24.9 | 7.7 | 7.7 | 7.7 | 478 | 479 | 479 | 6.7 | 6.9 | 6.8 | 50.5 | 50.8 | 50.8 |
| 0.8 | 25.2 | 25.2 | 25.2 | 7.7 | 7.7 | 7.7 | 481 | 481 | 481 | 7.3 | 7.3 | 7.2 | 51.1 | 51.1 | 50.9 |
| 0.9 | 25.4 | 25.4 | 25.4 | 7.7 | 7.7 | 7.7 | 482 | 483 | 483 | 7.3 | 7.5 | 7.5 | 50.6 | 51.6 | 51.6 |
| 1.0 | 25.4 | 25.4 | 25.4 | 7.7 | 7.7 | 7.7 | 485 | 485 | 485 | 7.4 | 7.5 | 7.2 | 52.0 | 53.0 | 52.1 |
| 1.1 | 25.6 | 25.3 | 25.2 | 7.7 | 7.7 | 7.7 | 485 | 487 | 488 | 6.4 | 7.1 | 7.3 | 50.6 | 51.0 | 52.5 |
| 1.2 | 25.1 | 25.2 | 25.2 | 7.7 | 7.7 | 7.7 | 491 | 488 | 482 | 7.3 | 7.2 | 5.5 | 51.5 | 51.6 | 50.4 |
| 1.3 | 25.1 | 25.1 | 25.9 | 7.7 | 7.7 | 7.7 | 494 | 491 | 486 | 7.7 | 7.3 | 6.2 | 51.3 | 52.6 | 52.0 |
| 1.4 | 25.2 | 25.3 | 25.2 | 7.7 | 7.7 | 7.7 | 495 | 483 | 494 | 7.6 | 7.9 | 7.0 | 51.7 | 53.2 | 52.6 |
| 1.5 | 26.1 | 25.4 | 25.3 | 7.7 | 7.7 | 7.7 | 494 | 497 | 498 | 7.1 | 7.5 | 7.8 | 52.3 | 51.9 | 53.3 |
| 1.6 | 25.8 | 25.3 | 25.3 | 7.7 | 7.6 | 7.6 | 489 | 494 | 501 | 7.9 | 7.2 | 8.2 | 52.9 | 53.5 | 54.0 |
| 1.7 | 25.0 | 25.0 | 25.3 | 7.7 | 7.7 | 7.7 | 504 | 505 | 505 | 7.7 | 8.0 | 7.7 | 52.9 | 53.5 | 53.5 |
| 1.8 | 25.1 | 25.0 | 25.0 | 7.7 | 7.6 | 7.6 | 507 | 505 | 508 | 7.7 | 7.7 | 7.7 | 54.0 | 54.3 | 54.5 |
| 1.9 | 25.3 | 25.0 | 25.0 | 7.7 | 7.7 | 7.6 | 508 | 510 | 511 | 8.0 | 8.1 | 8.1 | 53.5 | 54.0 | 54.2 |
| 2.0 | 24.3 | 25.0 | 25.0 | 7.6 | 7.6 | 7.6 | 516 | 512 | 512 | 7.8 | 7.7 | 7.6 | 52.7 | 55.9 | 56.0 |
| 2.1 | 25.2 | 25.0 | 24.8 | 7.6 | 7.5 | 7.5 | 513 | 516 | 517 | 8.2 | 8.0 | 7.6 | 54.3 | 54.7 | 54.7 |
| 2.2 | 25.2 | 24.9 | 25.2 | 7.6 | 7.6 | 7.5 | 461 | 521 | 524 | 7.6 | 7.3 | 7.3 | 55.4 | 55.5 | 55.4 |
| 2.3 | 25.4 | 25.2 | 25.1 | 7.6 | 7.6 | 7.6 | 524 | 528 | 528 | 7.3 | 7.4 | 7.6 | 55.9 | 56.3 | 56.7 |
| 2.4 | 25.3 | 25.4 | 25.3 | 7.6 | 7.6 | 7.6 | 532 | 531 | 530 | 7.0 | 7.2 | 7.1 | 56.5 | 56.8 | 56.3 |
| 2.5 | 25.3 | 25.4 | 25.4 | 7.6 | 7.6 | 7.6 | 534 | 534 | 534 | 7.3 | 6.9 | 7.0 | 56.8 | 56.7 | 57.2 |
| 2.6 | 25.4 | 25.4 | 25.4 | 7.6 | 7.6 | 7.6 | 537 | 536 | 535 | 7.1 | 7.2 | 6.9 | 57.1 | 57.6 | 57.3 |
| 2.7 | 25.9 | 25.9 | 25.9 | 7.7 | 7.7 | 7.7 | 534 | 512 | 531 | 7.9 | 8.0 | 7.2 | 58.4 | 59.8 | 59.5 |
| 2.8 | 26.0 | 26.0 | 26.0 | 7.7 | 7.7 | 7.7 | 534 | 535 | 529 | 8.0 | 8.1 | 8.0 | 58.3 | 58.7 | 58.8 |
| 2.9 | 26.1 | 26.0 | 26.0 | 7.7 | 7.7 | 7.7 | 536 | 537 | 537 | 8.3 | 8.2 | 8.2 | 58.0 | 58.3 | 58.6 |
| 3.0 | 24.3 | 24.2 | 24.4 | 7.6 | 7.6 | 7.6 | 520 | 521 | 518 | 6.3 | 5.4 | 5.3 | 60.3 | 60.4 | 60.4 |
| 3.1 | 24.1 | 24.0 | 24.0 | 7.5 | 7.5 | 7.5 | 525 | 525 | 522 | 5.0 | 4.4 | 4.5 | 61.3 | 61.1 | 61.0 |
| 3.2 | 23.9 | 24.0 | 24.0 | 7.5 | 7.5 | 7.5 | 529 | 528 | 528 | 4.5 | 5.8 | 4.5 | 61.2 | 60.4 | 61.3 |
| 3.3 | 24.0 | 24.0 | 24.1 | 7.5 | 7.5 | 7.5 | 527 | 527 | 527 | 4.9 | 6.6 | 5.7 | 62.1 | 62.5 | 61.8 |
| 3.4 | 24.0 | 24.0 | 24.0 | 7.5 | 7.5 | 7.5 | 529 | 530 | 529 | 5.6 | 5.0 | 5.0 | 62.6 | 63.1 | 61.6 |
| 3.5 | 24.0 | 24.1 | 24.0 | 7.5 | 7.5 | 7.5 | 531 | 532 | 533 | 5.0 | 5.2 | 5.6 | 63.6 | 63.3 | 63.3 |
| 3.6 | 24.4 | 24.4 | 24.4 | 7.6 | 7.6 | 7.6 | 533 | 533 | 535 | 5.5 | 5.5 | 5.3 | 64.4 | 64.0 | 63.5 |
| 3.7 | 24.4 | 24.4 | 24.5 | 7.6 | 7.6 | 7.6 | 538 | 538 | 537 | 5.5 | 5.5 | 5.8 | 65.3 | 65.1 | 63.8 |
| 3.8 | 24.2 | 24.3 | 24.4 | 7.6 | 7.6 | 7.6 | 540 | 539 | 539 | 6.1 | 7.1 | 6.2 | 65.6 | 64.9 | 64.7 |
| 3.9 | 24.6 | 24.5 | 24.5 | 7.6 | 7.5 | 7.6 | 541 | 542 | 542 | 5.6 | 9.8 | 9.0 | 65.8 | 65.0 | 65.9 |
| 4.0 | 24.7 | 24.8 | 24.8 | 7.5 | 7.5 | 7.5 | 545 | 544 | 543 | 8.4 | 8.4 | 7.1 | 66.0 | 65.8 | 65.7 |
| 4.1 | 25.0 | 25.0 | 25.1 | 7.6 | 7.6 | 7.6 | 544 | 545 | 543 | 8.6 | 6.6 | 7.5 | 66.6 | 66.4 | 66.1 |
| 4.2 | 25.3 | 25.3 | 25.2 | 7.6 | 7.6 | 7.6 | 546 | 547 | 547 | 7.8 | 8.6 | 8.5 | 67.2 | 66.8 | 67.0 |
| 4.3 | 25.7 | 25.7 | 25.6 | 7.6 | 7.6 | 7.6 | 550 | 550 | 546 | 8.9 | 7.6 | 7.4 | 67.6 | 67.8 | 66.7 |
| 4.4 | 25.7 | 25.7 | 25.6 | 7.6 | 7.5 | 7.5 | 553 | 553 | 552 | 8.9 | 8.9 | 7.9 | 69.1 | 69.2 | 68.5 |
| 4.5 | 26.0 | 26.1 | 26.2 | 7.6 | 7.5 | 7.5 | 556 | 556 | 555 | 8.7 | 7.7 | 7.6 | 69.4 | 68.8 | 69.0 |
| 4.6 | 26.1 | 26.1 | 26.1 | 7.6 | 7.6 | 7.6 | 555 | 555 | 555 | 7.3 | 7.4 | 9.3 | 70.1 | 70.0 | 69.5 |
| 4.7 | 26.1 | 26.2 | 26.2 | 7.6 | 7.6 | 7.6 | 557 | 557 | 556 | 9.0 | 8.1 | 8.5 | 71.1 | 70.9 | 70.1 |
| 4.8 | 26.1 | 26.0 | 25.9 | 7.6 | 7.6 | 7.6 | 558 | 558 | 558 | 8.0 | 8.4 | 7.6 | 71.3 | 70.6 | 70.8 |
| 4.9 | 26.1 | 25.9 | 25.9 | 7.6 | 7.6 | 7.6 | 558 | 559 | 560 | 6.8 | 10.1 | 6.6 | 72.1 | 71.0 | 72.4 |
| 5.0 | 26.0 | 25.9 | 25.6 | 7.6 | 7.6 | 7.6 | 559 | 560 | 562 | 7.1 | 9.4 | 10.3 | 72.1 | 71.8 | 72.3 |
| 5.1 | 26.3 | 25.6 | 25.4 | 7.6 | 7.6 | 7.6 | 559 | 562 | 561 | 8.2 | 7.8 | 9.4 | 71.0 | 72.2 | 71.9 |
| 5.2 | 25.4 | 25.5 | 25.9 | 7.6 | 7.6 | 7.6 | 560 | 560 | 558 | 10.2 | 8.7 | 8.2 | 72.4 | 71.9 | 71.3 |
| 5.3 | 25.7 | 25.5 | 25.4 | 7.6 | 7.6 | 7.6 | 558 | 559 | 559 | 8.5 | 8.8 | 9.0 | 70.5 | 70.7 | 70.7 |
| 5.4 | 25.3 | 25.3 | 25.3 | 7.6 | 7.6 | 7.6 | 560 | 560 | 559 | 6.8 | 9.2 | 8.8 | 70.9 | 71.7 | 70.9 |
| 5.7 | 25.9 | 25.7 | 25.5 | 7.6 | 7.6 | 7.6 | 557 | 558 | 559 | 8.4 | 7.0 | 7.0 | 70.4 | 68.7 | 70.1 |
| 5.6 | 25.5 | 25.6 | 25.6 | 7.6 | 7.6 | 7.6 | 559 | 559 | 561 | 7.4 | 7.5 | 7.3 | 70.8 | 70.6 | 70.6 |
| 5.7 | 26.2 | 25.5 | 25.4 | 7.6 | 7.6 | 7.6 | 580 | 533 | 536 | 7.1 | 8.0 | 8.2 | 73.0 | 68.2 | 67.7 |

APPENDIX C. August 17th Sample Data.

| R-km | Temp (ºC) | pH (std) | SC (uS/cm) | DO (mg/L) | Cl (mg/L) | Cl (mg/L) | TN (mg/L) | TP (mg/L) | *E. coli* MPN |
|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 22.1 | 7.9 | 525 | 8.5 | 53.6 | 48.7 | 1.63 | 0.035 | 63 |
| 0.2 | 22.3 | 7.9 | 526 | 8.7 | 57.2 | 52.3 | 1.75 | 0.036 | 99 |
| 0.4 | 22.7 | 7.9 | 527 | 8.9 | 57.2 | 56.1 | 1.54 | 0.037 | 140 |
| 0.6 | 22.5 | 7.9 | 531 | 8.1 | 56.6 | 56.4 | 1.57 | 0.062 | 56 |
| 0.8 | 22.8 | 7.9 | 531 | 8.5 | 57.2 | 56.8 | 1.73 | 0.037 | 26 |
| 1.0 | 23.1 | 7.9 | 531 | 8.5 | 58.1 | 57.2 | 1.71 | 0.038 | 29 |
| 1.2 | 22.8 | 7.9 | 535 | 8.0 | 57.1 | 57.3 | 1.46 | 0.038 | 63 |
| 1.4 | 23.0 | 7.8 | 537 | 8.2 | 58.8 | 56.7 | 1.54 | 0.037 | 63 |
| 1.6 | 23.1 | 7.8 | 539 | 8.9 | 60.1 | 50.9 | 1.63 | 0.036 | 66 |
| 1.8 | 22.9 | 7.8 | 543 | 7.4 | 59.0 | 59.3 | 2.09 | 0.032 | 39 |
| 2.0 | 22.6 | 7.8 | 546 | 7.9 | 61.8 | 60.8 | 1.67 | 0.035 | 40 |
| 2.2 | 22.7 | 7.7 | 548 | 7.8 | 62.9 | 60.5 | 1.63 | 0.034 | 33 |
| 2.4 | 23.2 | 7.7 | 546 | 8.2 | 62.5 | 63.0 | 1.59 | 0.030 | 91 |
| 2.6 | 23.3 | 7.7 | 546 | 8.1 | 61.4 | 51.5 | 1.59 | 0.032 | 157 |
| 2.8 | 23.8 | 7.8 | 545 | 8.9 | 63.3 | 53.5 | 1.59 | 0.030 | 184 |
| 3.0 | 22.4 | 7.7 | 489 | 7.7 | 52.2 | 53.4 | 1.67 | 0.031 | 122 |
| 3.2 | 22.1 | 7.7 | 490 | 7.2 | 53.5 | 53.8 | 1.48 | 0.029 | 81 |
| 3.4 | 22.0 | 7.7 | 490 | 7.1 | 55.4 | 54.0 | 1.57 | 0.028 | 101 |
| 3.6 | 22.2 | 7.7 | 490 | 7.7 | 53.5 | 55.0 | 1.65 | 0.032 | 88 |
| 3.8 | 22.0 | 7.7 | 492 | 7.2 | 54.2 | 54.1 | 1.57 | 0.029 | 113 |
| 4.0 | 22.2 | 7.7 | 493 | 7.4 | 54.8 | 53.9 | 1.59 | 0.028 | 144 |
| 4.2 | 22.5 | 7.7 | 493 | 7.9 | 54.6 | 55.2 | 1.57 | 0.029 | 231 |
| 4.4 | 22.7 | 7.7 | 494 | 7.7 | 54.3 | 57.6 | 1.69 | 0.028 | 272 |
| 4.6 | 23.1 | 7.7 | 494 | 8.4 | 53.9 | 57.0 | 1.59 | 0.027 | 173 |
| 4.8 | 23.0 | 7.7 | 495 | 8.4 | 56.1 | 57.5 | 1.59 | 0.027 | 147 |
| 5.0 | 22.8 | 7.7 | 494 | 8.1 | 56.2 | 60.5 | 1.69 | 0.031 | 121 |
| 5.2 | 22.4 | 7.7 | 485 | 8.0 | 58.5 | 54.3 | 1.77 | 0.061 | 361 |
| 5.4 | 22.3 | 7.6 | 480 | 7.6 | 54.3 | 56.0 | 1.65 | 0.030 | 378 |
| 5.6 | 22.6 | 7.6 | 477 | 7.6 | 54.5 | 55.7 | 1.59 | 0.034 | 157 |

APPENDIX D. August 29th Sample Data.

| R-km | Temp (ºC) | pH (std) | SC (uS/cm) | DO (mg/L) | Cl (mg/L) | Cl (mg/L) | TN (mg/L) | TP (mg/L) | *E. coli* MPN |
|---|---|---|---|---|---|---|---|---|---|
| 0.0 | 24.1 | 7.9 | 585 | 7.4 | 54.4 | 51.4 | 1.24 | 0.032 | 173 |
| 0.1 | 24.0 | 7.9 | 587 | 6.9 | 55.5 | 54.9 | 1.22 | 0.032 | 155 |
| 0.2 | 24.2 | 7.9 | 587 | 7.5 | 55.5 | 56.7 | 1.04 | 0.031 | 225 |
| 0.3 | 24.4 | 7.9 | 586 | 7.7 | 55.1 | 56.5 | 1.26 | 0.032 | 118 |
| 0.4 | 24.6 | 7.9 | 586 | 8.0 | 54.9 | 59.1 | 1.28 | 0.033 | 84 |
| 0.5 | 24.5 | 7.9 | 587 | 7.7 | 55.8 | 59.1 | 1.16 | 0.032 | 133 |
| 0.6 | 24.4 | 7.9 | 590 | 7.1 | 55.9 | 58.5 | 1.33 | 0.044 | 130 |
| 0.7 | 24.7 | 7.9 | 589 | 7.4 | 56.1 | 58.2 | 1.22 | 0.036 | 131 |
| 0.8 | 25.0 | 7.9 | 589 | 8.1 | 55.7 | 58.4 | 1.28 | 0.033 | 91 |
| 0.9 | 25.1 | 7.9 | 591 | 8.4 | 56.0 | 57.9 | 1.33 | 0.030 | 80 |
| 1.0 | 25.0 | 7.9 | 593 | 7.8 | 56.4 | 55.5 | 1.28 | 0.032 | 91 |
| 1.1 | 24.9 | 7.9 | 595 | 7.2 | 57.0 | 57.4 | 1.26 | 0.032 | 197 |
| 1.2 | 24.7 | 7.9 | 597 | 7.2 | 56.8 | 58.3 | 1.28 | 0.032 | 98 |
| 1.3 | 24.8 | 7.8 | 600 | 7.6 | 58.3 | 58.4 | 1.33 | 0.030 | 185 |
| 1.4 | 24.8 | 7.8 | 600 | 6.8 | 57.0 | 60.0 | 1.28 | 0.032 | 178 |
| 1.5 | 25.0 | 7.8 | 600 | 7.2 | 58.2 | 60.3 | 1.37 | 0.031 | 150 |
| 1.6 | 25.1 | 7.8 | 602 | 8.2 | 58.7 | 56.2 | 1.35 | 0.029 | 119 |
| 1.7 | 24.8 | 7.8 | 604 | 8.0 | 58.5 | 58.7 | 1.35 | 0.030 | 135 |
| 1.8 | 24.8 | 7.8 | 605 | 7.6 | 59.1 | 58.3 | 1.39 | 0.029 | 127 |
| 2.2 | 24.2 | 7.7 | 609 | 7.1 | 57.4 | 54.9 | 0.91 | 0.052 | 722 |
| 2.3 | 24.2 | 7.6 | 604 | 7.2 | 57.5 | 57.3 | 1.35 | 0.035 | 313 |
| 2.4 | 24.6 | 7.6 | 603 | 7.5 | 59.4 | 60.3 | 1.33 | 0.034 | 313 |
| 2.5 | 24.8 | 7.7 | 605 | 7.1 | 59.7 | 61.1 | 1.33 | 0.031 | 162 |
| 2.6 | 24.9 | 7.7 | 608 | 7.4 | 59.5 | 61.6 | 1.37 | 0.031 | 361 |
| 2.7 | 25.7 | 7.8 | 606 | 8.8 | 63.0 | 63.6 | 1.30 | 0.031 | 436 |
| 2.8 | 25.8 | 7.8 | 613 | 8.7 | 62.8 | 64.8 | 1.33 | 0.031 | 285 |
| 2.9 | 25.7 | 7.9 | 614 | 8.4 | 61.6 | 63.1 | 1.26 | 0.029 | 378 |
| 3.0 | 24.5 | 7.7 | 616 | 7.0 | 60.2 | 57.4 | 1.24 | 0.029 | 142 |
| 3.1 | 24.0 | 7.7 | 621 | 6.7 | 59.9 | 58.4 | 1.49 | 0.030 | 1011 |
| 4.0 | 23.9 | 7.7 | 622 | 6.7 | 60.4 | 60.0 | 1.39 | 0.028 | 659 |
| 4.1 | 23.7 | 7.7 | 625 | 6.1 | 61.6 | 62.6 | 1.37 | 0.026 | 167 |
| 4.2 | 24.3 | 7.6 | 625 | 6.8 | 60.9 | 63.0 | 1.41 | 0.023 | 133 |
| 4.3 | 24.5 | 7.7 | 626 | 7.0 | 62.4 | 64.6 | 1.39 | 0.023 | 173 |
| 4.4 | 24.5 | 7.6 | 624 | 7.3 | 61.7 | 64.3 | 1.35 | 0.071 | 206 |
| 4.5 | 24.3 | 7.6 | 625 | 6.8 | 63.1 | 63.1 | 1.33 | 0.025 | 158 |
| 4.6 | 25.0 | 7.6 | 623 | 7.7 | 61.5 | 61.7 | 1.37 | 0.033 | 146 |
| 4.7 | 25.4 | 7.7 | 622 | 8.0 | 62.1 | 64.6 | 1.35 | 0.027 | 135 |
| 4.8 | 25.5 | 7.7 | 623 | 7.7 | 62.0 | 67.7 | 1.41 | 0.030 | 204 |
| 4.9 | 25.2 | 7.7 | 630 | 7.5 | 64.3 | 69.2 | 1.39 | 0.030 | 190 |
| 5.0 | 25.0 | 7.7 | 632 | 7.6 | 64.9 | 69.7 | 1.55 | 0.062 | 199 |
| 5.1 | 24.7 | 7.7 | 637 | 7.1 | 65.5 | 67.6 | 1.39 | 0.030 | 272 |
| 5.2 | 24.3 | 7.7 | 639 | 7.4 | 66.2 | 61.7 | 1.41 | 0.033 | 168 |
| 5.3 | 23.9 | 7.7 | 639 | 7.5 | 66.4 | 63.6 | 1.43 | 0.032 | 162 |
| 5.4 | 23.5 | 7.7 | 640 | 7.1 | 67.4 | 66.2 | 1.45 | 0.026 | 249 |
| 5.7 | 23.9 | 7.7 | 638 | 7.4 | 66.1 | 65.3 | 1.45 | 0.030 | 260 |
| 5.6 | 23.8 | 7.7 | 637 | 7.5 | 65.8 | 65.0 | 1.22 | 0.030 | 167 |
| 5.7 | 24.0 | 7.6 | 635 | 7.5 | 65.3 | 64.4 | 1.39 | 0.062 | 250 |