MICROBIAL RISK PERSPECTIVE ON THE TEMPORAL AND SPATIAL VARIABILITY OF INDICATOR BACTERIA FOUND IN TEXAS URBAN AND RURAL WATERSHEDS

A Thesis

by

SRIAMBHARRISH SRINIVASAN RAVICHANDRAN

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2011

Major Subject: Civil Engineering

Microbial Risk Perspective on the Temporal and Spatial Variability of Indicator Bacteria Found in Texas Urban and Rural Watersheds

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Approved by:

Chair of Committee,	Robin Autenrieth
Committee Members,	Bryan Boulanger
	Jean Brender
Head of Department,	John Niedzwecki

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ABSTRACT

Microbial Risk Perspective on the Temporal and Spatial Variability of Indicator Bacteria Found in Texas Urban and Rural Watersheds.

(May 2011)

Sriambharrish Srinivasan Ravichandran, B.Tech, Visvesvaraya National Institute of Technology, Nagpur, India

Chair of Advisory Committee: Dr. Robin Autenrieth

The high incidence of pathogens is one of the main causes for impaired surface water quality designations in the United States. Pathogen presence in fresh water is monitored through the detection of indicator bacteria. Indicator bacteria concentrations, spatial and temporal variability, and microbial risks were evaluated in two rural watersheds, the Bosque and Leon Rivers, and one predominantly urban watershed, the San Jacinto River, all in Texas. Human health risk was predicted from contaminated waters as indicated by ingestion of *Escherichia coli* found in surface water for contact recreation scenarios. The watersheds were chosen because many segments were previously placed on the 303 (d) list (published by the TCEQ) for failing the indicator bacteria standards. Predominantly urban areas of the San Jacinto River and rural portions of the Bosque and Leon Rivers, where Concentrated Animal Feeding Operations (CAFOs) are numerous, were compared to relatively pristine rural watersheds. Spatial analysis of the watersheds with *E.coli* concentrations

exceeding the single sample (394 MPN/100mL) and the geometric mean standards (126 MPN/100mL) indicated that land use is a significant factor influencing the incidence of bacterial concentrations. Non-agricultural rural areas of the watersheds, such as forests and rangelands, had significantly lower *E.coli* concentrations compared to the agricultural areas and urban land uses. Human health risk due to ingestion of *E.coli* as an indicator organism indicated a similar pattern to that of their concentrations in that urban and agricultural areas had a greater risk compared to the other rural areas of the watersheds. The risk estimate for urban and agricultural areas exceeded the acceptable limit of one in ten thousand (10^{-4}), indicating a potential for adverse health effects to humans. Temporal variability in the watersheds as a function of streamflow, rainfall, and temperature indicated a positive correlation between bacterial concentration and high streamflow, rainfall and temperature. The positive correlation for these effects was greater in the rural areas compared to urban areas, indicating the presence of multiple factors responsible for *E.coli* concentrations in urban areas. Thus, land use was confirmed to be a major factor contributing to the presence of indicator bacteria in surface waters.

DEDICATION

Dedicated to my parents

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I am lucky to have a very supportive family who have always appreciated me and stood by my troughs and peaks. Many a thanks to my parents who gave me the dream of pursuing a master's degree and helped me through it financially and otherwise. Thanks are also due to all my friends who made my stay in College Station a memorable experience. Special thanks to my friend Tanushri Doshi for her support when the going got tough.

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1. INTRODUCTION AND LITERATURE REVIEW

The high incidence of pathogens is a major factor affecting the quality of surface waters in the United States. According to the U.S. Environmental Protection Agency's (USEPA) 2008 National Water Quality Inventory, thirteen percent of streams and river miles in the nation were impaired and unsuitable for contact recreation due to the presence of indicator bacteria (U.S. Environmental Protection Agency, 2008). In Texas, the 2004 Texas Water Quality Inventory and 303 (d) list identified 183 stream segments as impaired for contact recreation due to high concentrations of indicator bacteria.

The Texas Surface Water Quality Standard (SWQM) defines contact recreation in waters as those recreational activities that involve a significant risk due to ingestion of water, including wading by children, swimming, water skiing, diving, and surfing (Texas Natural Resource Conservation Commission, 2000). Exposure to surface water during contact recreation in the impaired segments has been known to cause irritation and infection of the eye, skin, nose, ear, and throat; lead to gastro-intestinal diseases; and cause respiratory illnesses due to the presence of various bacteria, viruses, and protozoa (Pruss, 1998). These health effects are of particular concern for the elderly, children and immune-compromised individuals. Apart from the direct exposure through contact

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This thesis follows the style of *Water Environment Research.*

recreation, the impairment of surface water threatens drinking water quality on which two-thirds of the United States depends for drinking water sources.

The EPA is responsible for maintaining water quality and administering the water quality standards program in the United States. The EPA is responsible for providing recommendations and guidelines to the states, evaluating standards set by states, and overseeing the enforcement of standards and compliance. Surface water quality standards are set by states, territories and Indian tribes for the area under their jurisdiction that define the purpose of the waterbody and set limits for use (U.S. Environmental Protection Agency, 2003a). The Clean Water Act (CWA) enacted by the EPA regulates the surface water standards through its National Pollution Discharge Elimination System (NPDES). The NPDES regulates the point sources that discharge pollutants into the national waters and is administered through the authorized states (U.S. Environmental Protection Agency, 2003a).

For the state of Texas, Title 30, Chapter 307 of the Texas Administrative Code (TAC) codifies the Texas Surface Water Quality Standards. These are written by the Texas Commission on Environmental Quality (TCEQ) under the authority of the CWA and the Texas Water Code (TWC). The water bodies have been divided into various segments based on their regional hydrologic and geologic diversity (Texas Commission on Environmental Quality, 2010a). The various segments that are impaired by the presence of bacteria are described in the Texas Water Quality Inventory and 303 (d) list.

Testing of waterway impairment due to contamination by microorganisms that pose a human health problem is based on indicator organisms. These organisms are used to indicate the potential presence of other more harmful organisms that are difficult to detect. The most commonly used indicator bacteria are fecal coliform, total coliform, *Enterococci* and *Escherichia coli*. Among these, *E.coli* are the bacteria recommended for fresh waters because their presence is correlated to the occurrence of many microorganisms that cause water-borne diseases. The incidence of *E. coli* presence is a measure of water safety for contact recreation (Myers *et al.*, 2007; U.S. Environmental Protection Agency, 1986). *E.coli* is a fecal coliform present in the gastrointestinal tract of warm-blooded animals, including humans (Haas *et al.*, 1999). The *E.coli* standards in surface waters are given in terms of Most Probable Number (MPN). MPN is a method to estimate the density of organism in a liquid without any direct count. A numeric estimate of microbial growth is determined after incubating a sample in a suitable culture medium and defined conditions (Cochran, 1950). For recreational use, the standards are 394 MPN/100 mL for single samples and 126 MPN/100mL for geometric mean of samples (Texas Natural Resource Conservation Commission, 2000). Segments with indicator bacterial concentrations exceeding these values are considered impaired.

Statistical methods were used to analyze and compare the incidence of indicator bacteria and variability with stream flow, precipitation and temperature in rural and urban watersheds in this study. The Bosque and Leon River

watersheds are predominantly agricultural watersheds with similar land-use (Brazos River Authority, 2010b; Rosenthal and Hoffman, 1999). The San Jacinto River watershed has a diverse land-use in the upper half, with a predominantly urban land-use in the lower half (Espey Consultants, 2009). These watersheds were chosen because many segments of these rivers were found to be impaired due to elevated levels of indicator bacteria (Brazos River Authority, 2010a; Texas Commission on Environmental Quality, 2008b). A microbial risk assessment of *E.coli* was also performed in this study to evaluate the potential human health risk due to the ingestion of *E.coli* during contact recreation.

1.1 Urban and Rural Watersheds

The land use characterization of a watershed affects the quality and quantity of runoff from the land to its surface waters. In a rural landscape, vegetation slows the flow of surface runoff, allowing more absorption into the soil. In an urban landscape, large areas are covered by impervious materials such as concrete and asphalt, leading to a greater quantity of runoff along with a decrease in percolation (Carlsen and Trautmann, 2004). This variation in land use has been documented to affect water quality (Smith *et al.*, 2001). Point and Nonpoint Sources (NPS) of pollution in the watershed are used to characterize the effect of land use. While a point source of pollution is a single, localized source of pollution, NPS pollution occurs when snowmelt or rainfall runoff from

large area sources, such as agricultural lands, highways, and backyards, cause pollution of surface water or groundwater.

Though it is difficult to measure and assess the effect of land use on stream quality (Landers *et al.*, 2002), a water quality report from the EPA indicates that agriculture is the leading source of water quality impairments, causing the degradation of sixty percent of the impaired river miles and half of the impaired lake acreage. The report also states that NPS pollutants such as organic waste from cattle, pesticides, nutrients, and sediments are the major contributors of pollution in rural areas (U.S. Environmental Protection Agency, 2010a). The United States has experienced a marked increase in animal production in the last 25 years, leading to increased water quality problems due to poor management of animal wastes (Arikan *et al.*, 2008). The last 50 years has also seen the reduction of small scale family owned farming operations and the increase of medium-sized and large Concentrated Animal Feeding Operations (CAFOs). The manure from CAFOs can pose a significant source of pollution because they generate large quantities of waste that exceed the capacity for land application, a common disposal practice. CAFOs produce more than 500 million tons of manure annually, which is three times greater than the human sanitary waste (U.S. Environmental Protection Agency, 2003b). The numbers of animals that constitute large and medium CAFOs are shown in Table 1.1.

The dense animal population housed at CAFOs necessitates effective management practices to protect environmental resources. Uncontrolled release of wastes from CAFOs to surface and ground water commonly occurs due to lagoon spills and seepage from storage units, and from poor siting in flood plains, aquifers, sandy soils and high water table areas and is exacerbated during storm events (Hodne, 2005).

Table 1.1 Number of animals that constitute a small and large CAFO

Animal	Size threshold (number of animals)	
	Large CAFOs	Medium CAFOs
Cattle or cow/calf pairs	1,000 or more	300-999
Mature dairy cattle	700 or more	200-699
Swine (< 55 pounds)	2,500 or more	750-2,499
Swine (> 55 pounds)	10,000 or more	3,000-9,999
Sheep or Lambs	10,000 or more	3,000-9,999
Chickens(not laying hens)	125,000 or more	37,500 to 124,999
Laying hens	82,000 or more	25,000 to 81,999
Turkeys	55,000 or more	16,500-54,999

Source: USEPA(2010b)

Runoff and release from urban areas have been identified as the second leading cause of impairment to surface waters in the country (U.S. Environmental Protection Agency, 2010a). Point sources identified as sources of pollution to surface water can include discharges from municipal and industrial Waste Water Treatment Plants (WWTPs) (Vega *et al.*, 1998) and leaks in sewer

collection systems (Whitlock *et al.*, 2002). Failing septic systems (Crabill *et al.*, 1999), urban storm water and sewage overflows (McLellan *et al.*, 2007), and presence of domestic and wild animals (Whitlock *et al.*, 2002) are some of the most significant NPS sources of bacterial pollution in urban areas.

The spatial and temporal variability of bacteria in watersheds is impacted by point and NPS sources as well as natural or induced environmental conditions. Variability in the stream flow due to varying precipitation and discharge from Waste Water Treatment Plants (WWTPs) leads to variability in water quality (Vega *et al.*, 1998). Peterson et al. *(*2005*)* found that bacterial concentration increased in the White Oak Bayou, San Jacinto River during wet weather, possibly due to the presence of resuspended sediment or overflows, bypasses and leaks in the sewage infrastructure. Traister and Anisfeld (2006) observed that the time of the sampling, incorporating both storm sampling and dry weather conditions, made a difference in the water quality observed. A high correlation was also observed between the water temperature and indicator bacterial concentrations (Silsbee and Larson, 1982). Lee et al.(2004) observed a distinctive effect of the first flush phenomenon on water quality. First flush is defined as the presence of higher concentrations of pollutants during the first part of a storm event (Gupta and Saul, 1996). Thus all these factors should be evaluated to determine the cause of variability in a watershed's water quality.

1.2 Microbial Risk Assessment

Risk assessment is the field of estimating (qualitatively and quantitatively) the potential health hazards to individuals or populations due to their exposure to physical, chemical or microbial agents (Haas *et al.*, 1999). Risk assessment is part of the larger subject of risk analysis, which involves risk management and risk communication, apart from risk assessment. Quantitative Microbial Risk Assessment (QMRA) is a branch of risk assessment involving the quantitative evaluation of risk arising from exposure to microorganisms. QMRA is increasingly being used to set standards for discharges into surface water. Previous studies have also used the QMRA to evaluate the public health hazards arising from contaminated surface water (Schroeder *et al.*, 2007). For example, An et al. (2007) used quantitative microbial risk assessment to assess the human health risk as a result of exposure to *E.coli* in reclaimed wastewater irrigation and concluded that significant risks greater than the acceptable limit exist . Ryu et al. (2005) used QMRA to calculate annual risk estimates from exposure to *Cryptosporidium* in the Rio-Grande River and found that risk to human health was two orders of magnitude greater than the acceptable limit. This estimation of risk through the QMRA process is prescribed as a four step process that begins with hazard identification, then exposure assessment and dose-response assessment, and followed by the risk characterization.

1.2.1 Hazard Identification

Hazard Identification (HI), the first step in QMRA, involves identifying the microorganisms of concern and evaluating the nature of the adverse health effects associated with the microorganisms and their toxins, either quantitatively or qualitatively (World Health Organization, 1999) Various segments in the watersheds under study have been placed on the impaired segments list by TCEQ due to the presence of pathogens(Texas Commission on Environmental Quality, 2008b). *E.coli* was chosen as the microorganism of concern because it serves as an indicator to various pathogens. A minimum of four types of *E.coli* have been identified as pathogenic to humans. These are enterotoxigenic (ETEC), enterohemorrhagic (EHEC-O157:H7), enteropathogenic (EPEC), and enteroinvasive (EIEC) *E.coli*. ETEC is known to cause many illnesses such as gastroenteritis, diarrhea, nausea, abdominal cramps, and vomiting. EPEC is known to affect infants and newborns predominantly, causing overt illnesses in 25% of the kids below age one (DuPont *et al.*, 2009). Infection by the *E.coli* O157:H7 strain can lead to a watery, bloody diarrhea with abdominal cramps, and eventually could lead to Hemolytic Uremic Syndrome (HUS), with a chance of mortality in up to 10% of the cases. Children and the elderly are the most adversely affected (Haas *et al.*, 1999). The U.S. Department of Agriculture (USDA) estimates that 62,000 cases of *E.coli* O157:H7 infections occur every year in the United States through the ingestion of contaminated food and water leading to 1,800 hospitalizations and 52 deaths. Among these cases 3,000

develop HUS, which has a higher incidence rate among children less than five years of age (U.S. Department of Agriculture, 2001).

1.2.2 Exposure Assessment and Dose-response Evaluation

Exposure assessment begins with the quantification of the number of organisms for a likely single exposure or a set of exposures (World Health Organization, 1999). Exposure is expressed in the form of probability distributions. The most commonly used distribution for microorganisms is Poisson. For samples obtained sources that do not fit the Poisson curve, other distributions need to be tested for the best fit. Regli et al.(1991) developed a beta-Poisson distribution for microorganisms that can be used to obtain the probability of infection for direct and recreational exposure of these surface waters. This distribution is obtained by replacing the fraction of ingested organisms in an exponential distribution by a beta distribution, resulting in a beta-Poisson distribution.

$$P_I = 1 - [1 + \frac{N(2^{\frac{1}{\propto}} - 1)}{N_{50}}]^{-\alpha} \qquad (1.1)$$

In equation (1.1), α characterizes the dose-response curve (obtained from dose-response evaluation); N is the number of microorganisms in V, the sample volume; N_{50} is the microbial risk resulting in infections to 50% of the population; and P_I is the probability of infection. Assumptions on host heterogeneity factors and the nature of infection process were used in deriving this equation (U.S.

Department of Agriculture, 2001). Equation (1.2) is used to determine the probability of annual risk from the probability of infection.

$$P_A = 1 - (1 - P_I)^n \quad (1.2)$$

where, n is the number of exposures annually. Alternatively, equation (1.1) can also be written in the following form:

$$P_I = 1 - (1 + \frac{D}{\beta})^{-\alpha} \quad (1.3)$$

where D is the dose of microorganisms, β is the fitting parameter related to dose for 50% of the population getting infected, and α is the co-efficient of the dose-response curve. Various point-estimate and distribution data are available for use in calculating final risk values. A large database of this information exists due to studies on exposure to other agents and the values have reached a consensual status (Haas *et al.*, 1999).

1.2.3 Risk Characterization

Risk characterization is the quantitative or qualitative determination of the probability and severity of occurrence of adverse health effects (World Health Organization, 1999). It also involves the communication of the risk values obtained. The most widely applied tool for performing risk characterization calculation is the Monte Carlo method, which is also used for obtaining uncertainty and variability (Burmaster and Anderson, 1994). In this method a series of trials are performed by selecting random values from the distribution

used for defining the variables in an equation. A resultant distribution of risks is obtained from the large number of trials. The accuracy of this output will depend on the variability and uncertainty of the data (Haas *et al.*, 1999).

After the risk is calculated, sensitivity and uncertainty analyses are performed to determine the most important factors affecting the result and the factors that contribute most to the uncertainty in the final risk values, due to the uncertainties associated with model inputs, assumptions and structure. This type of analysis is also useful in identifying data gaps (Schroeder *et al.*, 2007). Comparison of epidemiological data with calculated risk values can reveal the link between a particular pathogen and disease, thereby focusing the available resources on the right pathogen. This analysis combined with epidemiological data can help in identification of seasonal or other types of variations in risks and reveal possible disagreements between the epidemiological data and the characterized risk. If contradictions occur, it can result in a re-examination of the data used for the study or help validate the risk model used for the risk assessment (Miliotis *et al.*, 2008).

The results obtained can be used in prescribing the appropriate risk management options and communicate the risk to the general public. Modifying standards used for regulation of waterbodies to safeguard public health would be an example of the utility of performing such a risk analysis (Schroeder *et al.*, 2007).

1.3 Significance of Study

A statistical analysis of bacterial water quality and the various factors affecting it can be a useful approach in characterizing the watershed and predicting responses to various identified controlling factors. Although a mechanistic model can be used for the same purpose, such approaches can be time-consuming and costly due to set-up, calibration, and validation. Instead, an empirical model is useful to determine where a water quality model could be implemented for watersheds with similar characteristics and useful to study the spatial and temporal pattern within a river, especially since the physical, chemical, and biological fate and transport of bacteria pose such uncertainty (Desai *et al.*, 2010). Numerous regression models have been developed for a number of watersheds (Desai *et al.*, 2010; Hathaway and Hunt, 2010; McLellan *et al.*, 2007; Petersen *et al.*, 2005; Shah *et al.*, 2007; Traister and Anisfeld, 2006; Vega *et al.*, 1998). These statistical models are more watershed specific and must be calibrated for each application. The study being reported is unique in that it analyzes the water quality and its variability in rural and urban watersheds during the same time period and also combines the public health risks associated from the water quality using QMRA approach.

2. OBJECTIVES AND AIMS

The primary goal of this study is to develop a comparison of urban and rural watersheds based on the spatial and temporal variability of bacterial concentrations, public health risks, and response to the stressors of rainfall, temperature and stream flow.

The objectives of the study are to:

- Inventory available data on bacterial concentrations in select Texas watersheds, compile this data and compare the exceedances of single sample and geometric mean standards
- Use statistical analysis to evaluate the variability among the rivers and within the same river.
- Use Monte Carlo analysis to create distributions of *E.coli* concentrations and perform microbial risk assessments to obtain quantifiable human health risk estimates from ingestion due to water ingestion through contact recreation in the rivers.
- Use statistical methods to study the temporal variation of *E.coli* during the time of study and observe the increase or decrease in water quality.
- Analyze the effect of rainfall on the water quality in the rivers though statistical methods.
- Use statistical methods to study the effect of stream flow in the rivers
- Use statistical methods to analyze the effect of weather on water quality

3. MATERIALS AND METHODS

3.1 Watershed Characteristics

The San Jacinto River (SJR) watershed rises from the confluence of the East and West Fork San Jacinto Rivers that form Lake Houston, joins the Houston Ship Channel and drains into the Galveston Bay (Figure 3.1). The River drains an area of 11,650 km^2 along mostly level terrain. The lower end of the river is tidally influenced and is affected by storm surges (Harris County Flood Control District, 2010). The land use along this watershed is different for the upper and lower half. The upper half of the watershed consisting of the Spring Creek, West Fork SJR, and East Fork SJR has a predominantly rural land use as indicated in Table 3.1 and Figure 3.2.

The lower half of the watershed comprising the Buffalo, White Oak and Greens Bayous, and Houston Ship Channel is characterized by predominantly developed, urban and industrialized areas as shown in Table 3.1and Figure 3.2

Table 3.1 Land use and land cover distribution for the San Jacinto River watershed segments

	Upper SJR			Lower SJR
	Spring Creek	West Fork SJR	East Fork SJR	
	(%)	(%)	(%)	(%)
Water	0.50%	4.80%	0.50%	2.20%
Developed	24.80%	14.60%	10.90%	65.40%
Barren	0.50%	0.40%	0.10%	0.50%
Forest	23.60%	32.10%	44.00%	7.30%
Shrub/Grass	11.10%	13.50%	18.20%	4.10%
Agricultural	31.00%	20.00%	8.30%	13.30%
Wetlands	8.50%	14.60%	17.90%	7.10%

Source: Espey Consultant Inc.(2009)

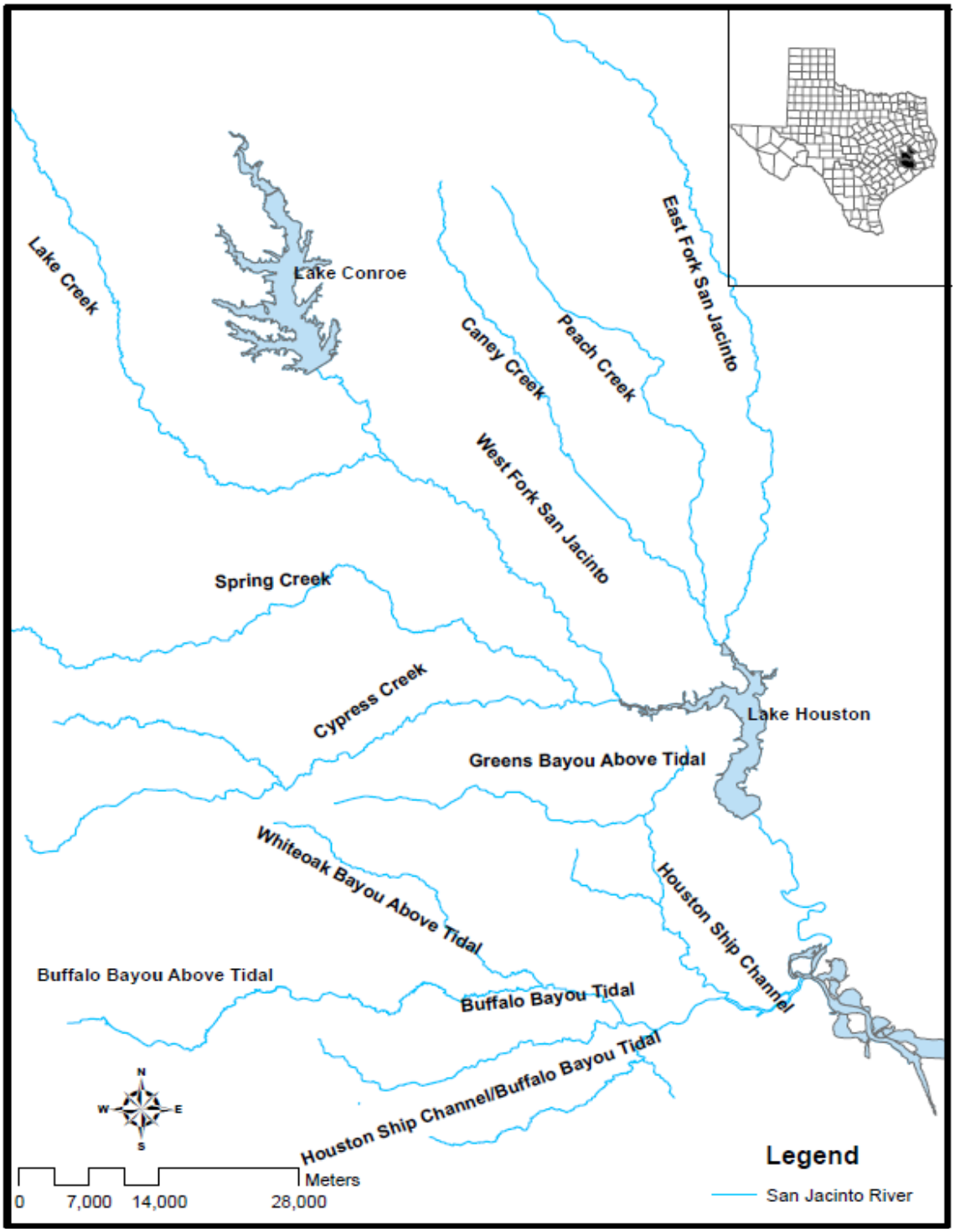


Figure 3.1 Map of San Jacinto River watershed with its stream segments

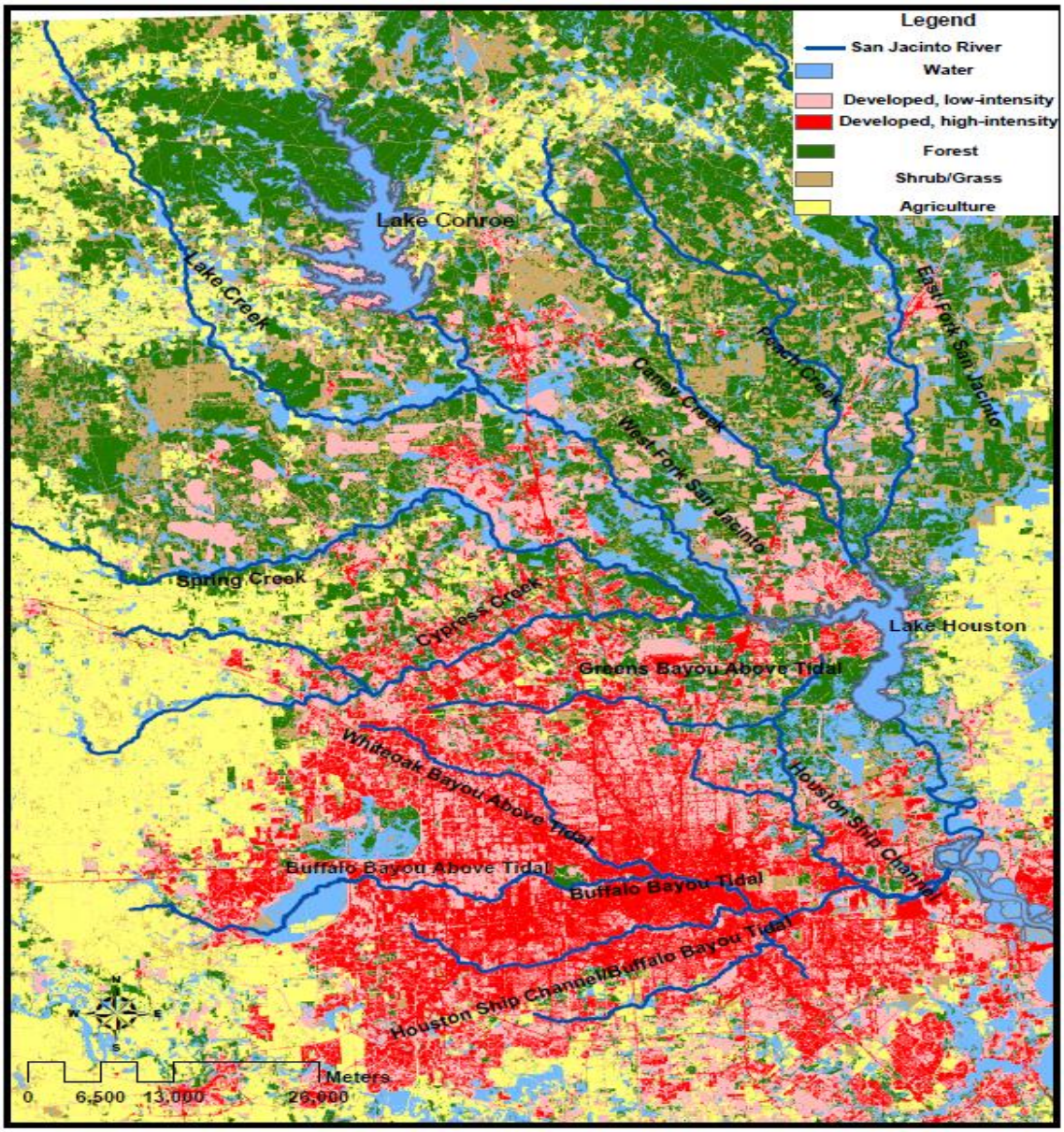


Figure 3.2 Land use map for the SJR watershed. Low-intensity developed areas are urban areas with a mixture of constructed materials and vegetation and include single-family housing units. Impervious cover occupies less than 50% of total cover. High-intensity developed areas are urban areas where high population density areas which house row-houses, apartment complexes, and commercial/industrial establishments. Impervious cover accounts for 50-100% of the total cover (Homer et al., 2004)

(Espey Consultants, 2009). The Lake Houston area is highly urbanized. The Houston Ship Channel region is heavily industrialized and supports the Port of Houston, the third largest port in the world (Harris County Flood Control District, 2010).

The SJR watershed has a subtropical humid climate with an average rainfall ranging from 1,270 mm to 1,397 mm. Rainfall peaks typically occur during the months of June and September (Estaville and Earl, 2008). For this study, the River was divided into segments consistent with the TCEQ designations. These are the Buffalo Bayou tidal and above tidal influence zones, Caney Creek, Cypress Creek, East Fork and West Fork SJR, Greens Bayou above tidal zone, Houston Ship Channel, Houston Ship Channel-Buffalo Bayou Tidal zone (HSC-BBT), Lake Creek, Peach Creek, Spring Creek, and the White Oak Bayou. These segments are indicated in Figure 3.1.

The Bosque River is present in the Brazos River watershed and consists of four main segments: North, East, South Bosque Rivers and Hog Creek (Figure 3.3). The Bosque river watershed drains an area of 4150 Km^2. The river extends from the City of Waco in McLennan County through Bosque, Coryell, Hamilton and Erath counties. The four major segments form Lake Waco at their confluence. Land cover in the watershed is predominantly rural consisting of cropland, pasture, forest, and rangeland as indicated in Table 3.2 and Figure 3.4(Brazos River Authority, 2010b). The watershed has a subtropical, sub-humid climate with hot summers and dry winters. Average annual precipitation is 760

mm with peaks in spring and fall. The river has intermittent flow and flash-floods during the heavy rains. Base flow is minimal and the river dries quickly due to a combination of impermeable soils and limestone rocks, and hence some of the tributaries have a tendency to become dry during the summer months. More than 100 dairy CAFOs are present, predominantly along the impaired waterways indicated in the 303(d) list. Other agricultural activities in this region include 13 turkey farms and production of peanuts, pecans, and beef cattle (Brazos River Authority, 2010b). The segments considered in this study are the North Bosque River, Duffau Creek, Green Creek, Indian Creek, Meridian Creek, Middle/South Bosque River, Neils Creek, Sims Creek and Spring Creek (Figure 3.3).

Table 3.2 Major land use and land cover distribution for the Bosque River watershed

	Bosque River (%)
Pasture	15
Range/Forest	64
Row and Non-row crops	17
Urban	2
Dairy Waste Application Fields	2

Source: Santhi et al. (2001)

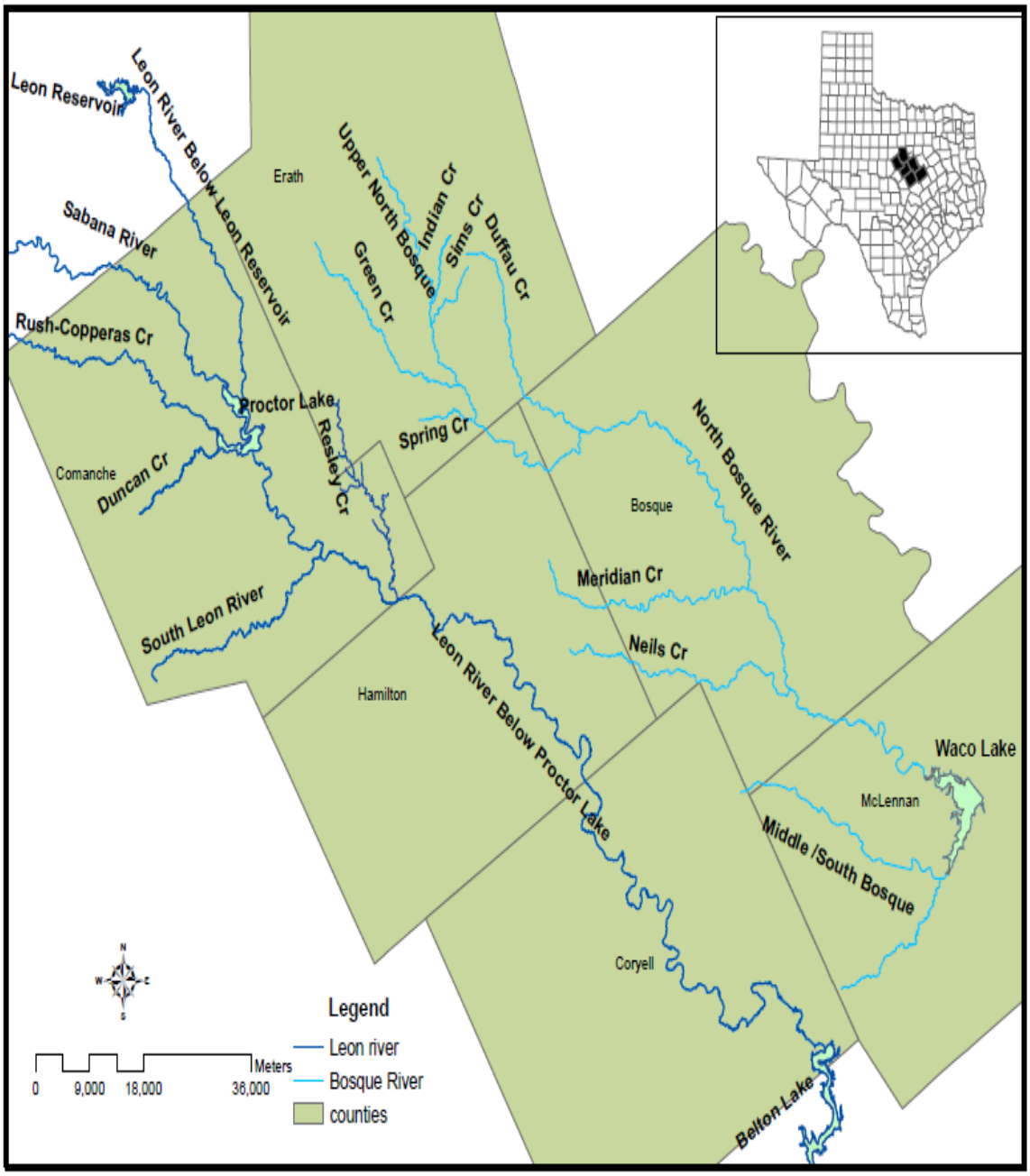


Figure 3.3 Map of Leon and Bosque River watersheds with their stream segments

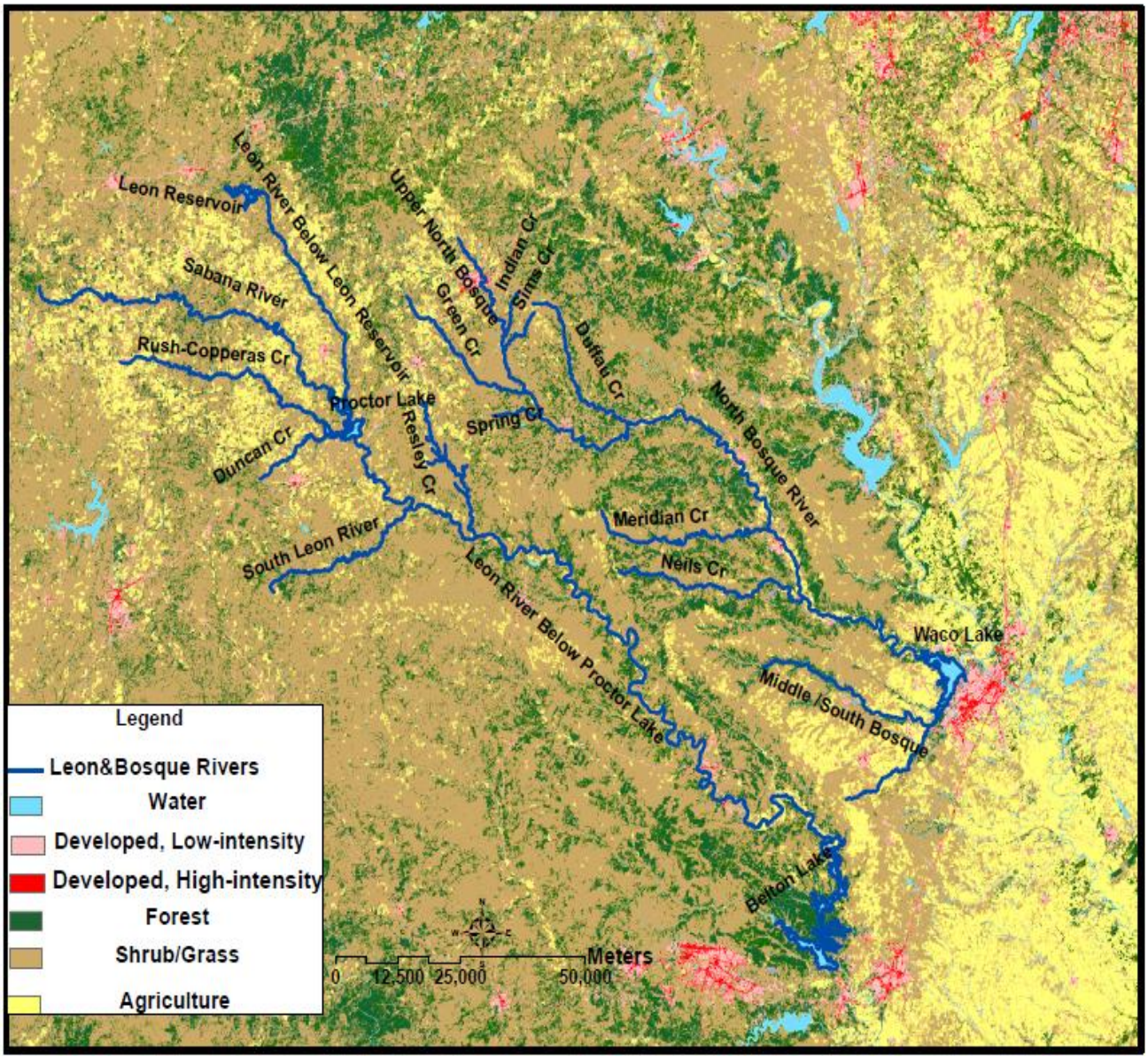


Figure 3.4 Land use map for the Bosque and Leon River watersheds. Low-intensity developed areas are urban areas with a mixture of constructed materials and vegetation and include single-family housing units. Impervious cover occupies less than 50% of total cover. High-intensity developed areas are urban areas where high population density areas which house row-houses, apartment complexes, and commercial/industrial establishments. Impervious cover accounts for 50-100% of the total cover (Homer et al., 2004)

The Leon River watershed drains 9000 Km^2 and runs through Bell, Coryell, Hamilton, Comanche and Eastland counties (Figure 3.3). The main segment is the Leon River which is divided into two parts by the Proctor Lake. The river empties into the Belton Lake, the drinking water source for 250,000 people. The predominant land uses in the watershed are cropland and pasture in the southern part and rangeland in the north. Urban areas account for about 20% of the overall area (Figure 3.4). Average precipitation in the region ranges from 627 to 864 mm, with average temperature ranging from 8° to 29° C. Over 100 dairy CAFOs are present in the watershed and farm sizes range from 50 to 1000 head per unit (Rosenthal and Hoffman, 1999). The segments considered in this study are the Leon River below Leon Reservoir, Leon River below Proctor Lake, Resley Creek and Duncan Creek (Figure 3.3).

3.2 Data Assembly

Data on the concentration of *E.coli*, stream flow, precipitation and temperature were compiled from several databases. *E.coli* concentration data for the San Jacinto River in the last 10 years were obtained from the TCEQ database (Ragland, 2010). The data for the Bosque and Leon River watersheds were obtained directly from the sampling data query page on the Surface Water Quality Monitoring (SWQM) section of the TCEQ website. Additional concentration data for the Bosque River watershed was obtained from the Texas Institute for Applied Environmental Research (TIAER) database (Personal communication through email with Anne McFarland, TIAER). The TCEQ, in turn,

obtains the concentration data from various monitoring agencies in the state. The data collected by the TCEQ is part of the routine physicochemical and bacterial monitoring data collected by the TCEQ, contributing river authorities, cities, and other state, local and federal agencies from 8500 monitoring stations spread across 347 classified stream segments and other unclassified stream segments (Texas Commission on Environmental Quality, 2010c). Surface water *E.coli* concentrations available for the years 2007, 2008 and 2009 were used for the San Jacinto River. The data from years 2005 to 2009 were used for Bosque and Leon Rivers. These consisted of data from samples taken on varying schedules, ranging from four times a year to twelve times a year.

Concentration data obtained were in the .txt format with the individual parameters delimited by the tab ('|') symbol. These files were imported into Microsoft Excel in the required format. The headings for all the parameters are in the form of acronyms, whose expanded forms can be obtained from the TCEQ website. (Texas Commission on Environmental Quality, 2010c) The data was further filtered to only have the *E.coli* concentrations.

The data accessed consisted of *E.coli* samples from classified and unclassified stream segments and lakes, which were taken over a 24-hour time period to constitute a composite sample. The SWQM guidelines published by TCEQ gives detailed guidance for the submitting agencies regarding the sampling procedure, including sampling containers, dilution, labeling, preparation, preservation and holding time. It also provides detailed guidance for

analysis of the sample using the IDEXX colilert method, which was used for the analysis by the various submitting agencies. These include the equipment and reagents used for the analyses, record keeping, standard sample dilutions, detailed analysis procedures, data interpretation and recording, determining the MPN and finally the reporting guidelines.

Recorded daily average stream flow for the monitoring stations in the San Jacinto, Bosque and Leon Rivers were obtained from the U.S. Geological Survey (USGS) database (U.S. Geological Survey, 2010). Additional daily average flow data for the Bosque River watershed were obtained from the TIAER database (McFarland, 2010). Recorded precipitation for the stations in the Harris County was obtained from the Harris County Homeland Security and Emergency Management database (Harris County Homeland Security and Emergency Management, 2010). Precipitation data for the other stations were obtained from the National Oceanic and Atmospheric Administration (NOAA) (National Climatic Data Center, 2010). The same *E.coli* monitoring stations (Figures 3.5 and 3.6) were used for studying concentration, flow and rainfall. The GIS layers used for creating the maps in the ArcMap software were obtained from the TCEQ database (Texas Commission on Environmental Quality, 2010b).

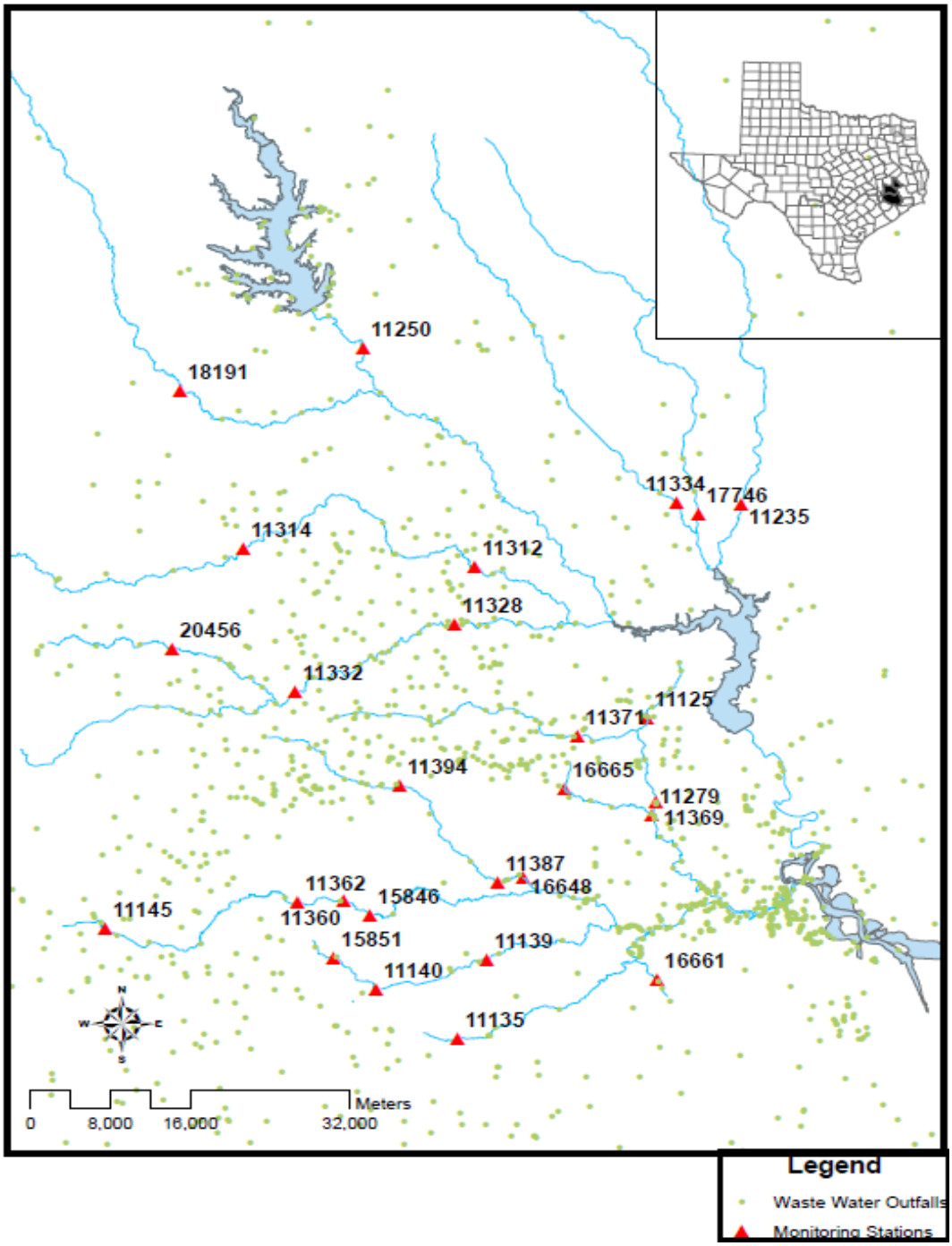


Figure 3.5 *E.coli* monitoring stations along with the municipal and industrial wastewater outfall for the San Jacinto River watershed. The outfall includes point source discharge from domestic and industrial facility (Texas Commission on Environmental Quality, 2009)

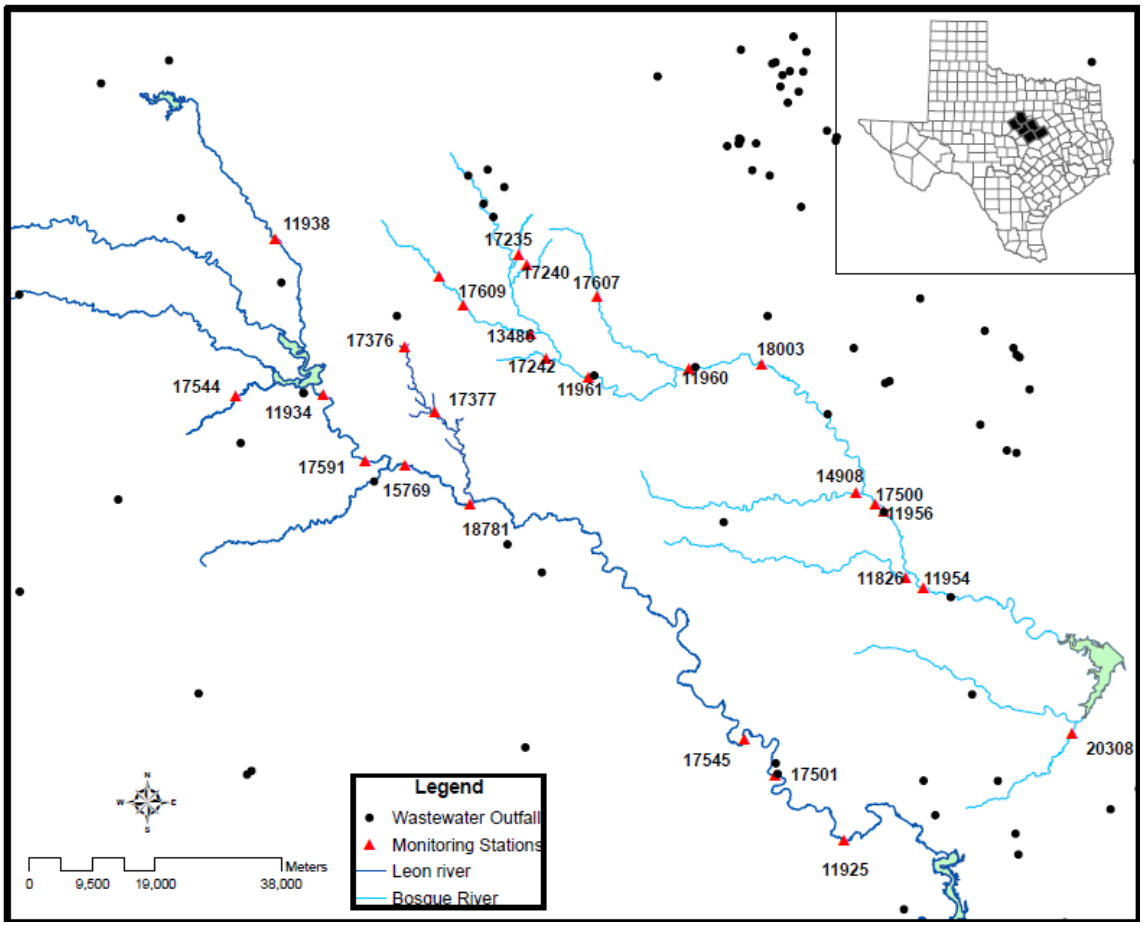


Figure 3.6 Map showing the *E.coli* monitoring stations along with the municipal and industrial wastewater outfall for the Leon and Bosque Rivers watershed. The outfall includes point source discharge from domestic and industrial facility (Texas Commission on Environmental Quality, 2009)

3.3 Microbial Risk Assessment

Monte Carlo Analysis was used to calculate the microbial risk for ingestion of *E.coli* through contact recreation in the streams. The @RISK software was used for this purpose (Palisade Corporation, 2009).

Risk assessments were performed for two scenarios: 1) children under the age

of 18; and, 2) adults over the age of 18. The bacterial concentrations from the entire period of study were used to calculate dosage to obtain a single risk value for a monitoring station for the period of study. Per swimming event, adults were assumed to ingest 0.02 L of water and children, 0.05 L. This point estimate for ingestion was calculated assuming the adults and children ingest 16 mL and 37 mL of water, respectively, during a forty-five minute swimming event (Dufour *et al.*, 2006). An average swimming event was assumed to last for sixty minutes (U.S. Environmental Protection Agency, 1997). This rate of ingestion of water was multiplied by the bacterial sample concentration to obtain the intake dosage, N, for each sample. Using the commercial software package @RISK, probability distributions of dosage for the period of study was characterized. The best fit distribution was obtained based on the chi-square rank test. Based on human dose-response analysis, point estimates for N_{50} and α were chosen to be 8.6×10^7 for and 0.1778, respectively (Haas *et al.*, 1999). Estimates for N_{50} were based on dose-response studies for seven strains of pathogenic *E.coli*, excluding the O157:H7 strain. Finally, Equation 1.1 was used to calculate the daily acceptable risk, P_I. The average number of swimming events in the streams, n, was assumed to be twelve in a year (U.S. Environmental Protection Agency, 1997). Values of P_I and n were substituted in Equation 1.2 to calculate the annual acceptable risk estimates. 10,000 iterations were performed as part of the partial Monte Carlo simulation. Risk estimates were calculated in the 95%

confidence interval region. 5th, 95th percentile and mean values of the risk estimates were used for the analysis.

3.4 Statistical Analysis

3.4.1 E.coli Incidences and Spatial Variability

The incidences of *E.coli* in all the watersheds were analyzed for compliance with standards. The number and percentage of samples in a monitoring station on a stream segment exceeding single sample and geometric mean standards were tabulated. The Wilcoxon multiple comparison test was used to identify if statistically significant differences existed among the bacterial concentrations between the different stream segments in a watershed and among the segments of all the watersheds. Wilcoxon Rank Sum test is a non-parametric test used to compare two sets of data without assuming a normal distribution. The presence of a large number of outliers (Figure 4.1) indicated a highly skewed data for which the Wilcoxon test is appropriate to use. This was used to analyze if the urban and rural watersheds differed in the way their bacteria were distributed. The 2010 Texas water quality standards were not used for identifying the impaired stream segments, since the EPA had not approved the standards at the time of the study. Hence, the 2000 standards that have already been approved by the EPA were used.

3.4.2 Temporal Variability

A simple regression analysis was performed to study temporal variability of *E.coli* concentrations for individual monitoring stations to determine if the bacterial incidences had a relationship with the time of the year. The results were tabulated and the percentage of stations having a statistical significant R^2 value was noted. A p-value less than 5% was assumed to indicate a statistically significant relationship. The data studied were variable, hence a statistically significant dataset with R^2 value exceeding 35% was considered to show a positive linear relationship between the data compared.

To study the effect of stream flow on water quality, a simple linear regression analysis was carried out between the bacterial count and the daily average flow to identify if a statistically significant relationship exists between them. The results were tabulated and the percentage of stations having a statistically significant relationship was indicated.

The effect of rainfall and first flush on bacterial counts was analyzed based on wet and dry weather data. *E.coli* data was categorized as wet (W) if a rainfall event was recorded within 5 days or less from the date of sampling. The data that did not qualify for this was considered dry (D) (Desai *et al.*, 2010). The Wilcoxon Rank Sum Test (Toutenburg, 1975) and box-plots were used to analyze the difference between the wet and dry datasets. Box-plots are used to present a visual representation of data points. They usually display the median value, 25th and 75th percentile values along with the upper and lower extremes in

value (McGill *et al.*, 1978). Values that are greater than twice the standard deviation on either side of the median are indicated as outliers. Temperature effects on the bacterial count were evaluated by dividing the data into summer and winter months and then comparing their *E.coli* concentrations. May, June, July, August, and September were considered to be summer months characterized by high temperature and the months of November, December, January and February were considered to be winter months, characterized by cooler temperatures (Desai *et al.*, 2010). The Wilcoxon Rank sum test and box-plots wereused to analyze the significant differences between samples of each monitoring station to identify significant differences. The results were tabulated and the percentage of stations having significant differences was identified. All the statistical analyses were carried out using the commercial software JMP (SAS, 2009).

4. RESULTS AND DISCUSSION

Overall, fifty-one stations were analyzed for the incidence of *E.coli*, effects of their spatial variability, and public health risk. Out of these stations, twenty-seven were located in the SJR watershed, fourteen in the Bosque River watershed and ten in the Leon River watershed (Figures 3.5 and 3.6). As shown in Figures 3.1 and Figure 3.3, the SJR was divided into thirteen segments, the Bosque River into ten segments and the Leon River into four segments for analyses The following sections present the resulting evaluation for the incidences, spatial, and temporal variability of *E.coli* concentrations in the selected watersheds.

4.1 *E.coli* Incidences and Spatial Variability

The bacterial concentrations from the years 2007 to 2009 for the SJR and from 2005 to 2009 for the Bosque and Leon Rivers comprised the datasets for analysis. A summary of the results for some selected monitoring stations, those with high concentrations along with their standard exceedances are presented in Table 4.1. The complete set of results for all the monitoring stations are presented in Appendix A.

Table 4.1 *E.coli* concentrations for selected stations on the San Jacinto River watershed. Geometric means exceeding standards and single samples exceeding standards seventy-five percent of the time at a station are indicated in bold

Stream Segment	Monitoring Station	Geometric Mean (MPN/100mL)[a]	Maximum Value (MPN/100mL)	Samples Exceeding Single Sample Std[b] (%)
Buffalo Bayou above Tidal zone	11360	**739**	120 000	67.9
	15846	**786**	17 000	57.1
Buffalo Bayou Tidal zone	16648	**2473**	100 000	**92.8**
Caney Creek	11334	**345**	23 000	37.7
Cypress Creek	11328	**1275**	41 000	**80.6**
East Fork San Jacinto	11235	**244**	20 000	36.3
Greens Bayou above Tidal zone	11371	**1222**	17 000	**78.5**
	11369	**527**	20 000	57.8
Houston Ship Channel-Buffalo Bayou Tidal (HST-BBT)	11140	**1629**	14 000	**92.8**
	11139	**2926**	41 000	**92.5**
	16661	**2102**	160 000	**85.7**
Houston Ship Channel	16665	**1681**	87 000	**82.1**
	11279	**1196**	20 000	71.4
Lake Creek	18191	**267**	24 000	25
Peach Creek	17746	**464**	14 000	45.4
Spring Creek	11314	**968**	17 000	60
West Fork San Jacinto	11250	**249**	4700	21.1
White Oak Bayou	11387	**3518**	29 000	**91.6**

[a] Geometric Mean standard is 126 MPN/100mL
[b] Single Sample Standard is 394 MPN/100mL

Table 4.2 *E.coli* concentrations for selected stations on the Bosque and Leon River watersheds. Geometric means exceeding standards and single samples exceeding standards fifty percent of the time at a station are indicated in bold

Stream Segment	Monitoring Station	Geometric Mean[a] (MPN/100mL)	Maximum Value (MPN/100mL)	Samples exceeding Single Sample Std[b] (%)
Bosque River				
North Bosque River	11954	63	22 000	12.5
	18003	48	17 000	6.3
Duffau Creek	17607	**149**	39 000	14.6
Indian Creek	17235	**189**	14 000	28
Sims Creek	17240	**180**	58 000	24.6
Leon River				
Leon below Leon Lake	11938	**242**	4400	46.2
Duncan Creek	17544	**461**	9171	40
Leon below Proctor Lake (LBP)	17591	**269**	2400	35.15
Resley Creek	17376	**401**	6500	**56.25**
	17377	**211**	2400	31.3

[a] Geometric Mean standard is 126 MPN/100mL
[b] Single Sample Standard is 394 MPN/100mL

Acceptable limits for *E.coli* counts were violated in several of the segments of the SJR watershed as indicated by bold numbers in Table 4.1. Single sample *E.coli* concentrations ranged across three orders of magnitude, from 10 to values as high as 120,000 MPN/100mL for the same station. Maximum concentrations for all the monitoring stations ranged from 720 MPN/100mL to 120,000 MPN/100mL. The single sample standard (394 MPN/100 mL) was exceeded greater than 75% of the time at 34% of the stations

(Table 4.1). The HST-BBT segment had the highest single sample standard exceedances with four out of five stations having greater than 75% of samples exceeding the single sample standard (92.8%, 92.5%, 85.7%, and 85.7%). In comparison, Buffalo Bayou above Tidal zone, Caney Creek, East Fork and West Fork SJR, Lake, Peach, and Spring Creeks did not have any station exceeding single sample standard 75% of the time. West Fork SJR had the lowest single sample standard exceedances, with monitoring station 11250 exceeding standard 21% of the time (Table 4.1). Geometric mean standard (126 MPN/100mL) was exceeded by 96% of the stations. Only monitoring stations 11145 and 20456 on the Buffalo Bayou above Tidal zone and Cypress Creek (Figure 3.5), respectively, did not exceed geometric mean standards. This review of *E.coli* exceedances incidences in all the stations indicated the need to analyze the spatial variability among the segments in the rivers.

Box-plots and Wilcoxon tests for multiple groups were used to analyze the spatial variability of segments of the SJR. Box-plots display batches of data and show their variability. From the results obtained from the Wilcoxon test, the segments were categorized into three groups ($p<0.05$) based on their median concentrations. The first group (median > 1000 MPN/100mL) consisting of the HST-BBT, Houston Ship Channel, White Oak Bayou and Buffalo Bayou Tidal was significantly different ($p<0.05$) from the second group (median >450 MPN/100mL) consisting of the Buffalo Bayou above Tidal, Greens Bayou, Cypress Creek and Spring Creek (Figure 4.1). The first group had the highest

median concentrations. The second group was significantly different ($p<0.05$) from the third group (median < 450 MPN/100mL) comprising Lake Creek, Peach Creek, Caney Creek, and the East and West Fork SJR as shown in Figure 4.1. The third group had less than 50% of the samples exceeding standard. This difference in *E.coli* concentrations between these segments could be attributed to their land use characteristics. Changes in land use from forest areas and rangelands to urban areas across a landscape has been demonstrated to negatively influence the bacterial quality in streams (Crim, 2007; Nash *et al.*, 2009). Similarly, in this study, the segments belonging to the first group that are present in the lower half of SJR, have a predominantly urban land use (Table 3.1 and Figure 3.2) and hence have high *E.coli* concentrations. The segments in the third group with the lowest *E.coli* concentrations comprise in the upper half of the SJR watershed that is characterized by forests and rangeland as indicated in Table 3.1 and Figure 3.2. It follows then that a predominantly rural portion of the watershed has lower *E.coli* concentrations.

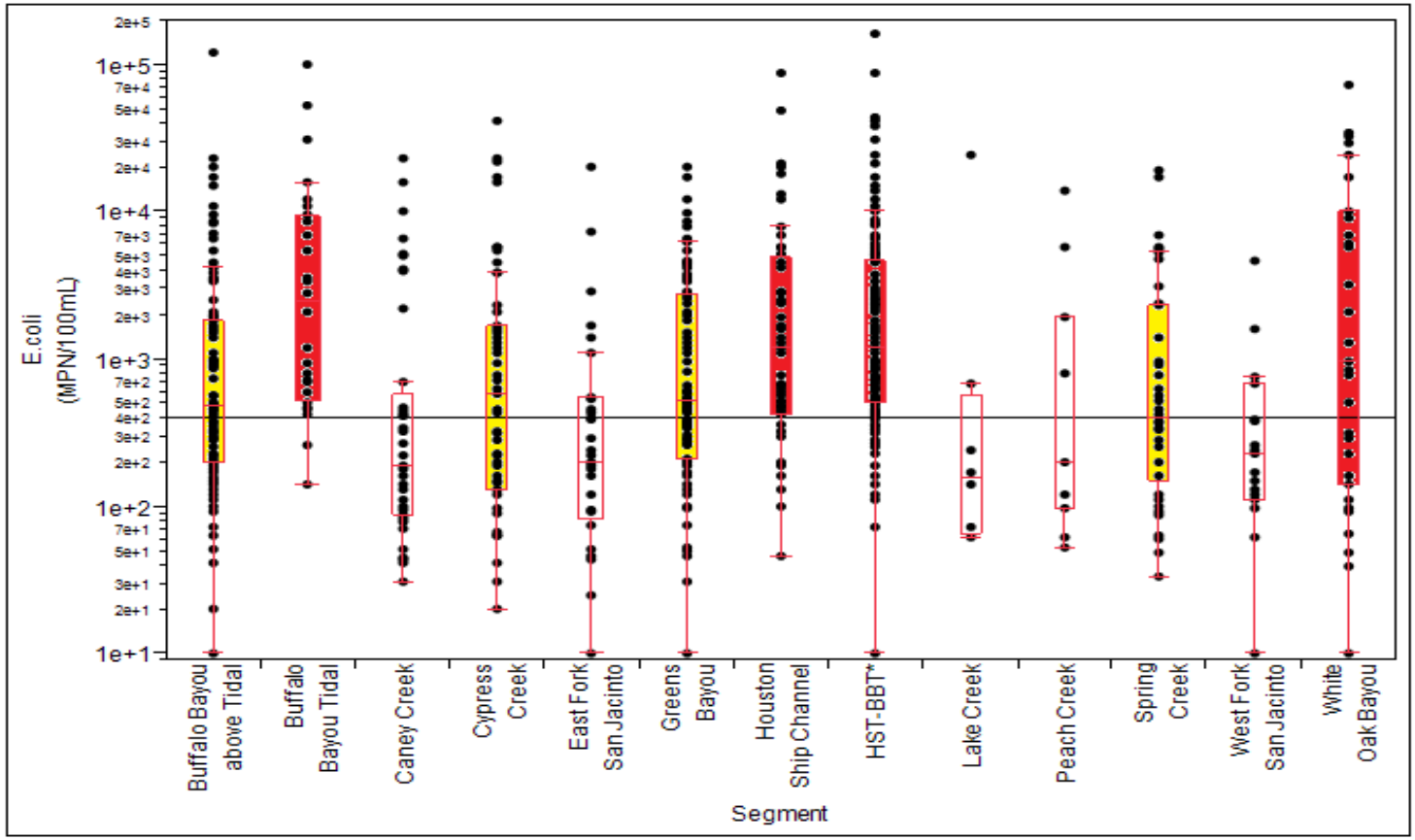


Figure 4.1 Box-plots of *E.coli* concentrations in the SJR segments. Box-plots indicate the median, 25th, and 75th percentile, lower and upper extreme values. Outliers are also shown outside the box. Concentrations are shown on a log scale. The segments indicated in red constitute the first group with median concentrations greater than 1000 MPN/mL. The yellow group has median concentrations between 450 and 1000 MPN/mL. The remaining segments have concentration less than 450 MPN/100mL

*Horizontal line indicates single sample standard of 394 MPN/100mL

E.coli concentrations were also significantly different ($p<0.05$) between the Buffalo Bayou above Tidal and Buffalo Bayou Tidal influence segments. The monitoring station (16648) on the tidally influenced zone of the Buffalo Bayou had 93% of the samples exceeding standard, whereas the zone not influenced by tides had less than 70% standard exceedances at all its stations (67.9%, 53.9%, 25%, and 57.1%). This indicated tidal action resulted in higher *E.coli* concentrations. The relationship between tidal action and *E.coli* concentrations was also documented by Sanders et al. (2005). This tidal action scours the bottom sediments that contain indicator bacteria suspending them in the water column thereby increasing the concentration. In contrast, the Bosque River had no station and the Leon River had only one station with greater than 50% of its samples exceeding single sample standard. The *E.coli* concentrations for selected stations having high concentrations are presented in Table 4.2. Complete results are presented in Appendix A. Only monitoring station (17376) on Resley Creek had 50% of its sample exceeding the single sample standard. Maximum concentrations for all the monitoring stations in the Bosque and Leon Rivers ranged from 160 MPN/100mL to 58,000 MPN/100mL and 860 MPN/100mL to 28,000 MPN/100mL, respectively (Table 4.2). For the Bosque River watershed, Indian Creek had the highest *E.coli* concentrations with a geometric mean of 189 MPN/100mL and 28% of its stations exceeding standard. Meridian Creek had the least concentrations with a geometric mean of 29 MPN/100mL and none of its samples exceeding standard. The Leon River,

monitoring station (17376) on Resley Creek had the highest concentrations with 57% of its samples exceeding the single sample standard. The geometric mean was 401 MPN/100mL. The geometric mean standard was exceeded by 29% of the Bosque River stations and 90% of the Leon River Stations indicating a spatial variability between the segments in the watersheds.

The variation of *E.coli* concentrations in the Bosque and Leon Rivers was analyzed using box-plots and the Wilcoxon multiple comparison test. The results are shown in Figures 4.2 and 4.3. For the Bosque River watershed, the segments can be divided into two broad groups based on their median concentrations and variance. The first group (median >80 MPN/100mL) consisting of Sims Creek, Green Creek, Duffau Creek, Indian Creek and the Middle/South Bosque River was significantly different ($p<0.05$) from the second group (median < 80 MPN/mL) consisting of the Meridian Creek, North Bosque River, Neils Creek, and Spring Creek (Figure 4.2). The Leon River segments were not significantly different (Figure 4.3), but the monitoring stations on Leon River below Proctor Lake (LBP) had lower single standard exceedances (30.3%, 17.6%, 16.2%, 16.2%, 31.5%, and 32.5%) compared to the other segments (46.2%, 40%, 56.3%, and 31.3%).

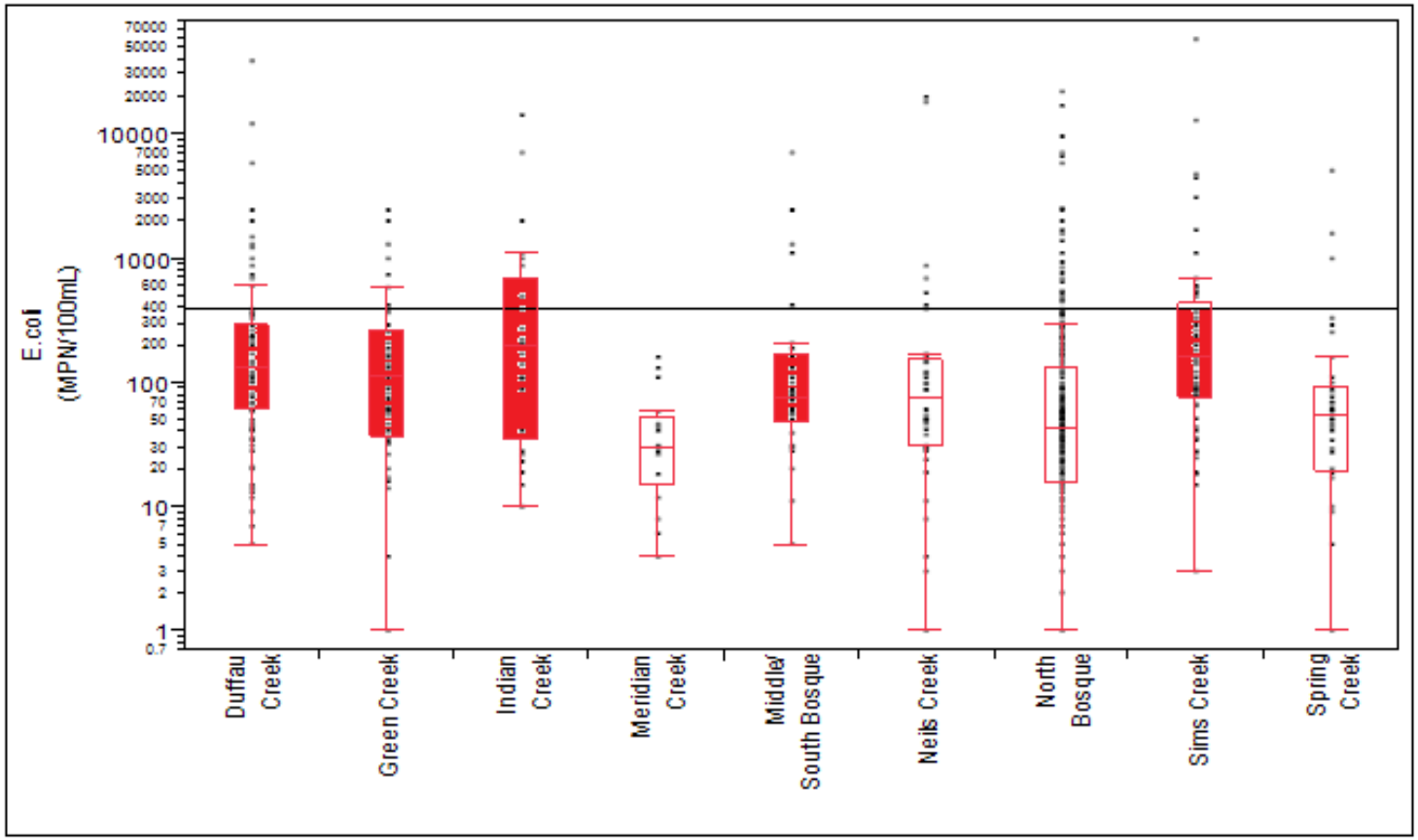


Figure 4.2 Box-plots of *E.coli* concentrations in the Bosque River segments. Box-plots indicate the median, 25th, and 75th percentile, lower and upper extreme values. Outliers are also shown outside the box. Concentrations are shown on a log scale. The segments indicated in red constitute the first group with median concentrations greater than 80 MPN/mL. The remaining segments have concentration less than 80 MPN/100mL

*Horizontal line indicates single sample standard of 394 MPN/100mL

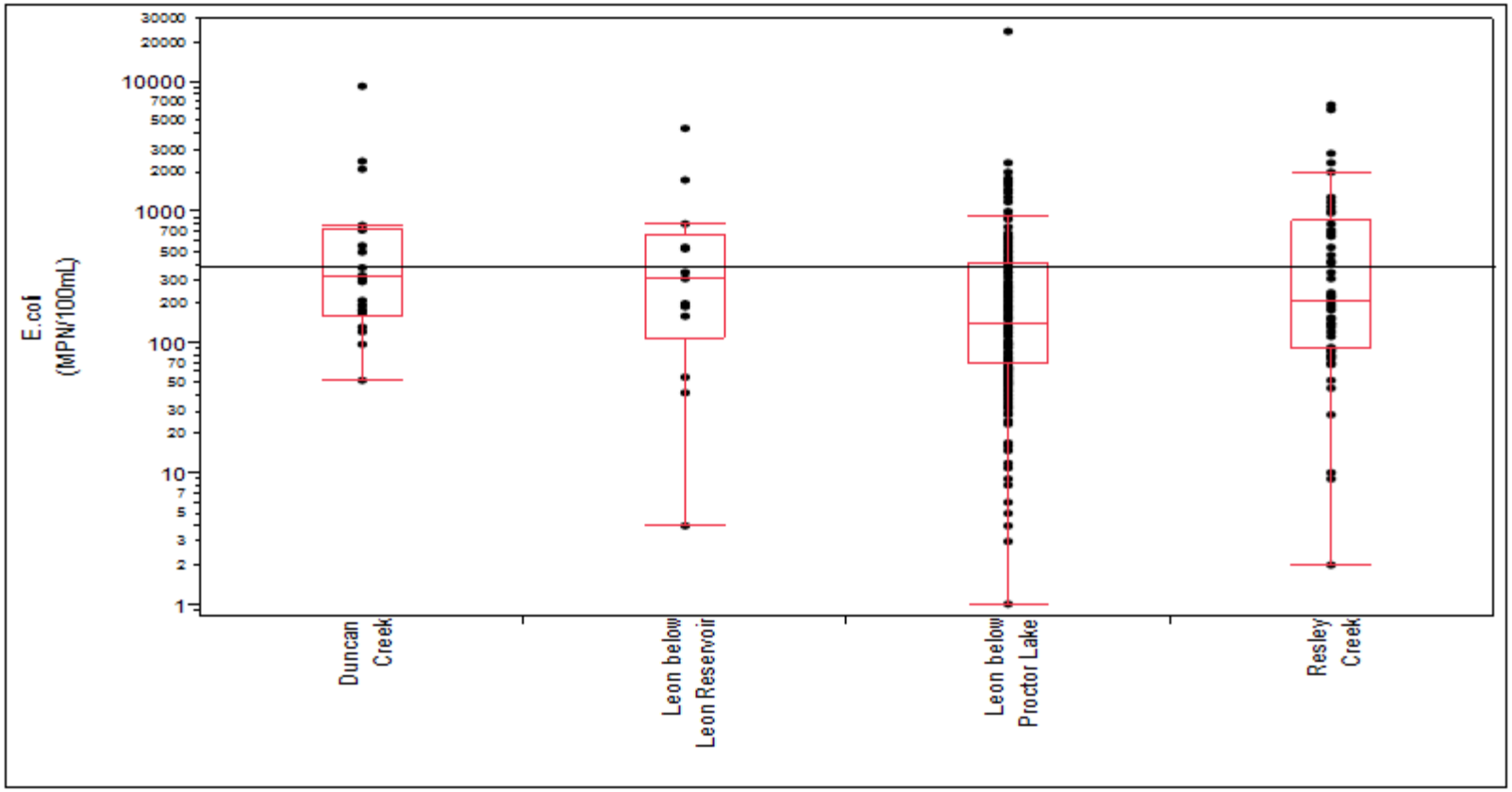


Figure 4.3 Box-plots of *E.coli* concentrations in the Leon River segments. Box-plots indicate the median, 25th, and 75th percentile, lower and upper extreme values. Outliers are also shown outside the box. Concentrations are shown on a log scale

*Horizontal line indicates single sample standard of 394 MPN/100mL

The variability among the segments in the Bosque River could be attributed to their agricultural land use and the presence of CAFOs. The link between the presence of dairy farms and high concentrations of *E.coli* is well documented (Hodne, 2005; Lewis *et al.*, 2005). Sims, Green, Duffau, and Indian Creeks are tributaries of the Upper North Bosque River and are located in Erath County as shown in Figure 3.3. Erath county is home to more than 100 dairy CAFOs (Stewart *et al.*, 2006) and agricultural activities (Figure 3.4), which could be the reason for the high bacterial concentrations in these segments. Similarly, Resley Creek, Duncan Creek, and Leon River below Leon Lake flow through Comanche County, where more than 100 dairy CAFOs are located (Texas Commission on Environmental Quality, 2008a). Runoff from these CAFOs could cause the bacterial concentrations in these segments to be greater than LBP.

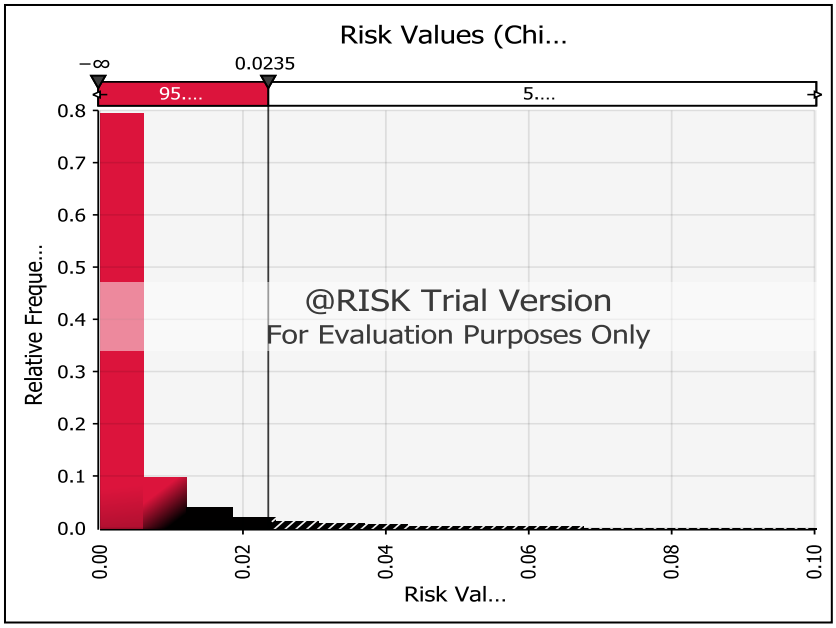
In general, the differences in *E.coli* concentrations among the monitoring stations in the SJR and Leon and Bosque Rivers can be attributed to their land use characteristics. While the heavily urbanized and industrialized lower half of the SJR had chronically high concentrations of *E.coli* (geometric mean densities of 2,473 MPN/100mL, 2102 MPN/100mL, 3,518 MPN/100mL, and 2,926 MPN/100mL), the predominantly forest and rangeland portions of the Leon and Bosque Rivers had significantly lower concentrations (geometric mean densities of 29 MPN/100mL, 48 MPN/100mL, 41 MPN/100mL, and 30 MPN/100mL).

4.2 Microbial Risk Assessment

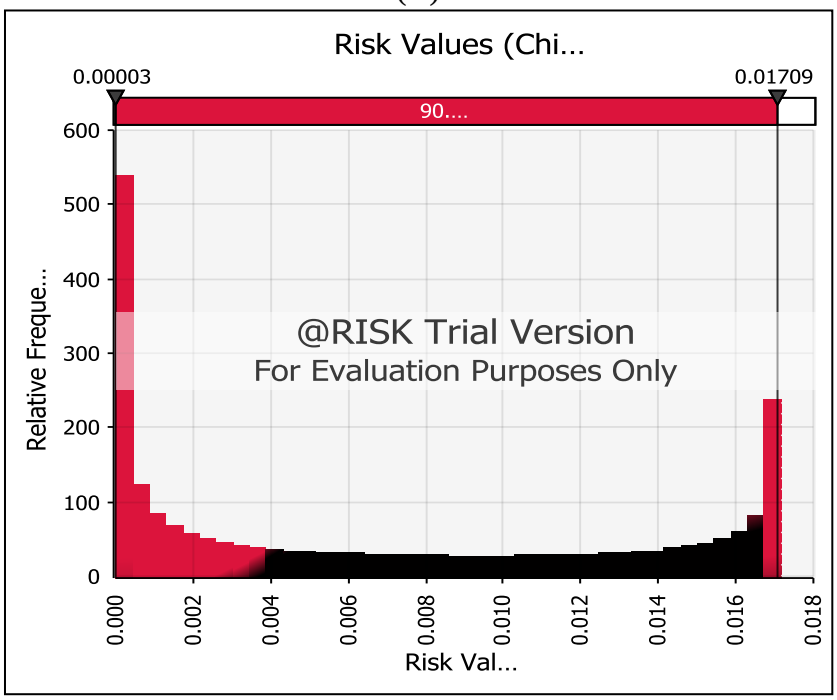
The high concentrations of *E.coli* observed in the previous section indicated the potential for a public health risk due to ingestion of water from the rivers through contact recreation. The QMRA process was used to calculate the risk of infection from *E.coli*. All the stations indicated in Figures 3.5 and 3.6 were used for calculating the public health risk.

E.coli concentrations were used to create distributions of dosage. Some of the distributions that resulted in a high risk of infection are presented in Table 4.3. A complete list of distributions is presented in Appendix B. The concentration dataset used for creating the probability distribution of dosage was highly skewed due to the presence of *E.coli* concentrations greater than 20,000 MPN/mL. This is indicated by the presence of long tails in the box-plots fitted to the concentrations in Figures 4.1, 4.2, and 4.3. The input distributions that fit the bacterial concentrations were dominated by Inverse Gaussian, Log Normal, Beta, and Exponential distributions, which are distributions used to fit highly skewed data.

Partial Monte Carlo simulation was used to obtain the annual risk estimates. An annual risk estimate ranging from 10^{-4} to 10^{-6} is considered tolerable for the occurrence of diseases and a risk estimate greater than 10^{-4} was considered unacceptable (Haas *et al.*, 1993). 5th, and 95th percentile, and mean risk estimates that were used to analyze the human health risks are shown for a few monitoring stations in Table 4.3 and 4.4. Complete Risk Values are presented in Appendix B. Mean risk values, rather than median values were used to characterize results because these represent the highly skewed dataset better. The highly skewed nature of the dosage probability distributions that resulted in skewed risk distributions is shown through the different distributions used for the various monitoring stations in Figure 4.4 A, B, C, and D. While the 95th percentile estimate is useful to study the upper limit of the risk, median and 95th percentile values do not provide a realistic picture when the tail of the distribution is very long. In highly skewed distributions, the mean risk value could even be greater than the 95th percentile risk value. Hence, mean risk values characterize the risk better for skewed distributions. The 5th percentile risk values are used to indicate the lower limit of the risk values in a distribution.

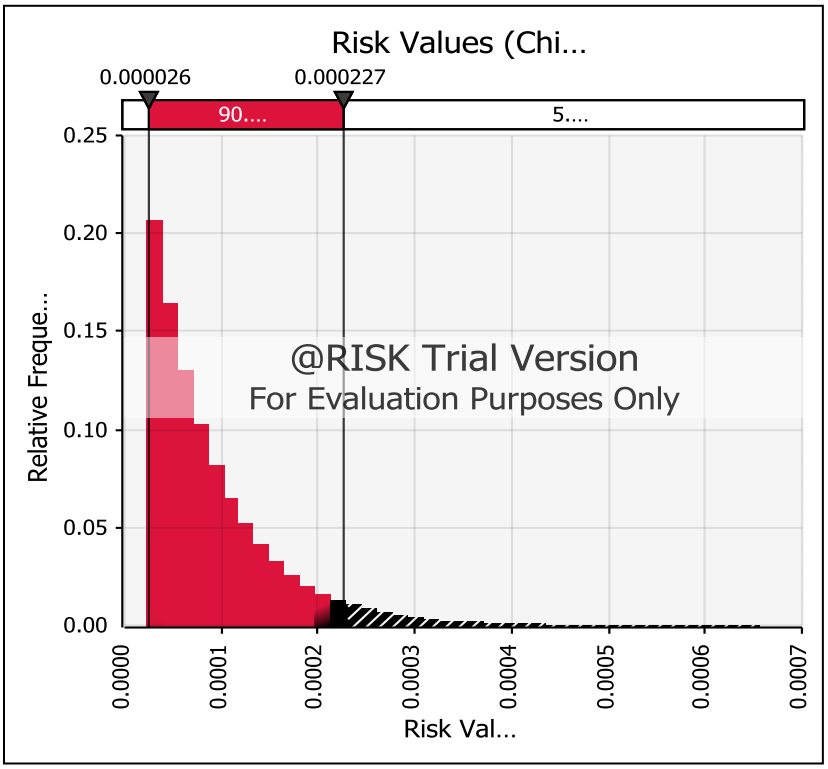


(A)

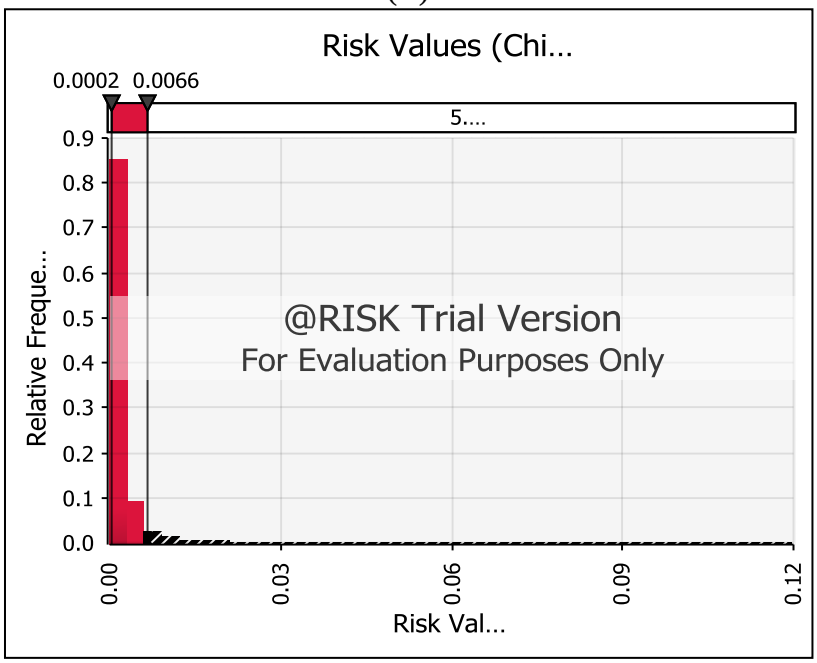


(B)

Figure 4.4 Monte Carlo simulation outputs after 10,000 trials. (A) Inv-Gaussian distribution for station 11139 at Houston Ship Channel, San Jacinto River, (B) Beta distribution for station 11387 at White Oak Bayou, San Jacinto River, (C) Exponential distribution for station 17609 at Green Creek, Bosque River, and (D) Log-Normal distribution for station 11140 at Houston Ship Channel, San Jacinto River.



(C)



(D)

Figure 4.4 Continued

Table 4.3 Annual risk estimates for monitoring stations on the SJR watershed. The values in bold indicate risk estimates greater than 10^{-4}, considered to be unacceptable. All dosage distribution parameters are expressed in MPN/100mL. Risk was calculated separately for adult (age over 18) and child (age under 18). Parameters that define the distribution are also indicated along with the distribution

Segment	Monitoring Station	Best-Fit *E.coli* Dosage Distribution		Annual Risk		
				5th Percentile	Mean	95th Percentile
Buffalo Bayou above Tidal	11360	Inv-Gaussian	Adult	1.04E-05	**1.41E-03**	**6.11E-03**
		(μ=6051.8,λ=391.9)	Child	2.59E-05	**3.45E-03**	**1.52E-02**
	11362	Log-Normal	Adult	1.46E-05	**7.06E-04**	**2.69E-03**
		(μ=2969.1,σ=16567.1)	Child	3.66E-05	**1.74E-03**	**6.70E-03**
Buffalo Bayou Tidal	16648	Log-Normal	Adult	4.91E-05	**3.12E-03**	**1.21E-02**
		(μ=13804.1,σ=94152.1)	Child	**1.23E-04**	**7.37E-03**	**2.98E-02**
Caney Creek	11334	Inv-Gaussian	Adult	1.02E-05	**4.60E-04**	**1.86E-03**
		(μ=1905.9,λ=200.35)	Child	2.55E-05	**1.14E-03**	**4.65E-03**
Cypress Creek	11328	Inv-Gauss	Adult	3.13E-05	**1.08E-03**	**4.79E-03**
		(μ=4524.4,λ=537.03)	Child	7.82E-05	**2.66E-03**	**1.19E-02**
Greens Bayou	11371	Beta	Adult	1.57E-05	**7.20E-04**	**2.61E-03**
		(a1 = 0.52, a2 = 8.32)	Child	3.93E-05	**1.80E-03**	**6.51E-03**
Houston Ship Channel- Buffalo Bayou Tidal	16661	Log-Normal	Adult	3.42E-05	**7.64E-03**	**1.65E-02**
		(μ=12612.9,σ=71985.4)	Child	8.56E-05	**1.39E-02**	**4.05E-02**
	11139	Inv-Gaussian	Adult	5.98E-05	**2.18E-03**	**9.52E-03**
		(μ=9403.6,λ=1871.6)	Child	**1.49E-04**	**5.38E-03**	**2.36E-02**
Houston Ship Channel	16665	Inv-Gaussian	Adult	3.27E-05	**1.87E-03**	**8.43E-03**
		(μ=8000.8,λ=836.93)	Child	8.19E-05	**4.58E-03**	**2.09E-02**
Spring Creek	11314	Beta	Adult	2.40E-05	**1.46E-03**	**4.05E-03**
		(a1 = 0.21, a2 = 0.37)	Child	6.00E-05	**3.63E-03**	**1.01E-02**
White Oak Bayou	11394	Inv-Gaussian	Adult	6.03E-06	**2.63E-03**	**4.78E-03**
		(μ=8572.9,λ=166.96)	Child	1.51E-05	**5.90E-03**	**1.19E-02**
	11387	Beta	Adult	9.84E-06	**2.85E-03**	**6.89E-03**
		(a1 = 00.29, a2 = 0.42)	Child	2.46E-05	**7.07E-03**	**1.71E-02**

Table 4.4 Annual risk estimates for monitoring stations on the various segments of the Leon and Bosque Rivers watersheds. The values in bold indicate risk estimates greater than 10^{-4}, considered to be unacceptable. Values between 10^{-4} and 10^{-6} are considered tolerable. Risk was calculated separately for adult (age over 18) and child (age under 18). Parameters that define the distribution are also indicated along with the distribution

Segment	Monitoring Station	Best-Fit *E.coli* Dosage Distribution		Annual Risk		
				5th Percentile	Mean	95th Percentile
Bosque River						
North Bosque River	18003	Inv-Gaussian	Adult	1.14E-06	**1.17E-04**	**4.59E-04**
		(μ=488.85,λ=22.1)	Child	2.86E-06	**2.93E-04**	**1.15E-03**
	17500	Inv-Gaussian	Adult	4.53E-07	8.49E-05	**2.74E-04**
		(μ=356.71,λ=9.32)	Child	1.13E-06	**2.11E-04**	**6.85E-04**
Green Creek	13486	Inv-Gaussian	Adult	1.83E-06	7.70E-05	**3.35E-04**
		(μ=329.42,λ=66.176)	Child	4.57E-06	**1.92E-04**	**8.37E-04**
Neils Creek	11826	Log-Normal	Adult	9.56E-07	**1.07E-04**	**4.01E-04**
		(μ=443.5,σ=2487.5)	Child	2.39E-06	**2.66E-04**	**1.00E-03**
Sims Creek	17240	Log-Normal	Adult	3.10E-06	**1.67E-04**	**6.35E-04**
		(μ=685.74,σ=2576.9)	Child	7.76E-06	**4.15E-04**	**1.59E-03**
Leon River						
Leon below Proctor Lake	11925	Inv-Gaussian	Adult	4.07E-06	**2.27E-04**	**6.94E-04**
		(μ=1093.3,λ=72.02)	Child	1.02E-05	**5.66E-04**	**1.73E-03**
Resley Creek	17377	Inv-Gaussian	Adult	5.10E-06	**3.44E-04**	**7.29E-04**
		(μ=633.5,λ=180.85)	Child	1.27E-05	**7.99E-04**	**1.82E-03**
Resley Creek	17376	Exponential	Adult	4.07E-06	**2.27E-04**	**6.94E-04**
		(β = 978.38)	Child	1.02E-05	**5.66E-04**	**1.73E-03**
Leon Below Leon Lake	11938	Exponential	Adult	3.43E-06	**1.58E-04**	**4.98E-04**
		(β = 711.46)	Child	8.57E-06	**3.96E-04**	**1.25E-03**

The highest risk estimates among the three rivers were calculated for the SJR due to the high concentration of *E.coli* compared to the other rivers. The Houston Ship Channel, Buffalo Bayou, White Oak Bayou, and Greens Bayou had the highest mean risk estimates, ranging from 10^{-2} to 10^{-5}. Some of the values are up to two orders of magnitude higher than the tolerable limit, indicating elevated public health risks (Table 4.3). Other segments such as Caney Creek, East and West Fork San Jacinto River, and Peach Creek had a comparatively lesser value of risk, ranging from 10^{-3} to 10^{-5}. These segments are present in the upper half of the SJR, a predominantly forest and rangeland landuse compared to the Bayous and the Houston Ship Channel, that flow through heavily urbanized and industrialized regions in the lower half of SJR (Table 3.1 and Figure 3.2). More than 90% of the mean and 95th percentile risk values are greater than the tolerable limit, indicating elevated public health risk from contact recreation in SJR. While there are no studies that applied the QMRA process to *E.coli* concentrations in urban surface waters, recreational use of urban surface waters has been linked to elevated public health risks (Frumkin, 2002) through epidemiological studies (Pruss, 1998)

In comparison, the Bosque and Leon River watersheds had lower risk estimates, although 50% of mean risk estimates in the Bosque River and 80% of the mean risk estimates in the Leon River exceed the tolerable limit of 10^{-4}, watersheds. The risk of infection for the Bosque and Leon watersheds were similar, which could be attributed to the similar type of land use in the two

regions, consisting of predominantly rural and agricultural characteristics (Table 3.2 and Figure 3.4). The upper limit of mean risk values in these rivers corresponded to the 25th percentile of mean risk values calculated in the lower half of SJR (Figure 4.5). This contrast in the mean risk estimates indicates the influence of land use in determining human health risk effects in these rivers, a direct consequence of their high bacterial concentrations.

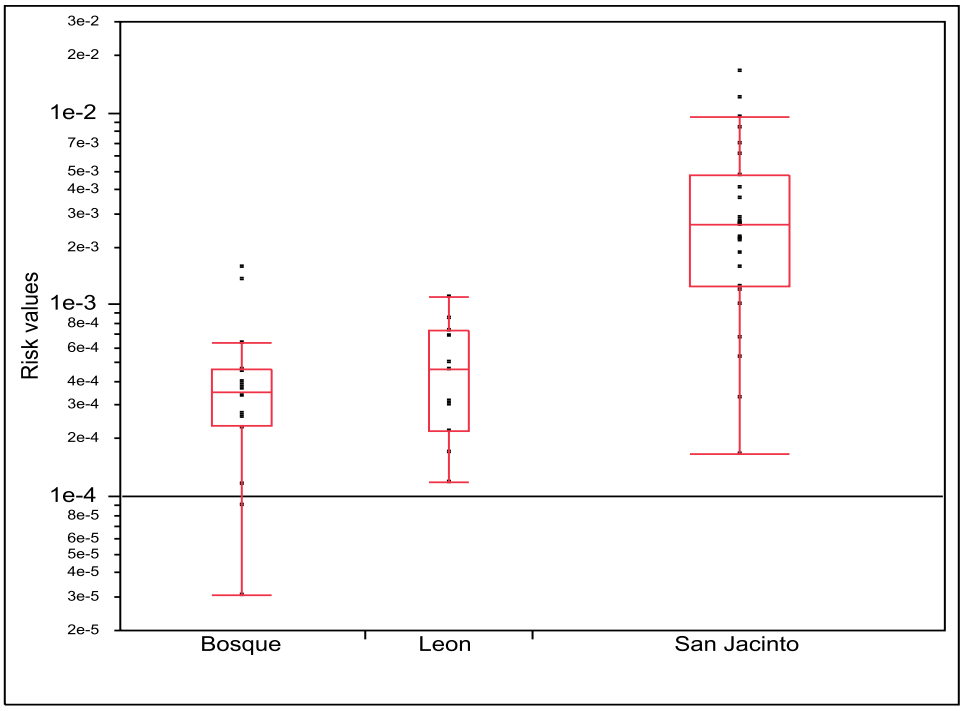


Figure 4.5 Comparison of adult mean risk values for the three watersheds. Risk values are presented on a log scale due to a wide range of risk values. The box plots indicate the 25th, 50th and 75th percentile data, along with extreme values and outliers. The upper limits of risk values for Bosque and Leon Rivers correspond to the 25th percentile risk value for SJR. Reference line corresponds to upper limit of tolerable risk, 10^{-4}

The calculated mean risk values were higher for children compared to adults as shown in (Table 4.3 and Table 4.4). Children have higher exposure to pathogens during contact recreation, especially with swimming when they ingest more water and swim longer. Their head is also immersed in the water for longer durations while swimming (Nwachuku and Gerba, 2004).

Overall, these results indicate a high public health risk from contact recreation due to concentrations of *E.coli* that exceed public health standards. All the segments that exceeded the geometric mean standard had risk estimates greater than the tolerable limit. However, some of the rural watershed segments that were under the geometric mean standard (Leon River below Proctor Lake, North Bosque River, Middle/South Bosque River, and Neils Creek) had mean risk estimates greater than the tolerable limit, indicating a potential need to modify standards to be more health protective. More than an estimate for the diseases caused by *E.coli*, the risk estimates here indicate the possibility of adverse effects from the viruses, protozoa and bacteria for which *E.coli* is an indicator.

The values obtained here are conservative estimates for risk of infection. The infectivity value used are based on studies conducted on just seven different pathogenic strains of *E.coli* (excluding O157:H7), whereas the *E.coli* sampling data obtained does not specify the percentage of pathogenic *E.coli* present in the concentrations. If the *E.coli* count included a high percentage of O157:H7, risk estimates would increase due to its high virulence compared to

other *E.coli* strains (Haas *et al.*, 2000). The N_{50} value for the O157:H7 strain is a few thousands compared to 8.6 x 10^7 for the other pathogenic strains considered for the study, which could result in risk values four orders of magnitude higher than those calculated.

The risk estimates obtained here were only for the ingestion of surface water through swimming. Inhalation during contact recreation and other activities leading to ingestion could also lead to additional human health risks. Apart from this, other sources of bias and uncertainty could have occurred from the other point estimates used for calculations. Twelve swimming events were assumed for risk calculations, based on a value developed by EPA for the whole country. For Texas, the events could be higher due to warm climate prevalent during most of the year. The ingestion rates given by USEPA (1997) are based on estimates for swimming in a freshwater pool. Adapting this to surface water streams could also be a source of uncertainty. Risk was also calculated assuming equal exposure from all the stream segments on the watershed. This could have made the risk estimates conservative since all the segments are not used for recreational purposes. Some of the segments like the Houston Ship Channel are not used to recreational purposes due to their high pollution level.

4.3 Temporal Variability

The high concentrations of *E.coli* in all three watersheds and the elevated public health risks indicated a need to analyze the cause for the high concentrations. Temporal variability of *E.coli* concentrations was analyzed to

identify patterns in their concentrations. *E.coli* concentrations were analyzed for the years 2007 to 2009 for the SJR watershed. A regression analysis of the *E.coli* concentrations against time did not yield any statistically significant relationship (R^2 <0.2, p>0.05) for any of the stations and segments. A plot of *E.coli* incidences across time showed that some of the stations in the San Jacinto River, particularly in the Buffalo Bayou and Houston Ship channel (Figures 4.6 and 4.7), tended to have decreasing concentrations from 2007 to 2009. For the Bosque and Leon rivers, the concentrations were studied from 2005 to 2009. No statistically significant correlations and relationships were observed between the date of sampling and the concentrations. A plot of concentration across time showed a peak during the year 2007 as shown in Figure 4.8. Complete results for all the monitoring stations in the three rivers can be found in Appendix C. The year 2007 recorded the highest rainfall and streamflow during the period of study. This could have caused the high bacterial concentrations this year. This indicated a link between concentrations and flow and rainfall, necessitating the need to further study the variation of bacterial concentrations with rainfall and streamflow. The lack of trend in bacterial concentrations across time could be a direct result of the short duration of study. Concentration data spanning a longer duration is required to get a statistically significant trend across time.

For the Bosque and Leon Rivers, bacterial water quality remained constant during the years 2005, 2006, 2008, and 2009, even though Total

Maximum Daily Loads (TMDL) programs were planned to improve water quality in the Upper North Bosque River (Duffau Creek, Sims Creek, and Indian Creek), which had the highest concentrations (Table 4.2) (TCEQ Strategic Assessment Division, 2002). Adoption of the TMDL implementation plan in the Bosque River Watershed has been delayed potentially due to various political and social reasons such as the litigation between the City of Waco and the dairy industry (McFarland and Millican, 2008). Also, in this watershed there has been a slow adoption of Water Quality Management Practices (WQMP) such as composting and waste hauling commonly practiced in other watersheds. Improvement in water quality from controlling nonpoint source contribution lags the improvements due to better land management practices, as a consequence of the impact from past management practices (McFarland and Millican, 2008).

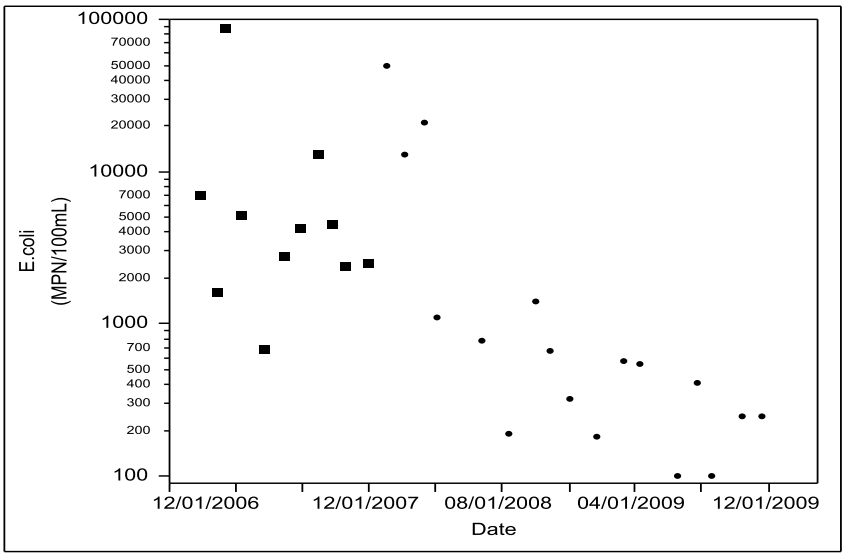


Figure 4.6 *E.coli* concentrations across time for monitoring station 16665 at the Houston Ship Channel on the SJR watershed showing a decline from 2007 to 2009. Values for the year 2007 are shown with a square marker.

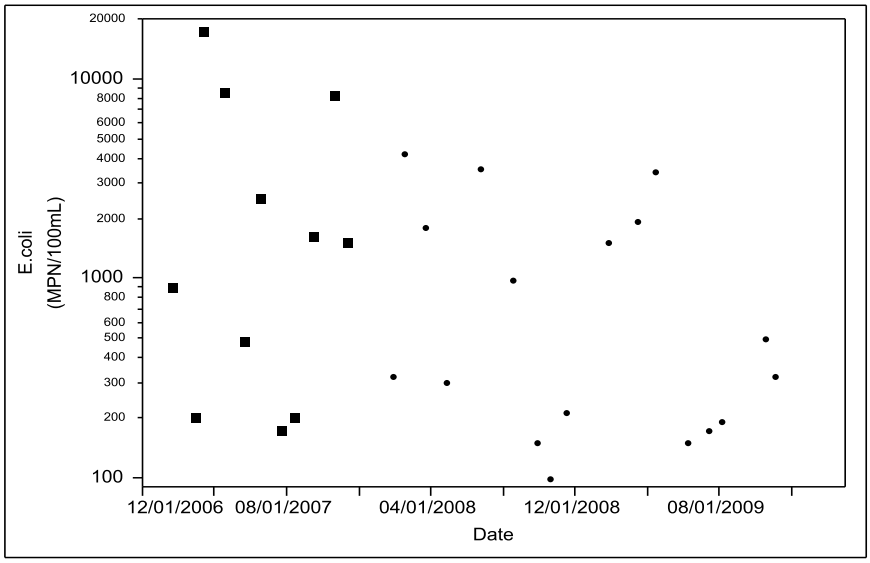


Figure 4.7 *E.coli* concentrations across time for monitoring station 15846 at Buffalo Bayou Tidal on the SJR River watershed showing a decline from 2007 to 2009. Values for 2007 are shown with a square marker.

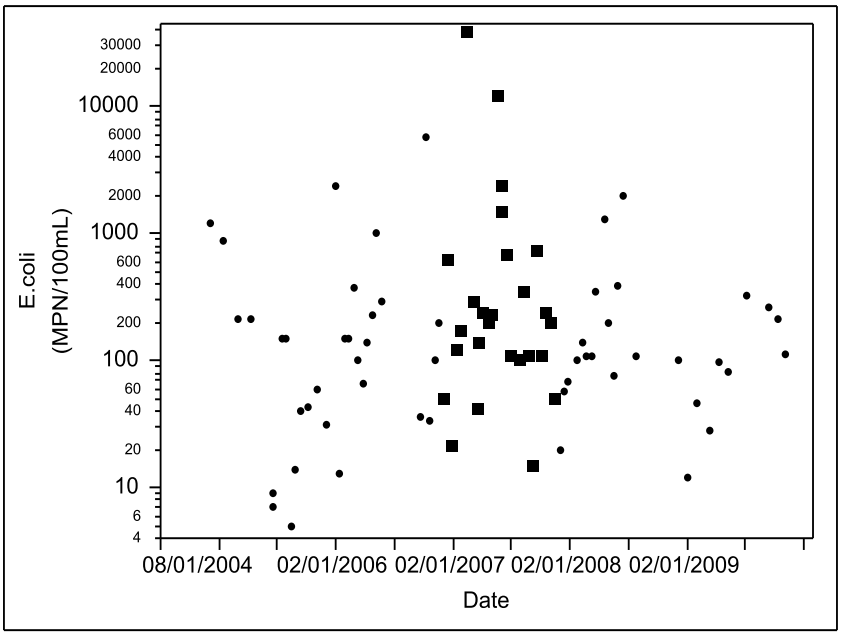


Figure 4.8 *E.coli* concentrations across time for monitoring station 17607 at Duffau Creek on the Bosque River watershed showing high bacterial concentrations in the year 2007. Values for 2007 are shown with a square marker.

4.3.1 Variation with Flow

The temporal variation of *E.coli* concentrations indicated a peak during the year 2007 when high streamflow was recorded, a simple regression analysis between daily mean flow and bacterial concentrations was used to evaluate if a relationship exists between streamflow and concentrations. R^2 values greater than 0.35 were assumed to indicate a strong relationship (Desai *et al.*, 2010). This analysis indicated that 60% of the stations in the Bosque watershed showed a linear relationship ($R^2 > 0.35$, $p < 0.05$). This relationship is shown in

Figure 4.9 for monitoring station 11826 at Neils Creek. Plots for all the stations analyzed in the three watersheds are presented in Appendix D. Although only 60% of the stations showed a strong relationship, streamflow had a positive influence on bacterial concentration. This has been well characterized in many studies that correlated flow and *E.coli* concentration. This relationship is the result of rainfall events leading to increase in municipal storm sewer discharges and increase in surface runoff (Vega *et al.*, 1998). Some of the segments of this watershed (Indian Creek, Meridian Creek, and Middle/South Bosque River) did not have sufficient data for the study period that resulted in lack of a strong relationship. Discharge from waste water treatment outfalls (Figure 3.5) is a major contributor to the volume of dry weather flows. But the *E.coli* concentrations remained low during the low flow season for this watershed indicating that WWTP discharges do not add to the bacterial population in the receiving stream, which has also been observed by Petersen et al. (2005).

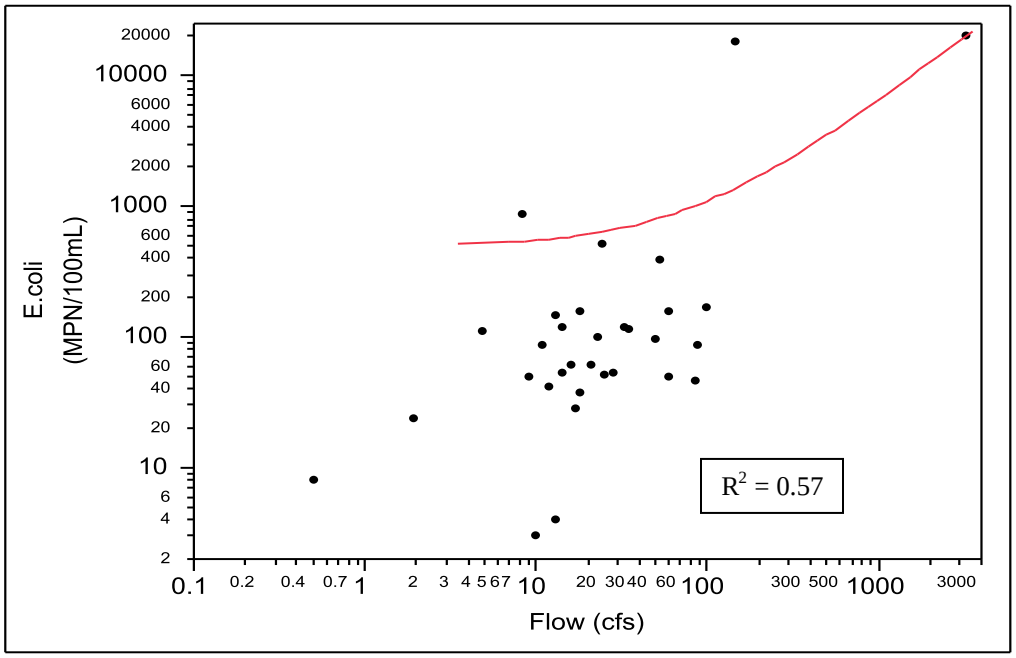


Figure 4.9 *E.coli* concentrations as a function of daily mean flow for monitoring station 11826 at Neils Creek, Bosque River watershed. The concentration and flow are depicted on a log scale. The red line represents a simple linear fit. Calculated linear relationship R2 is also shown.

No statistically significant conclusions could be reached for the Leon River, since adequate stream flow data was not available. Only four stations (11938, 11934, 17545, and18781) among the ten monitoring stations shown in Figure 3.6 had stream flow data available. A strong relationship was obtained in two of these stations. Flow-concentration relationship is shown for station 18781 in Figure 4.10. Results for other stations can be found in Appendix D. No conclusions can be made based on the limited data for the Leon River.

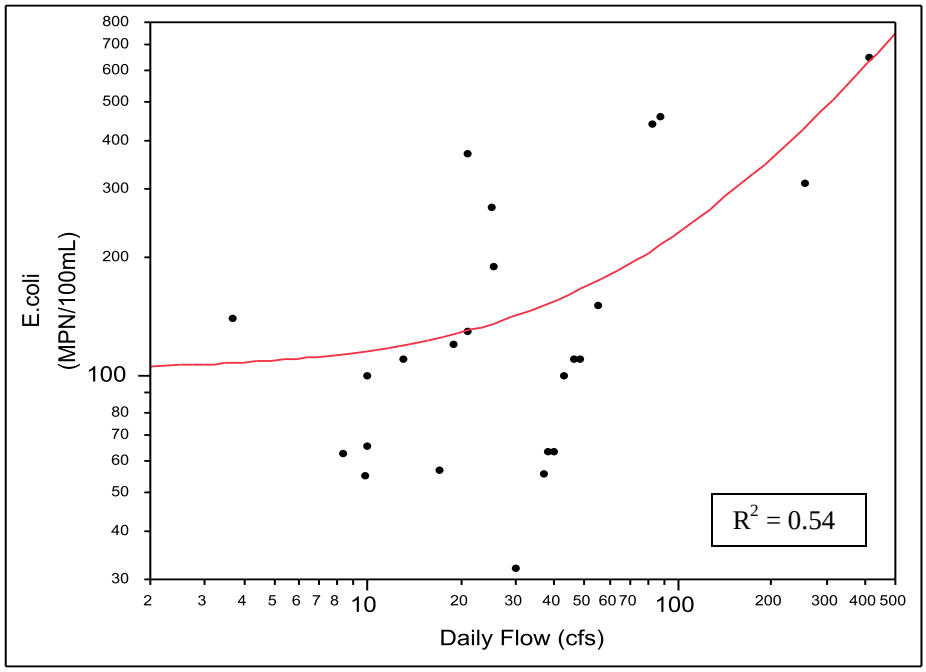


Figure 4.10 *E.coli* concentrations as a function of daily mean flow for monitoring station 18781 at Leon River below Proctor Lake, Leon River watershed. The concentration and flow are depicted on a log scale. The red line represents a simple linear fit. Calculated linear relationship R2 is also shown.

In comparison with the Bosque River, it was observed that only 30% of the stations in the SJR watershed had any linear relationship (R^2 >0.35, p<0.05). Flow-concentration relationships for two stations that have strong correlations are shown in Figures 4.11 and 4.12. Complete results are located in Appendix D. Further analysis in the San Jacinto segments showed that the predominantly urban lower SJR segments (Table 3.1, Figure 3.2), comprising the various Bayous and the Houston Ship channel, had lower percentage of stations (less than 20%) showing strong relationship with flow. In comparison, the segments in

the less urbanized upper half of SJR (Table 3.1) had a strong relationship for 50% of the stations. This result is consistent with previous studies conducted in this watershed, which state that the urban watersheds are less sensitive to any one factor. Seasonal variation and the responses are altered due to the heavy urbanization and presence of multiple sources of point and non point source pollution must also be considered (Desai *et al.*, 2010; Petersen *et al.*, 2006).

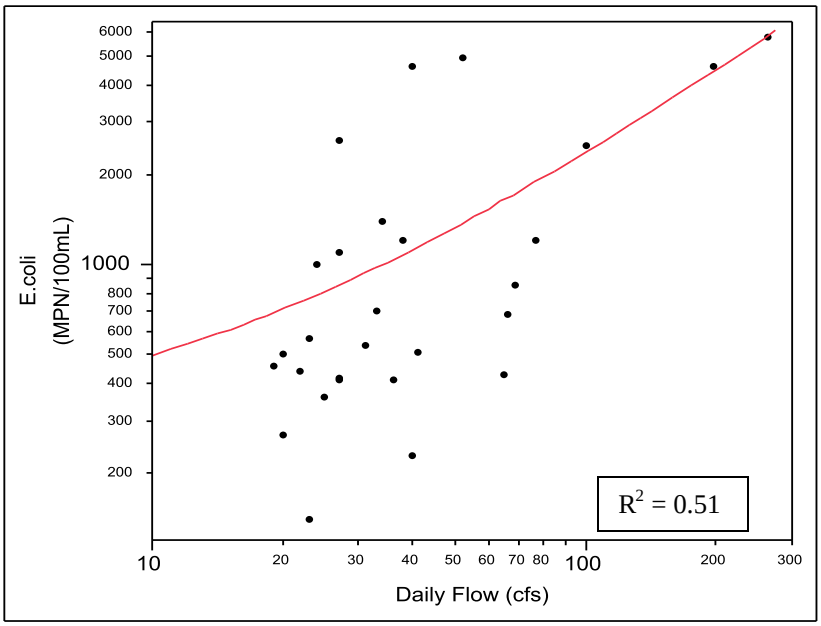


Figure 4.11 *E.coli* concentrations as a function of daily mean flow for monitoring station 15851 in the Houston Ship Channel-Buffalo Bayou Tidal zone segment on the urbanized lower SJR watershed. The concentration and flow are depicted on a log scale. The red line represents a simple linear fit. Calculated linear relationship R2 is also shown.

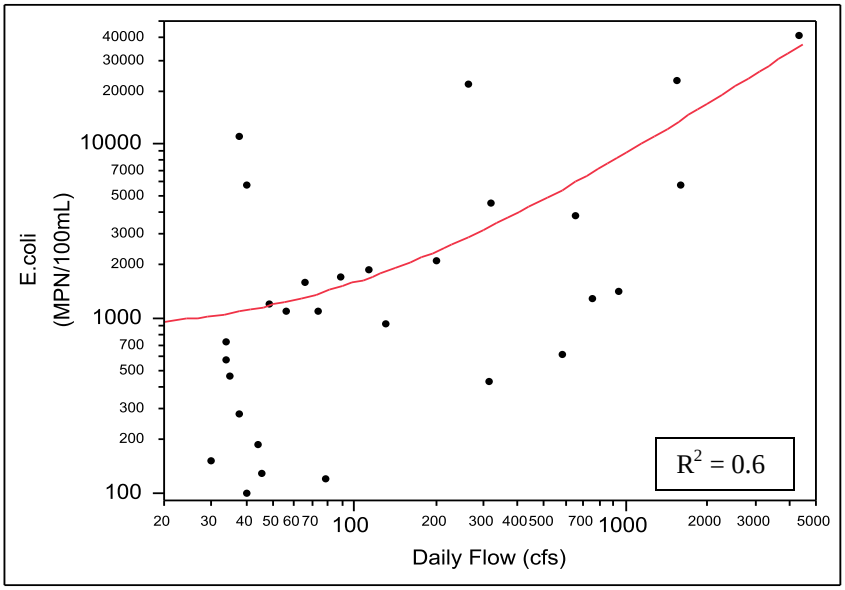


Figure 4.12 *E.coli* concentrations as a function of daily mean flow for monitoring station 11328 at Cypress Creek on the predominantly rural lower SJR watershed. The concentration and flow are depicted on a log scale. The red line represents a simple linear fit. Calculated linear relationship R2 is also shown.

4.3.2 Effect of Rainfall

Since a positive relationship was obtained between high flow and high indicator bacteria concentrations, the effect of rainfall on bacterial concentrations was analyzed as rainfall events lead to high flow conditions. A Wilcoxon Rank Sum Test (Toutenburg, 1975) was used to analyze the difference between dry and wet weather sample concentrations on the basis on their median concentrations and variance.

Among all the monitoring stations analyzed (Figure 3.5), 70% of the stations in the Bosque River watershed and 65% of the stations in the San Jacinto River had statistically significant ($p<0.05$) difference between the two data sets, as shown by the box-plots in Figures 4.13, 4.14, and 4.15 for monitoring stations that had a strong relationship. Complete results are presented in Appendix E. In the Leon River watershed segments, only four stations (11938, 11934, 17545, and18781) among the ten monitoring stations shown in Figure 3.6 had rainfall data. Three out of these four stations had a statistically significant ($p<0.05$) relationship, as shown by the box-plots in Figure 4.16 for monitoring station 17591. Bacterial concentrations during wet weather were higher compared to the dry weather flows in all the stations, indicating that rainfall and surface runoff are major contributors to decreases in bacterial water quality.

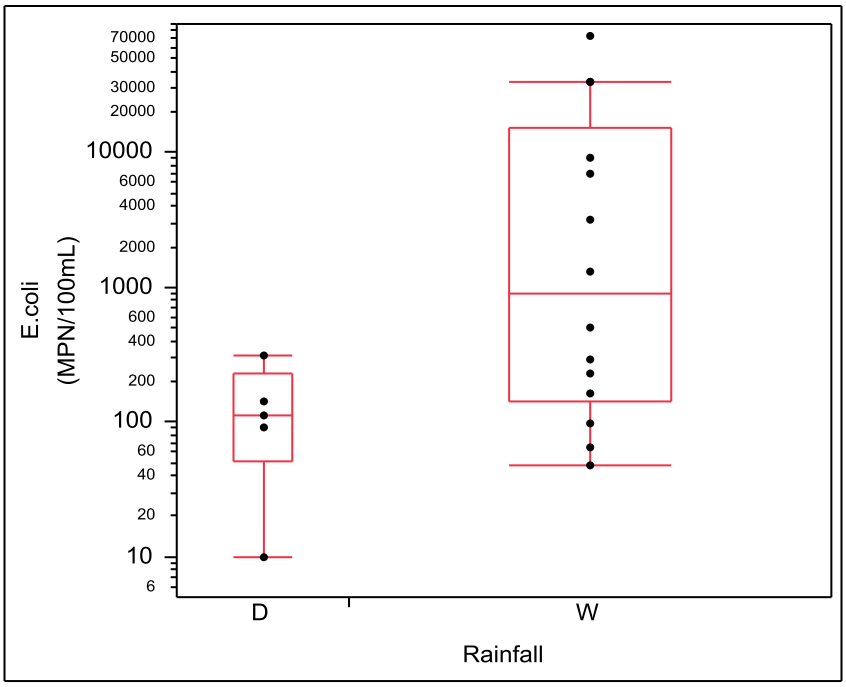


Figure 4.13 Difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11394 at White Oak Bayou on the SJR watershed. The box plots indicate the 25th, median and 75th percentile concentrations, lower and upper extreme along with outliers. E.coli concentrations are shown on a log scale

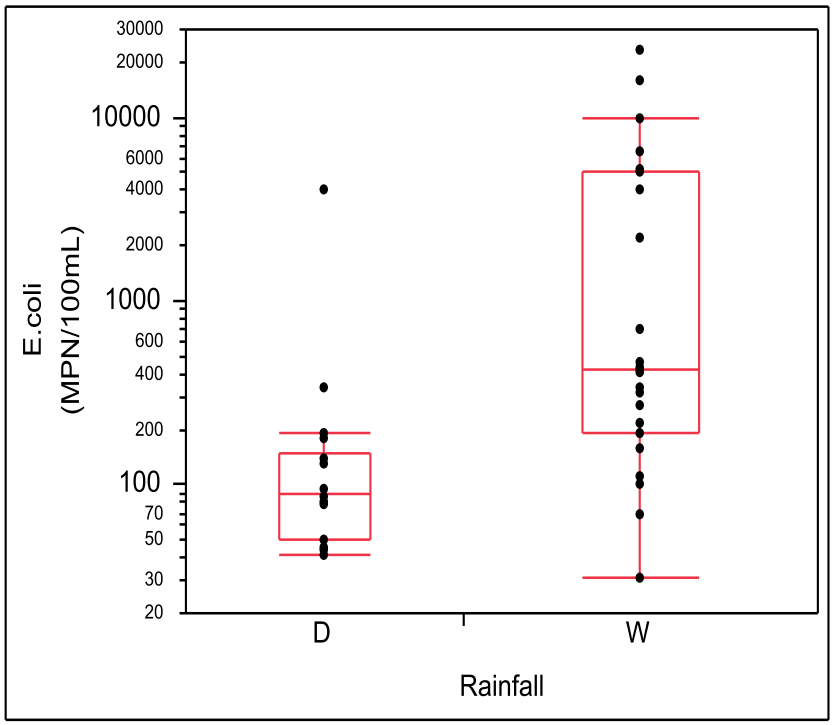


Figure 4.14 Difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11334 at Caney Creek on the SJR watershed. The box plots indicate the 25th, median and 75th percentile concentrations, lower and upper extreme along with outliers. E.coli concentrations are shown on a log scale

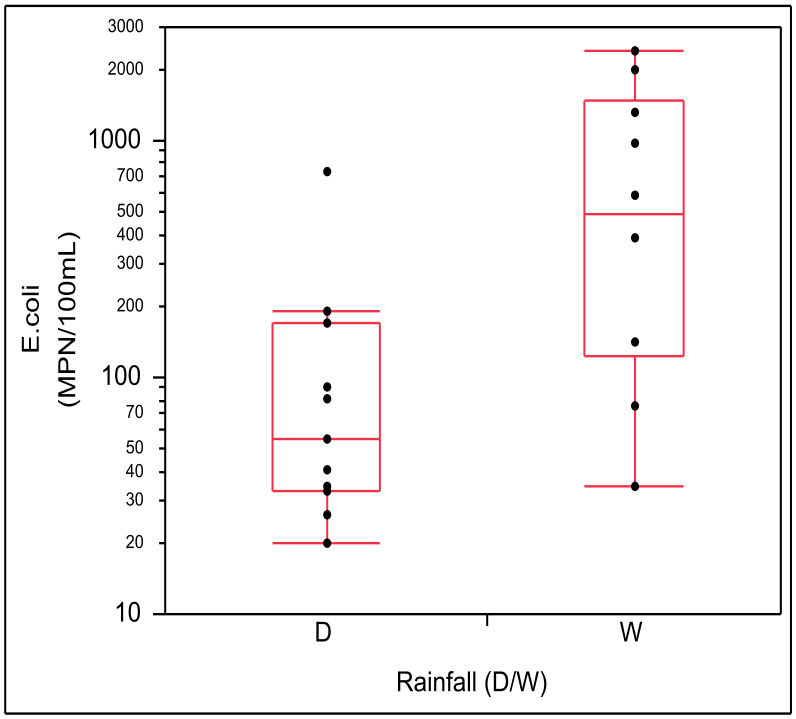


Figure 4.15 Difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 13486 at Green Creek on the Bosque River watershed. The box plots indicate the 25th, median and 75th percentile concentrations, lower and upper extreme along with outliers. E.coli concentrations are shown on a log scale

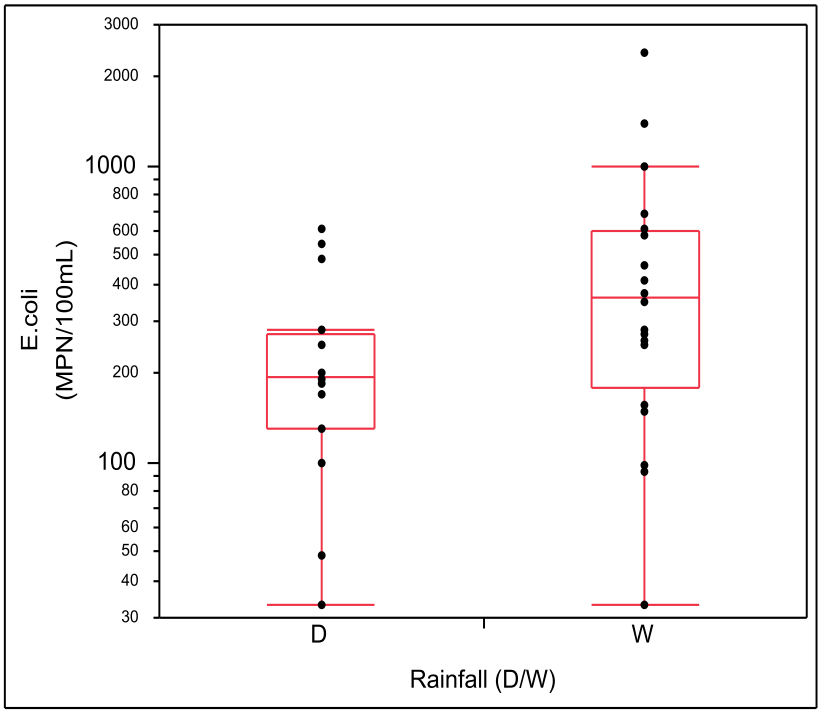


Figure 4.16 Difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17591 at Leon River below Proctor Lake segment on the Leon River watershed. The box plots indicate the 25th, median and 75th percentile concentrations, lower and upper extreme along with outliers. E.coli concentrations are shown on a log scale

The high density of CAFOs in the Comanche and Erath Counties could have influenced the results obtained for the rural watershed of the Leon and Bosque Rivers (Table 3.2). This first flush effect of runoff from CAFO dominated areas during storm events that constitute wet weather samples leading to higher indicator bacteria concentrations has been well established (Hodne, 2005; Simon and Makarewicz, 2009).

The relationship between storm events and high bacterial concentration has also been established for urban areas (Desai *et al.*, 2010; Hathaway and Hunt, 2010), explaining the high percentage (65%) of stations showing statistically significant difference in the SJR watershed. Hathaway and Hunt (2010), indicated that stormwater runoff from residential areas, where domestic animals and rodents are common, increased the bacterial concentration in these areas. The runoff from lawns in residential areas has also been associated with high concentrations indicator bacteria (Sartor *et al.*, 1974). In addition, factors other than surface run-offs during wet weather flow, like resuspended sediments and overflows in storm sewers, and leaks in the sewage system have also been linked to higher concentrations in both residential and industrial areas (Petersen *et al.*, 2005). All the samples available for the study are part of a routine monitoring process, not based on particular rain events. Further, the lower half of the SJR watershed also receives frequent rainfall at an average rate of once in four days (Desai *et al.*, 2010). Non-event driven sampling and frequent rainfalls could have masked the first flush effect in the SJR watershed from showing higher correlation. Further, Hathaway and Hunt (2010) indicated the masking of first flush effect during the summer due to abundance of bacteria during warmer temperatures.

4.3.3 Temperature Variations

As the results obtained for the effect of rainfall on bacterial concentrations indicated the effect of warm temperatures in masking the first flush effect,

difference between *E.coli* concentrations during summer and winter months were analyzed. A Wilcoxon Rank Sum Test was used to analyze the difference between sample concentrations during summer and winter months on the basis on their median concentrations and variance. From all the monitoring stations analyzed (Figure 3.6), no statistically significant relationship was obtained for the Leon River. This is shown in Figure 4.17 for monitoring station 17545 at the Leon River below Proctor Lake segment. Also, 30% of the monitoring stations on the Bosque River watersheds and less than 15% of the monitoring stations in the SJR watershed showed a statistically significant relationship ($p<0,05$) between *E.coli* concentrations during summer and winter. The box-plots shown in Figures 4.18 and 4.19 indicate that median concentrations were higher in summer than in winter. The results obtained here are consistent with previously documented results showing higher bacterial concentrations in summer than in winter (Petersen *et al.*, 2006; Silsbee and Larson, 1982). Complete results for all three watersheds are presented in Appendix F.

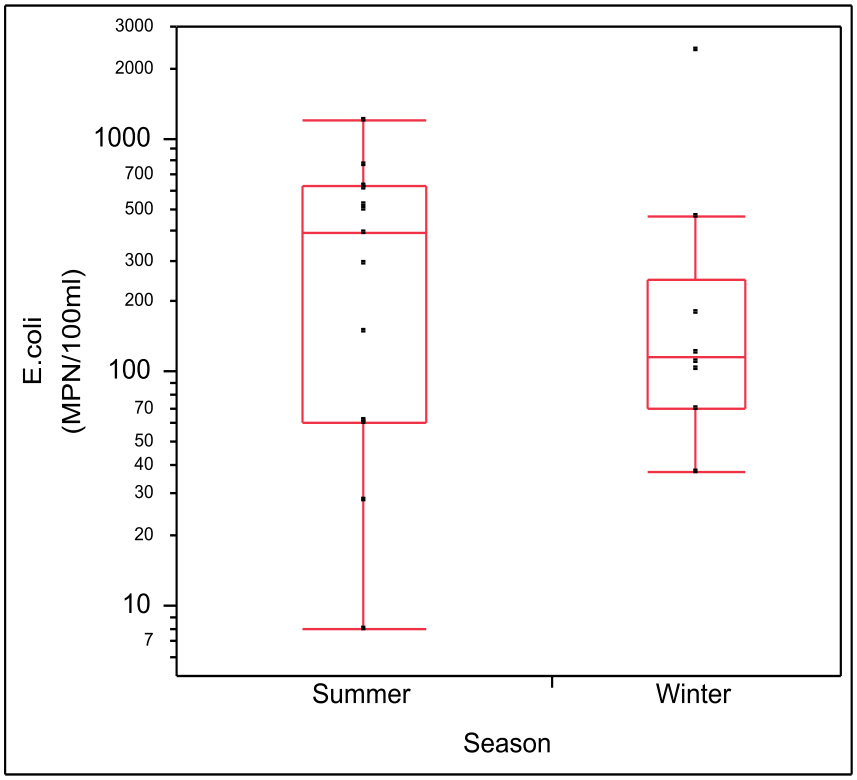


Figure 4.17 Comparison of *E.coli* concentrations observed between the summer and winter months for monitoring station 17545 at the Leon River below Proctor Lake on Leon River watershed. The box plots indicate the 25th, 75th percentile and median concentrations, extreme upper and lower concentrations along with outliers. E.coli concentrations are shown on a log scale.

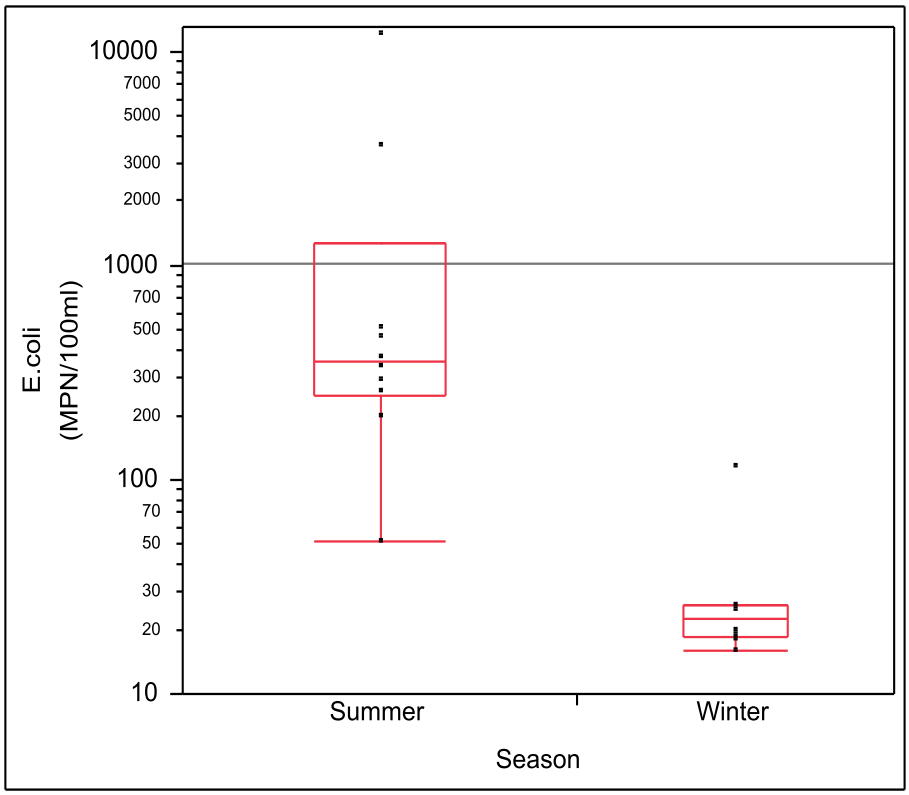


Figure 4.18 Comparison of *E.coli* concentrations observed between the summer and winter months for monitoring station 11925 at Greens Bayou on SJR watershed. The box plots indicate the 25th, 75th percentile and median concentrations, extreme upper and lower concentrations along with outliers. E.coli concentrations are shown on a log scale.

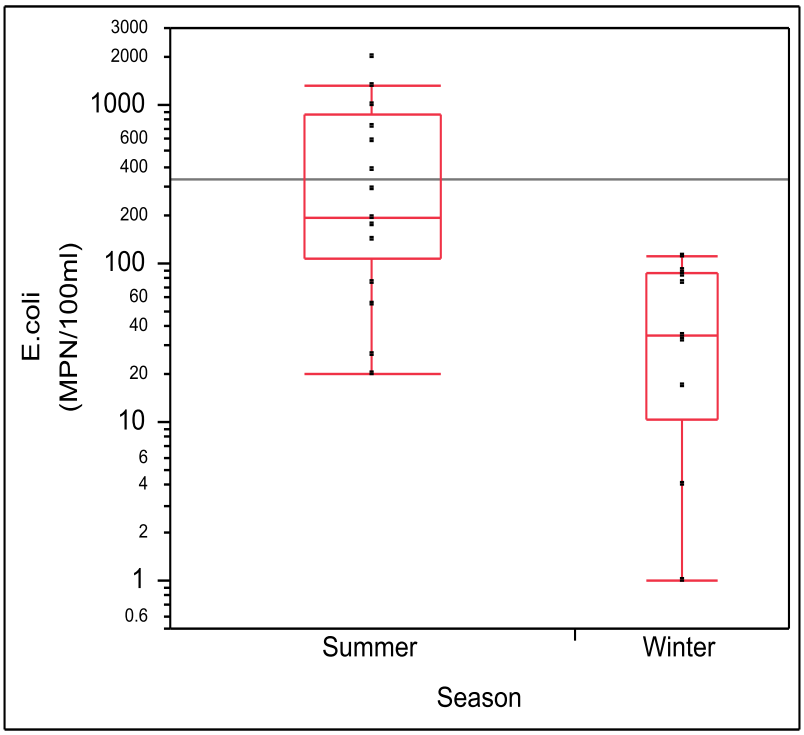


Figure 4.19 Comparison of *E.coli* concentrations observed between the summer and winter months for monitoring station 13486 at Green Creek on the Bosque River Watershed. The box plots indicate the 25th, 75th percentile and median concentrations, extreme upper and lower concentrations along with outliers. E.coli concentrations are shown in log scale.

While some studies have shown that indicator bacterial concentrations were higher in the cooler months than in warmer months (Lipp *et al.*, 2001; Traister and Anisfeld, 2006), results obtained in this study show that concentrations were higher during summer months. Average temperatures during summer months in the watersheds under study exceeded 30°C (National Climatic Data Center, 2010). Studies have indicated that temperatures greater than 30°C could help *E.coli* survive and even allow regrowth to occur (Ishii *et al.*,

2006; Solo-Gabriele *et al.*, 2000). Desai et al. (2010) also suggested that the concentration differences between summer and winter months decreased as a result of high urbanization, and increase in the nonpoint source pollution. This could explain the difference in significant differences of *E.coli* concentrations between summer and winter months for the urban SJR(less than 15%) and rural Bosque River (30%) watersheds. Alternatively the occurrence of frequent storm events in the SJR watershed throughout the year could also mask the effect of temperature on concentration for this urban watershed. The lack of sufficient concentration data in the Leon River resulted in the lack of statistically significant analysis.

5. CONCLUSIONS

A total of fifty-four monitoring stations were analyzed for the presence of indicator bacteria, their temporal and spatial variability in the San Jacinto, Bosque and Leon River watersheds. The monitoring stations in the San Jacinto River watershed had consistently higher *E.coli* concentration, that exceeded single sample standard compared to the monitoring stations in the Bosque and Leon Rivers. In particular, the concentrations were found to be exceeding single and geometric mean standards by many orders of magnitude in the lower half of the SJR watershed comprising the Houston Ship Channel, Buffalo Bayou Tidal and the White Oak Bayou. The bacterial concentrations in the Bosque and Leon Rivers were also found to exceed single sample and geometric mean standards. Human health risks through ingestion of surface water beyond the acceptable limits were also present in the three watersheds due to the high concentration of *E.coli.*

Urbanization and land use were found to play a major role in the concentration and spatial variability of indicator bacteria. More urbanized segments were found to have a higher concentration of *E.coli* than the lesser urbanized segments within the same watershed. The lower half of the SJR watershed that had a predominantly urban (residential and industrial) watershed had significantly higher concentrations of *E.coli* compared to the segments in the upper half that were predominantly rangeland and forests. Increased runoff due to surface imperviousness, resuspended sediments, leakages from pipes in the

sewage system, runoff from residential yards and overflow in storm sewers are some of the factors that have been associated with elevated concentration levels in the urbanized areas. Agricultural lands which house CAFOs in the Bosque and Leon River watersheds also recorded high *E.coli* concentrations. CAFOs have been generally associated with high bacterial concentrations due to the poor management of animal waste generated, NPS pollutant runoff, and lagoon spills and seepage.

QMRA processes were useful in both problem formulation and determining the human health risks from ingestion of indicator bacteria during contact recreation in the surface waters. Though risk through ingestion of water does not exist in all the segments because they are not used for contact recreation, human health is affected due to the consumption of fish and other seafood that have been affected by the contamination. Human health risk estimates (mean and 95th percentile) values for the SJR watershed were found to be significantly greater than the acceptable limit of 10^{-4}. Mean risk values in the Bosque and Leon Rivers were also found to be greater than the acceptable limit. The risk was also found to be greater in the highly urbanized regions than the agricultural areas. Children were found to be at a greater risk due to contact recreation than adults. This indicates the need to have warning signs in the heavily contaminated stream segments to prevent the public from using these segments for recreational activities. The risk value calculated should be taken as an indicator and a first step in the assessment of human health risks in these

watersheds rather than conclusive evidence of health risks due to the general nature of the study that involved multiple strains of indicator bacteria.

Temporal variations were also observed in the bacterial concentrations in the watersheds. No increase or decrease in indicator bacteria concentrations was observed during the period of study. This lack of trend was attributed to the short duration of the period of study. Positive correlation was observed between incidence of bacteria with the streamflow, rainfall and temperature. High streamflow, rainfall and temperature resulted in high incidences of indicator bacteria. The positive correlation between rainfall and high concentrations indicated the effect of first flush in influencing bacterial concentrations. These effects were more pronounced for the less urban and agricultural regions indicating the presence of multiple contributing factors that affect the bacterial concentrations in highly urbanized areas. Overall, the study reiterated that the land use and urbanization of watersheds influenced the bacterial concentrations and thus the human health risk.

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APPENDIX A

A.1 *E.coli* concentrations for monitoring stations on the San Jacinto River watershed.

Segment	Station (MPN/100mL)	Geometric Mean (MPN/100mL)	Maximum Value (MPN/100mL)	Samples exceeding Single Sample Std (%)
Buffalo Bayou above tidal	11360	739	120 000	67.9
	11362	640	23000	53.9
	11145	165	730	25
	15846	786	17 000	57.1
Buffalo Bayou Tidal	16648	2473	100 000	92.8
Caney Creek	11334	345	23 000	37.7
Cypress Creek	11328	1275	41 000	80.6
	11332	368	46 000	33.3
	20456	125	720	25
East Fork San Jacinto	11235	244	20 000	36.3
Greens Bayou above Tidal	11371	1222	17 000	78.5
	11369	527	20 000	57.8
	11125	497	12000	50
Houston Ship Channel-Buffalo Bayou Tidal	11140	1629	14 000	92.8
	11139	2926	87 000	92.5
	11135	629	41 000	64.3
	15851	830	5 800	85.7
	16661	2102	160 000	85.7
Houston Ship Channel	16665	1681	87 000	82.1
	11279	1196	20 000	71.4
Lake Creek	18191	267	24 000	25
Peach Creek	17746	464	14 000	45.4
Spring Creek	11314	968	17 000	60
	11312	444	19 000	46.4
West Fork San Jacinto	11250	249	4700	21.1
Whiteoak Bayou	11394	630	73 000	42.1
	11387	3518	29 000	91.6

A.2 *E.coli* concentrations for monitoring stations on the Bosque River watershed.

Segment	Station (MPN/100mL)	Geometric Mean (MPN/100mL)	Maximum Value (MPN/100mL)	Samples exceeding Single Sample Std (%)
Bosque River				
North Bosque River	11954	63	22 000	12.5
	18003	48	17 000	6.3
	11956	41	6 600	5.6
	11961	92	5700	17.5
	17500	30	7 100	12.9
Duffau Creek	17607	149	39 000	14.6
Indian Creek	17235	189	14 000	28
Sims Creek	17240	180	58 000	24.6
Green Creek	13486	103	2 400	24.3
Meridian Creek	14908	29	160	0
Middle/South Bosque	20308	96	7000	14.7
Neils Creek	11826	79.6	20 000	14.2
Sims Cr	17240	180.7	58 000	24.6
Spring cr	17242	51.9	5000	7.1

A.3 *E.coli* concentrations for monitoring stations on the Leon River watershed

Segment	Station (MPN/100mL)	Geometric Mean (MPN/100mL)	Maximum Value (MPN/100mL)	Samples exceeding Single Sample Std (%)
Leon below Leon Lake	11938	242	4400	46.2
Duncan Creek	17544	461	9171	40
Leon below Proctor Lake	17591	269	2400	35.15
	11925	162	24 000	30.3
	11934	138	860	17.6
	15769	161	2400	16.2
	17501	95	2400	31.5
	17545	182	2400	32.5
Resley Creek	17376	401	6500	56.25
	17377	211	2400	31.3

APPENDIX B

B.1 Annual risk estimates for monitoring stations on the SJR watershed. All dosage distribution parameters are expressed in MPN/100mL.

Segment	Station	Best-Fit *E.coli* Dosage Distribution		Annual Risk 5th Percentile	Annual Risk Mean	Annual Risk 95th Percentile
Buffalo Bayou above Tidal	11360	InvGaussian	Adult	1.04E-05	1.41E-03	6.11E-03
		(μ=6051.8,λ=391.9)	Child	2.59E-05	3.45E-03	1.52E-02
	11362	Log Normal	Adult	1.46E-05	7.06E-04	2.69E-03
		(μ=2969.1,σ=16567.1)	Child	3.66E-05	1.74E-03	6.70E-03
	11145	Log Normal	Adult	5.95E-06	9.05E-05	3.30E-04
		μ=4.95, σ=1.38	Child	1.49E-05	2.26E-04	8.23E-04
	15846	InvGauss	Adult	3.02E-05	5.21E-04	2.26E-03
		μ = 2119.4, λ = 266.92	Child	7.54E-05	1.30E-03	5.64E-03
Buffalo Bayou Tidal	16648	Log Normal	Adult	4.91E-05	3.12E-03	1.21E-02
		(μ=13804.1,σ=94152.1)	Child	1.23E-04	7.37E-03	2.98E-02
Caney Creek	11334	InvGaussian	Adult	1.02E-05	4.60E-04	1.86E-03
		(μ=1905.9,λ=200.35)	Child	2.55E-05	1.14E-03	4.65E-03
Cypress Creek	11328	InvGaussian	Adult	3.13E-05	1.08E-03	4.79E-03
		(μ=4524.4,λ=537.03)	Child	7.82E-05	2.66E-03	1.19E-02
	11332	InvGaussian	Adult	9.07E-06	6.84E-04	2.74E-03
		μ = 2883.8, λ = 136.84	Child	2.27E-05	1.68E-03	6.82E-03
	20456	Normal	Adult	4.53E-05	6.00E-05	1.65E-04
		μ=250.25, σ=267.03	Child	1.13E-04	1.50E-04	4.13E-04
East fork San Jacinto	11235	Log Normal	Adult	4.53E-06	2.65E-04	1.01E-03
		μ=1101.9, σ=5486.6	Child	1.13E-05	6.60E-04	2.52E-03
Greens Bayou	11371	Beta	Adult	1.57E-05	7.20E-04	2.61E-03
		(a1 = 0.52, a2 = 8.32)	Child	3.93E-05	1.80E-03	6.51E-03
	11125	Log Normal	Adult	1.85E-05	5.24E-04	1.25E-03
		μ=6250, σ=6250	Child	4.62E-05	1.19E-03	3.13E-03
	11369	InvGaussian	Adult	8.94E-06	4.79E-04	2.15E-03
		μ = 2035.7, λ = 275.22	Child	1.49E-04	5.38E-03	2.36E-02

Segment	Station	Best-Fit *E.coli* Dosage Distribution		Annual Risk 5th Percentile	Annual Risk Mean	Annual Risk 95th Percentile
Houston Ship Channel-Buffalo Bayou Tidal	16661	Log Normal	Adult	3.42E-05	7.64E-03	1.65E-02
		(μ=12612.9,σ=71985.4)	Child	8.56E-05	1.39E-02	4.05E-02
	11139	InvGaussian	Adult	5.98E-05	2.18E-03	9.52E-03
		(μ=9403.6,λ=1871.6)	Child	1.49E-04	5.38E-03	2.36E-02
	15851	InvGauss	Adult	4.80E-05	4.19E-04	1.19E-03
		μ = 4000, λ = 4000	Child	1.20E-04	1.03E-03	2.97E-03
	11140	Log Normal	Adult	8.28E-05	7.57E-04	2.64E-03
		μ=2971.9, σ=6263.5	Child	2.07E-04	1.89E-03	6.57E-03
	11135	InvGauss	Adult	1.39E-05	6.49E-04	2.88E-03
		μ = 2756.1, λ = 422.82	Child	3.47E-05	1.61E-03	7.19E-03
Houston Ship Channel	16665	InvGaussian	Adult	3.27E-05	1.87E-03	8.43E-03
		(μ=8000.8,λ=836.93)	Child	8.19E-05	4.58E-03	2.09E-02
	11279	InvGauss	Adult	3.44E-05	8.22E-04	3.59E-03
		μ = 3433.5, λ = 551.59	Child	8.60E-05	2.04E-03	8.94E-03
Lake Creek	18191	InvGauss	Adult	1.48E-05	6.81E-04	6.68E-04
		μ = 3433.5, λ = 551.59	Child	3.69E-05	1.53E-03	1.67E-03
Peach Creek	17746	Exponential	Adult	8.69E-06	4.97E-04	1.56E-03
		β = 2226.4	Child	2.17E-05	1.24E-03	3.89E-03
Spring Creek	11314	Beta	Adult	2.40E-05	1.46E-03	4.05E-03
		(a1 = 0.21, a2 = 0.37)	Child	6.00E-05	3.63E-03	1.01E-02
	11312	Log Normal	Adult	1.03E-05	6.08E-04	2.22E-03
		μ=2560.4, σ=19586.9	Child	2.57E-05	1.49E-03	5.52E-03
West Fork San Jacinto	11250	InvGauss	Adult	6.83E-06	1.44E-04	5.36E-04
		μ = 642.27 λ = 230.88	Child	1.71E-05	3.60E-04	1.34E-03
White Oak Bayou	11394	InvGauss	Adult	6.03E-06	2.63E-03	4.78E-03
		(μ=8572.9,λ=166.96)	Child	1.51E-05	5.90E-03	1.19E-02
	11387	Beta	Adult	9.84E-06	2.85E-03	6.89E-03
		(a1 = 00.29, a2 = 0.42)	Child	2.46E-05	7.07E-03	1.71E-02

B.2 Annual risk estimates for monitoring stations on the Bosque River watershed. All dosage distribution parameters are expressed in MPN/100mL.

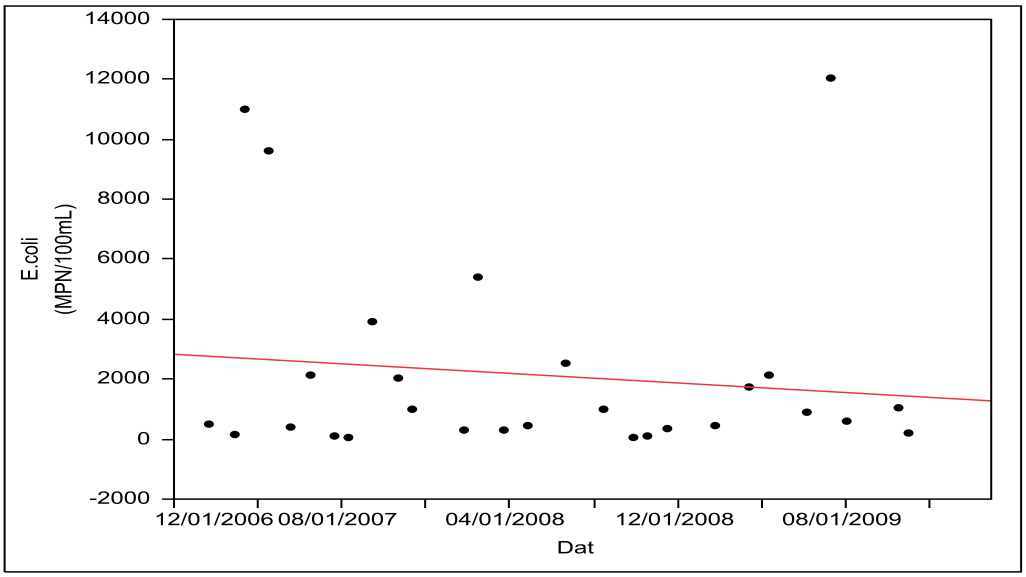
Segment	Station	Best-Fit E.coli Dosage Distribution		Annual Risk 5th Percentile	Annual Risk Mean	Annual Risk 95th Percentile
North Bosque River	18003	InvGaussian	Adult	1.14E-06	1.17E-04	4.59E-04
		(μ=488.85,λ=22.1)	Child	2.86E-06	2.93E-04	1.15E-03
	17500	InvGaussian	Adult	4.53E-07	8.49E-05	2.74E-04
		(μ=356.71,λ=9.32)	Child	1.13E-06	2.11E-04	6.85E-04
	11956	InvGaussian	Adult	1.33E-06	5.44E-05	1.16E-04
		(μ=1250,λ=1250)	Child	3.31E-06	1.34E-04	2.89E-04
	11954	Log Normal	Adult	1.07E-06	6.74E-05	2.58E-04
		(μ=280.8,σ=1328.4)	Child	2.67E-06	1.68E-04	6.46E-04
	11961	InvGaussian	Adult	2.26E-06	8.62E-05	3.83E-04
		(μ=362.22,λ=47.24)	Child	5.65E-06	2.15E-04	9.58E-04
Duffau Creek	17606	InvGaussian	Adult	3.55E-06	8.74E-05	3.63E-04
		(μ=362.22,λ=47.24)	Child	8.88E-06	2.18E-04	9.06E-04
Indian Creek	17235	Log Normal	Adult	3.13E-06	4.05E-04	1.37E-03
		(μ=1771.1,σ=22084.4)	Child	7.83E-06	9.94E-04	3.42E-03
Middle/South Bosque	20308	InvGaussian	Adult	2.85E-06	1.02E-04	4.53E-04
		(μ=428.7,λ=57.9)	Child	7.11E-06	2.56E-04	1.13E-03
Spring Creek	17242	Log Normal	Adult	7.76E-06	4.15E-04	1.59E-03
		(μ=160.3,σ=467.5)	Child	2.63E-06	9.59E-05	3.68E-04
Meridian Creek	14908	Exponential	Adult	8.83E-07	1.04E-05	3.04E-05
		(β = 41.89)	Child	2.21E-06	2.60E-05	7.61E-05
Green Creek	13486	InvGaussian	Adult	1.83E-06	7.70E-05	3.35E-04
		(μ=329.42,λ=66.176)	Child	4.57E-06	1.92E-04	8.37E-04
Neils Creek	11826	Log Normal	Adult	9.56E-07	1.07E-04	4.01E-04
		(μ=443.5,σ=2487.5)	Child	2.39E-06	2.66E-04	1.00E-03
Sims Creek	17240	Log Normal	Adult	3.10E-06	1.67E-04	6.35E-04
		(μ=685.74,σ=2576.9)	Child	7.76E-06	4.15E-04	1.59E-03

B.2 Continued

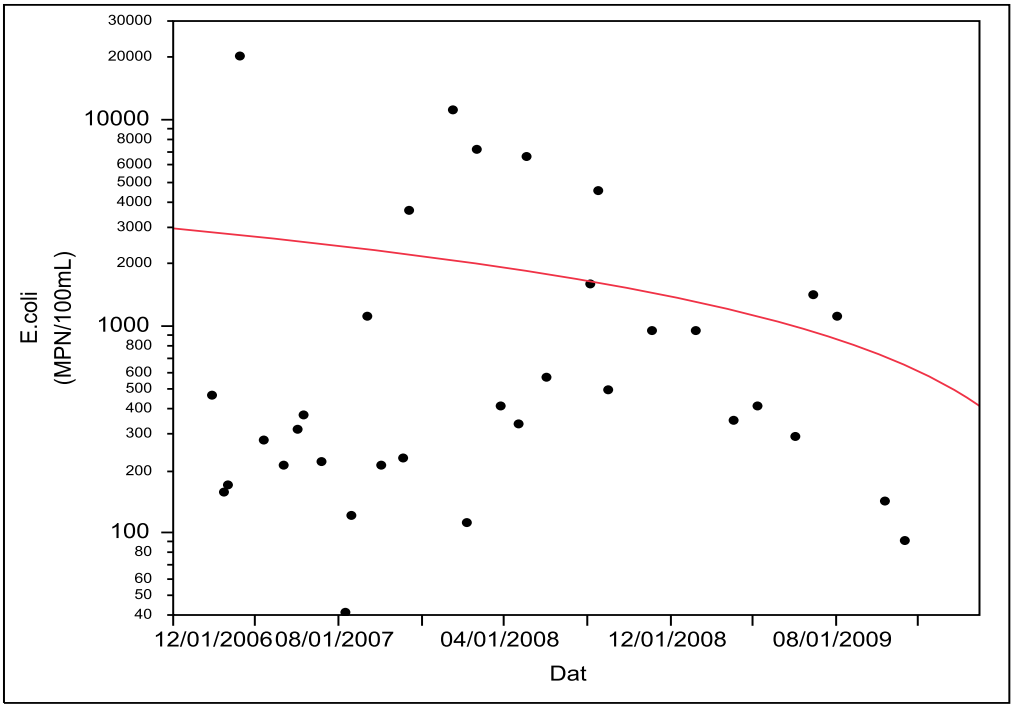
Segment	Station	Best-Fit E.coli Dosage Distribution		Annual Risk 5th Percentile	Annual Risk Mean	Annual Risk 95th Percentile
Resley Creek	17377	InvGaussian	Adult	5.10E-06	3.44E-04	7.29E-04
		(μ=633.5,λ=180.85)	Child	1.27E-05	7.99E-04	1.82E-03
Resley Creek	17376	Exponential	Adult	4.07E-06	2.27E-04	6.94E-04
		(β = 978.38)	Child	1.02E-05	5.66E-04	1.73E-03
Leon Below Leon Lake	11938	Exponential	Adult	3.43E-06	1.58E-04	4.98E-04
		(β = 711.46)	Child	8.57E-06	3.96E-04	1.25E-03
Duncan Creek	17544	Exponential	Adult	1.91E-05	2.90E-04	8.59E-04
		(β = 1190.7)	Child	4.77E-05	7.24E-04	2.14E-03
Leon below Proctor Lake	11925	InvGaussian	Adult	4.07E-06	2.27E-04	6.94E-04
		(μ=1093.3,λ=72.02)	Child	1.02E-05	5.66E-04	1.73E-03
	11934	InvGaussian	Adult	2.46E-05	4.72E-05	1.19E-04
		(μ=100,λ=100)	Child	6.16E-05	1.18E-04	2.98E-04
	15769	Log Normal	Adult	7.47E-06	5.97E-05	1.71E-04
		(μ=268.89,σ=258.62)	Child	1.87E-05	1.49E-04	4.27E-04
	17501	InvGaussian	Adult	1.13E-06	1.03E-04	4.60E-04
		(μ=435.42,λ=46.1)	Child	2.83E-06	2.57E-04	1.15E-03
	17545	InvGaussian	Adult	6.18E-06	8.67E-05	3.16E-04
		(μ=376.8,λ=190.33)	Child	1.54E-05	2.17E-04	7.91E-04
	17591	Log Normal	Adult	1.33E-05	1.01E-04	3.02E-04
		(μ=424.11,σ=494.26)	Child	3.33E-05	2.51E-04	7.56E-04
	18781	InvGaussian	Adult	3.61E-06	5.93E-05	2.21E-04
		(μ=258.38,λ=120.76)	Child	9.03E-06	1.48E-04	5.53E-04

APPENDIX C

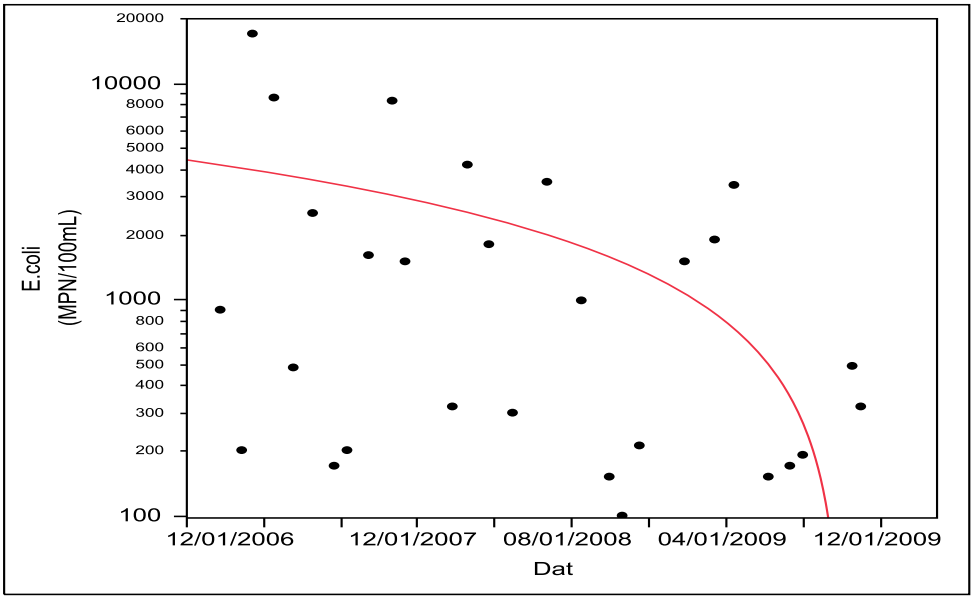
C.1 *E.coli* concentrations across time for monitoring station 11360 at Buffalo Bayou above Tidal on the SJR River watershed. The red line represents linear fit.



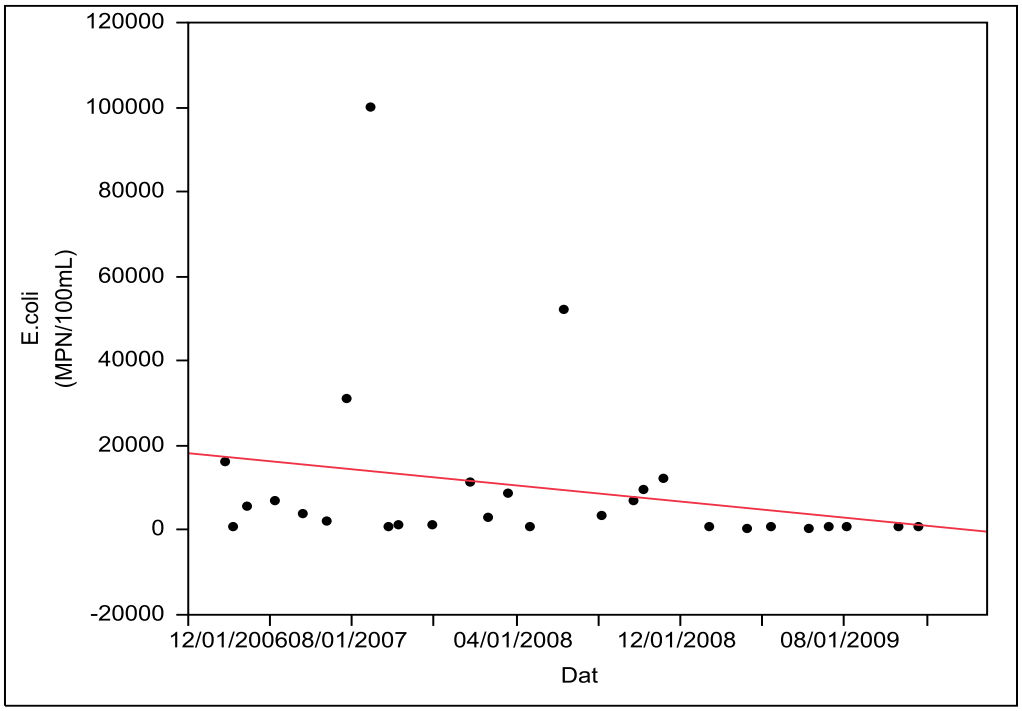
C.2 *E.coli* concentrations across time for monitoring station 11362 at Buffalo Bayou above Tidal on the SJR River watershed. The red line represents linear fit.



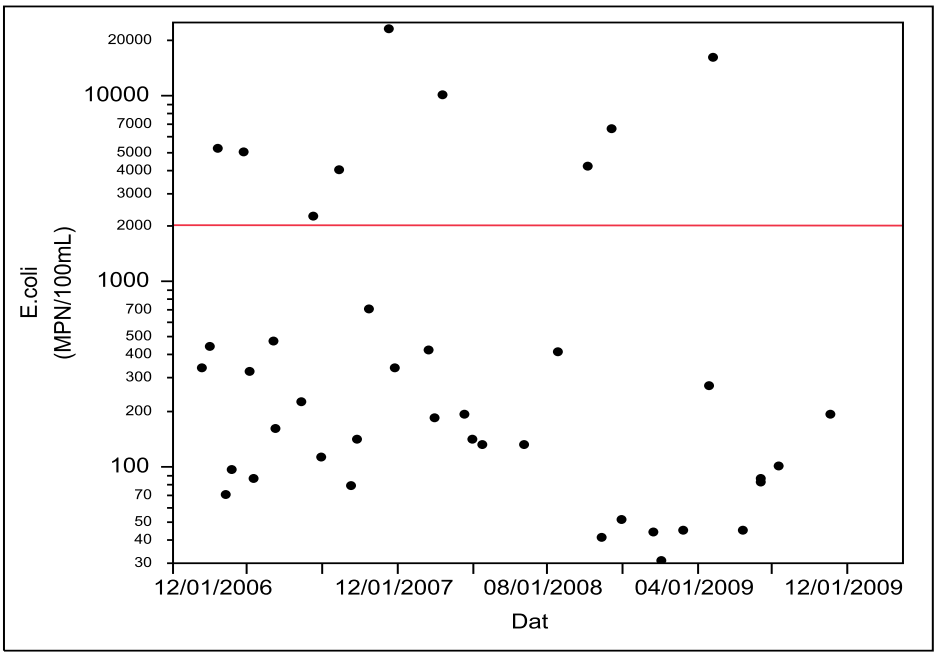
C.3 *E.coli* concentrations across time for monitoring station 15846 at Buffalo Bayou above Tidal on the SJR River watershed. The red line represents linear fit.



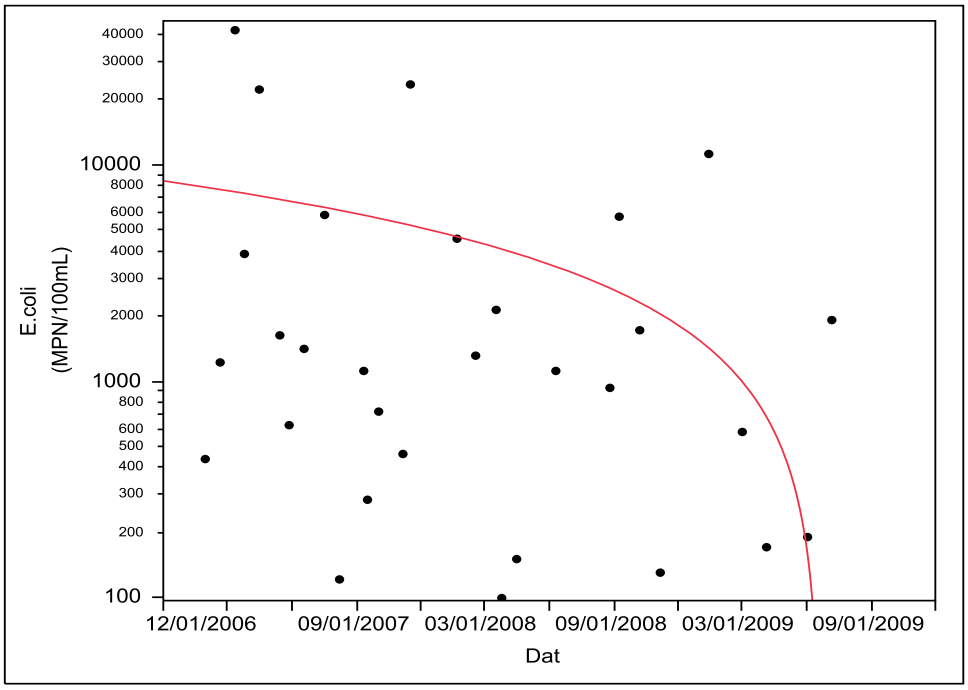
C.4 *E.coli* concentrations across time for monitoring station 16648 at Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



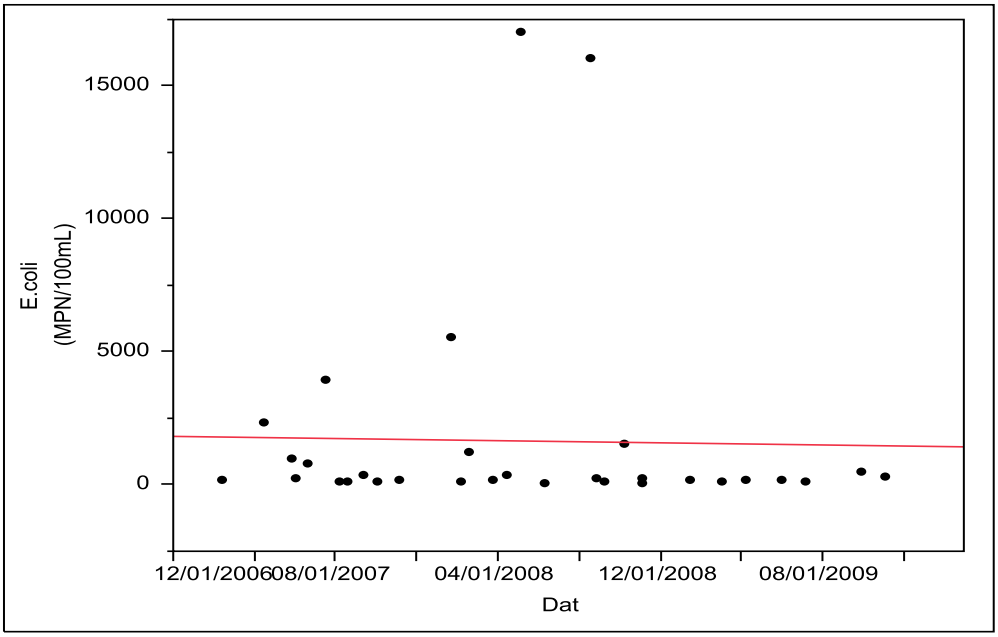
C.5 *E.coli* concentrations across time for monitoring station 11334 at Caney Creek on the SJR River watershed. The red line represents linear fit.



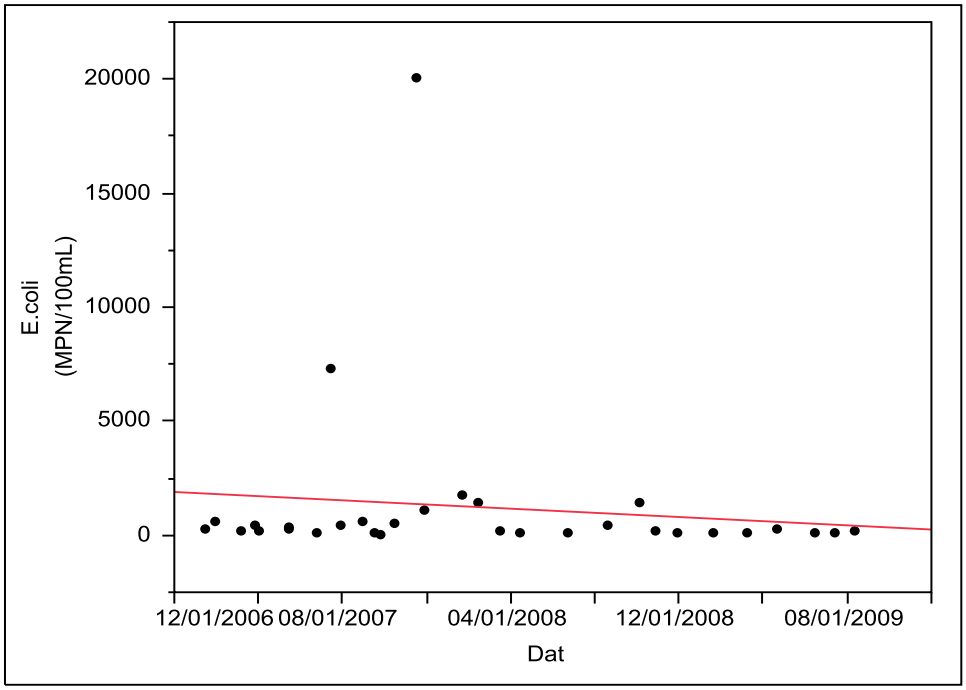
C.6 *E.coli* concentrations across time for monitoring station 11328 at Cypress Creek on the SJR River watershed. The red line represents linear fit.



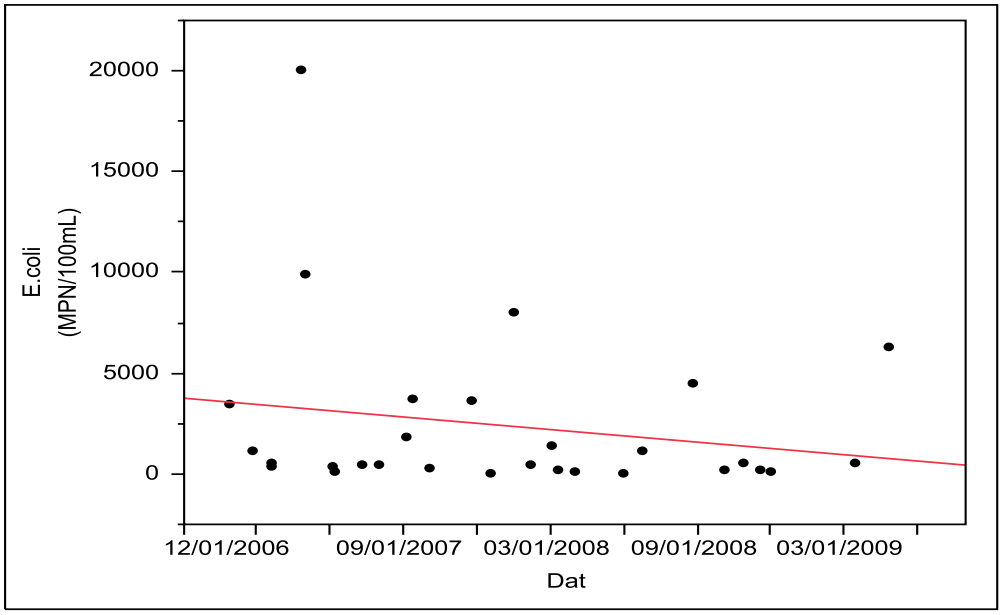
C.7 *E.coli* concentrations across time for monitoring station 11332 at Cypress Creek on the SJR River watershed. The red line represents linear fit.



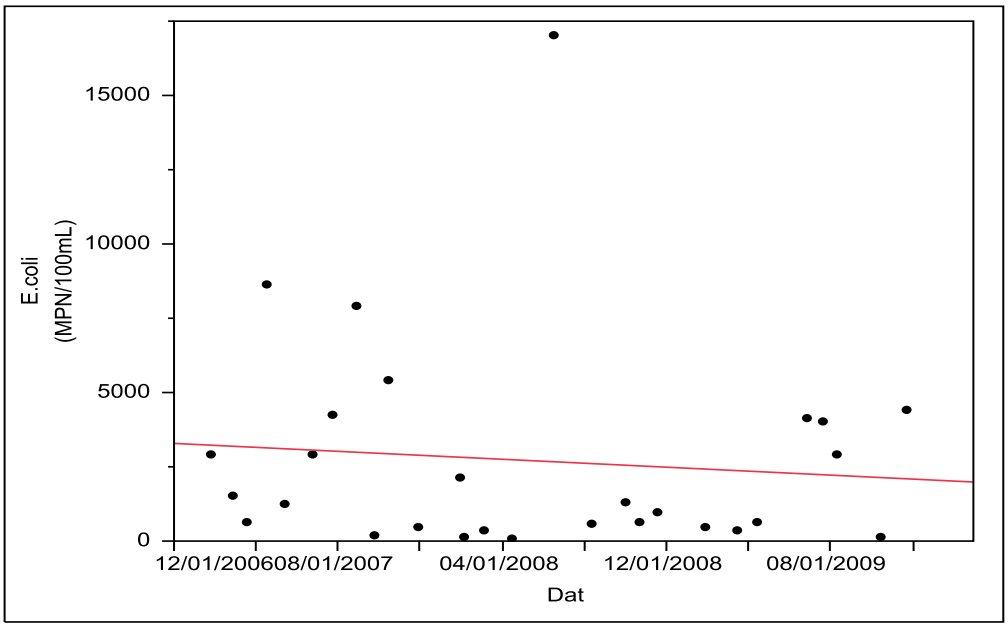
C.8 *E.coli* concentrations across time for monitoring station 11235 at East Fork San Jacinto River on the SJR River watershed. The red line represents linear fit.



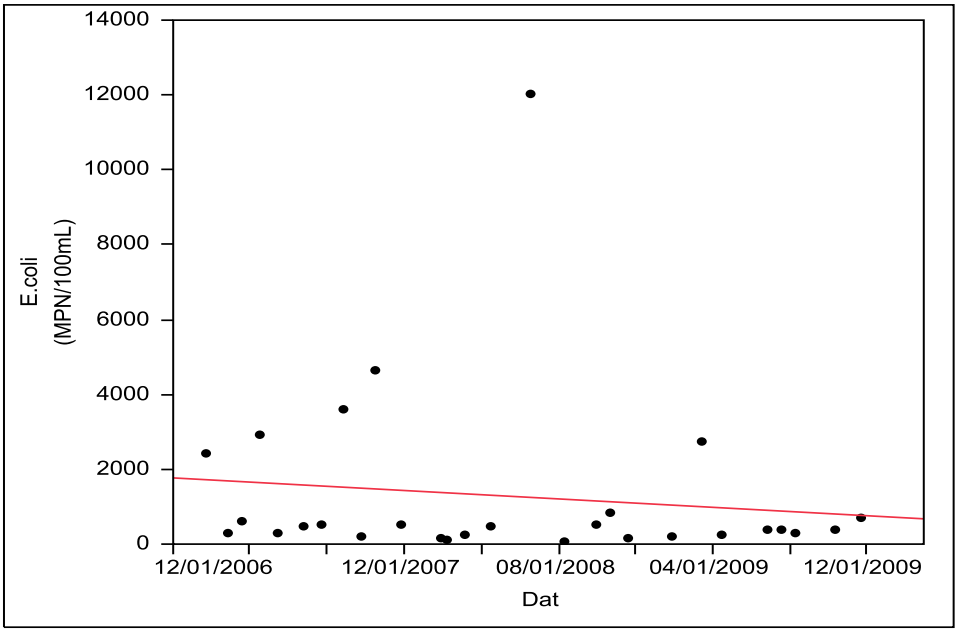
C.9 *E.coli* concentrations across time for monitoring station 11369 at Greens Bayou on the SJR River watershed. The red line represents linear fit.



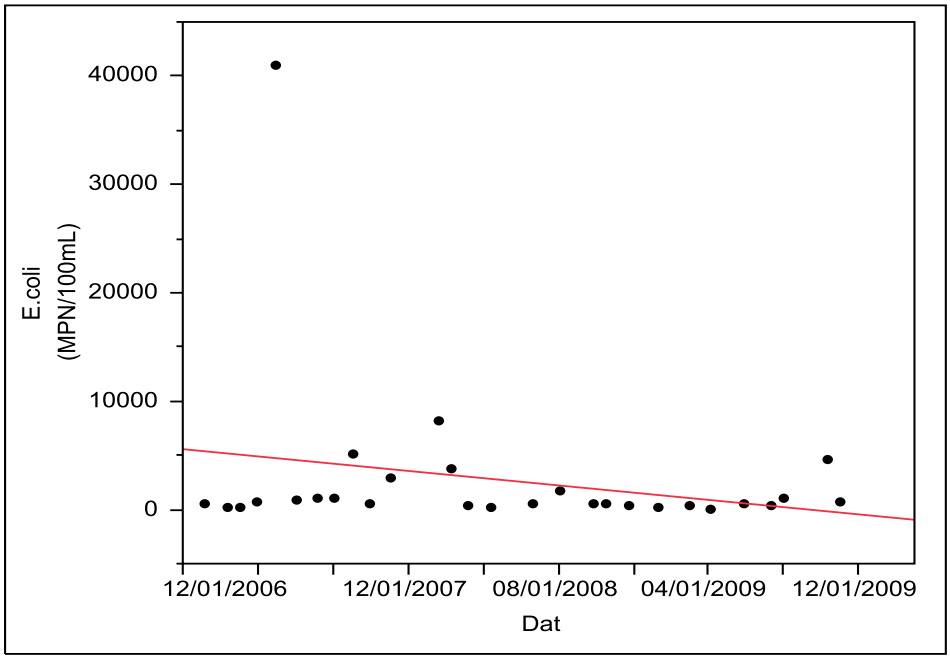
C.10 *E.coli* concentrations across time for monitoring station 11371 at Greens Bayou on the SJR River watershed. The red line represents linear fit.



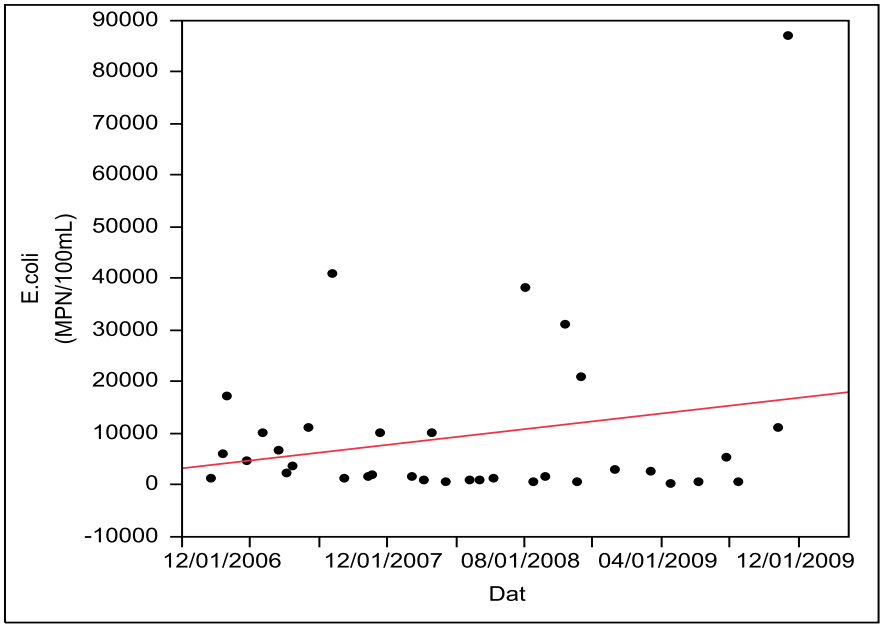
C.11 *E.coli* concentrations across time for monitoring station 11925 at Greens Bayou on the SJR River watershed. The red line represents linear fit.



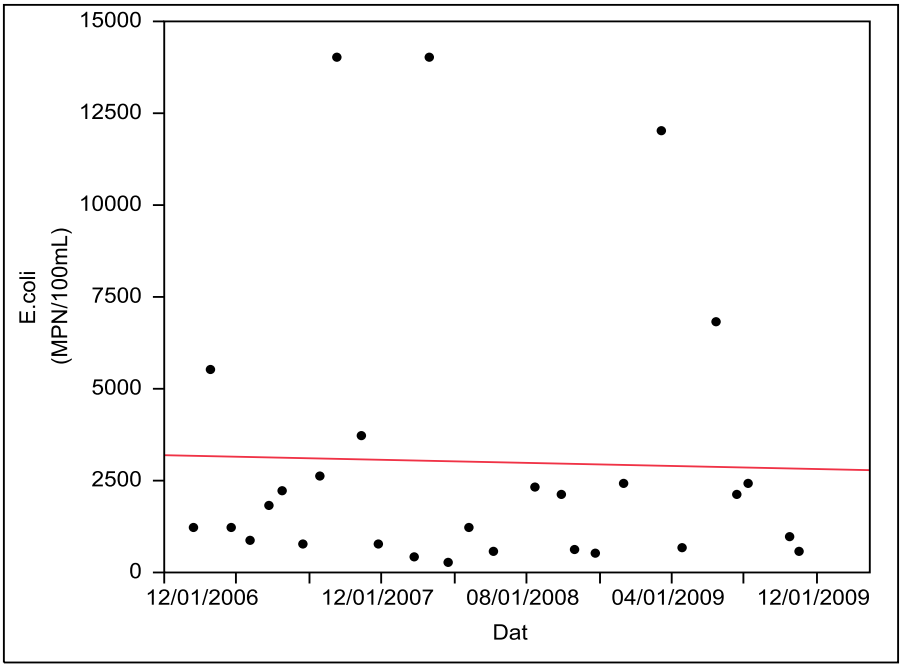
C.12 *E.coli* concentrations across time for monitoring station 11925 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



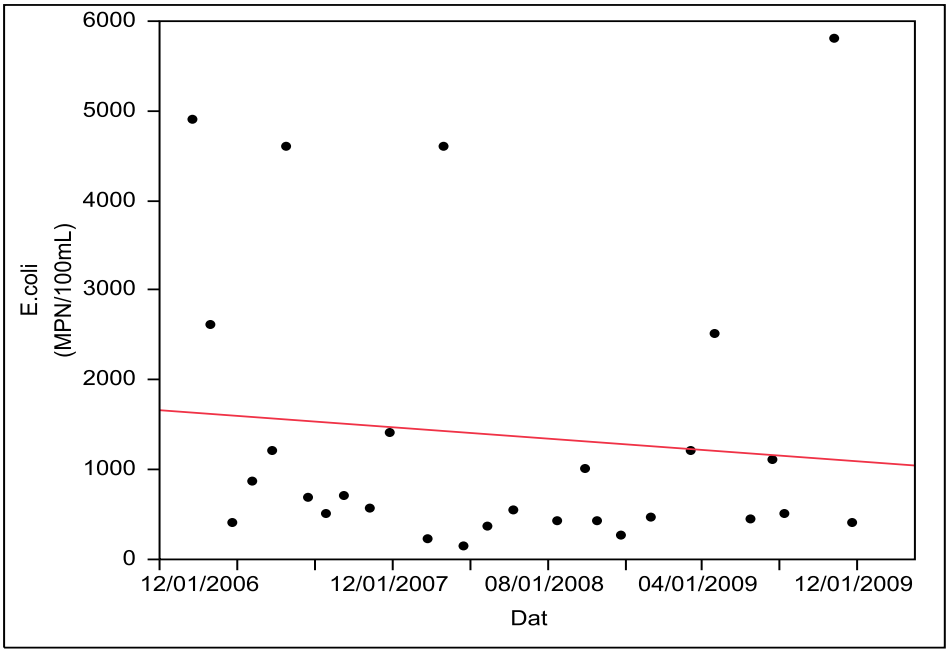
C.13 *E.coli* concentrations across time for monitoring station 11139 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



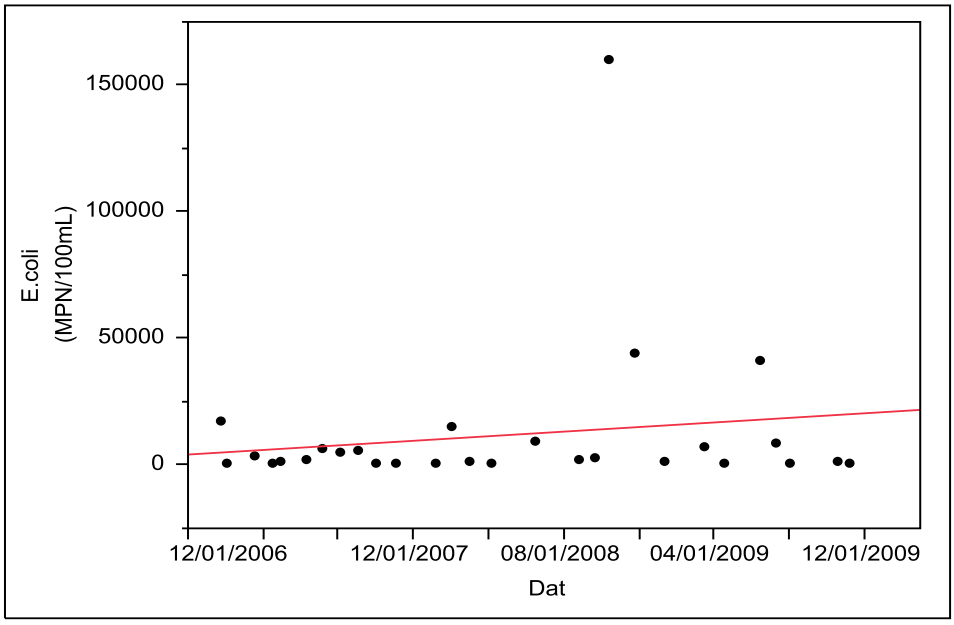
C.14 *E.coli* concentrations across time for monitoring station 11140 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



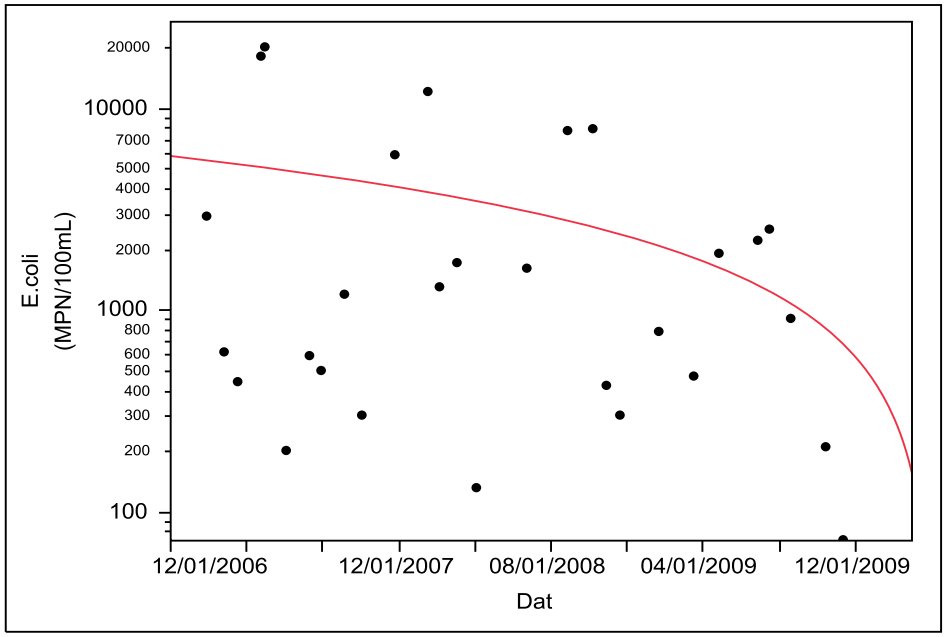
C.15 *E.coli* concentrations across time for monitoring station 15851 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



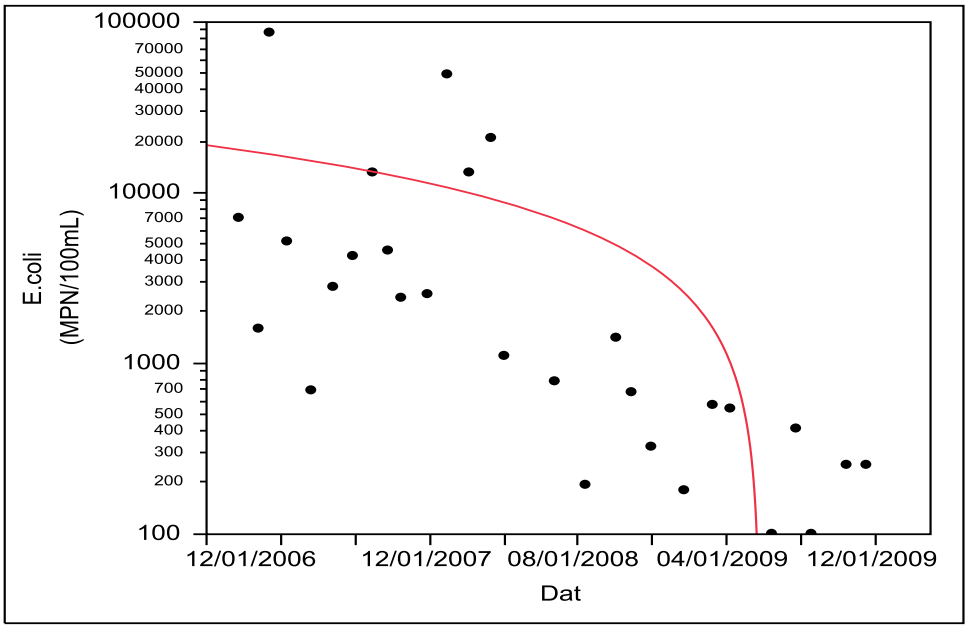
C.16 *E.coli* concentrations across time for monitoring station 16661 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



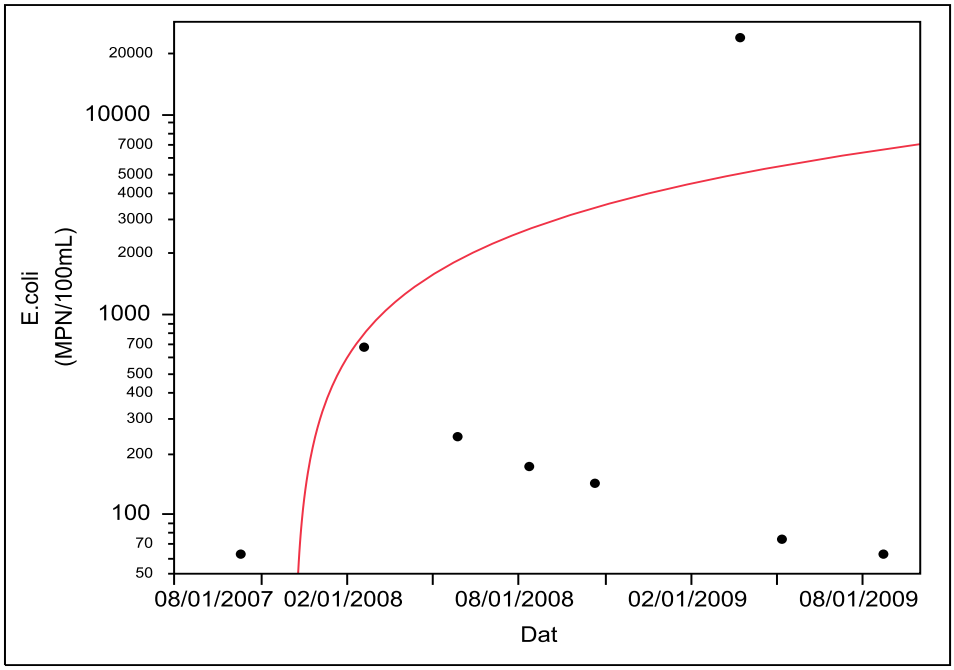
C.17 *E.coli* concentrations across time for monitoring station 11279 at Houston Ship Channel on the SJR River watershed. The red line represents linear fit.



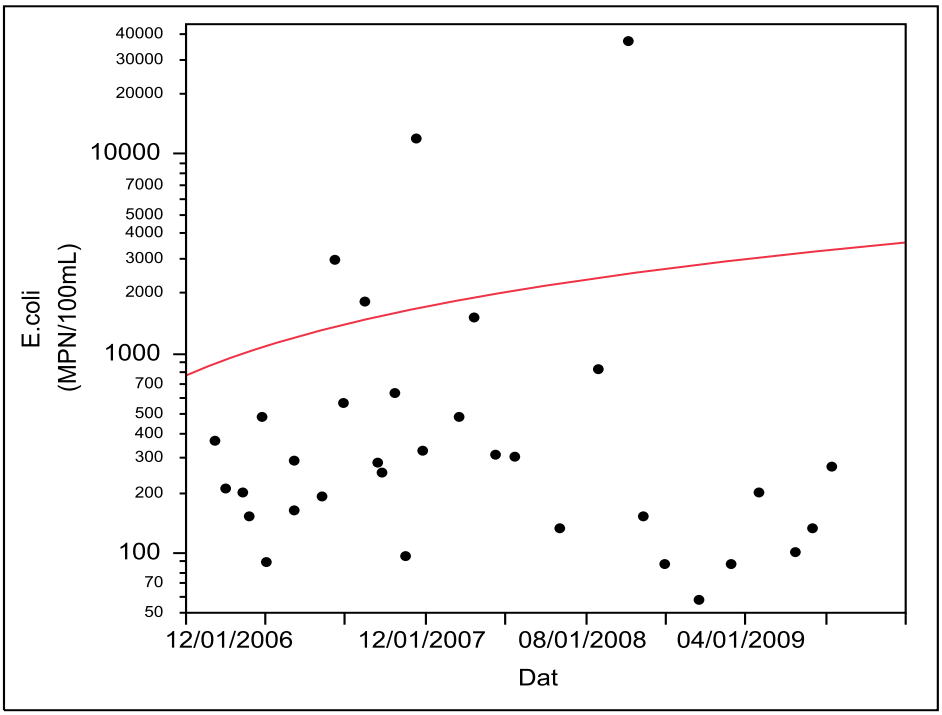
C.18 *E.coli* concentrations across time for monitoring station 16665 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR River watershed. The red line represents linear fit.



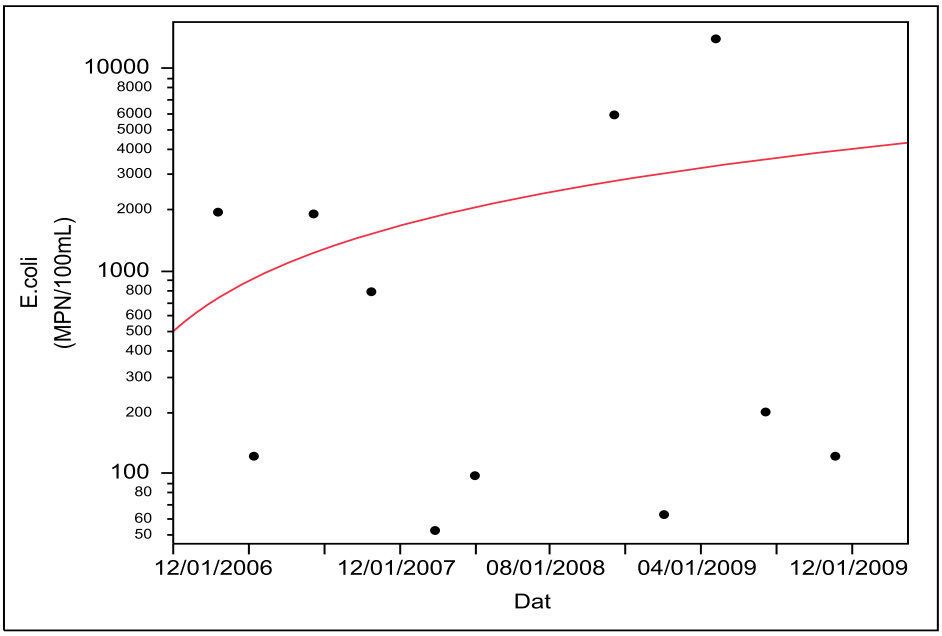
C.19 *E.coli* concentrations across time for monitoring station 18191 at Lake Creek on the SJR River watershed. The red line represents linear fit.



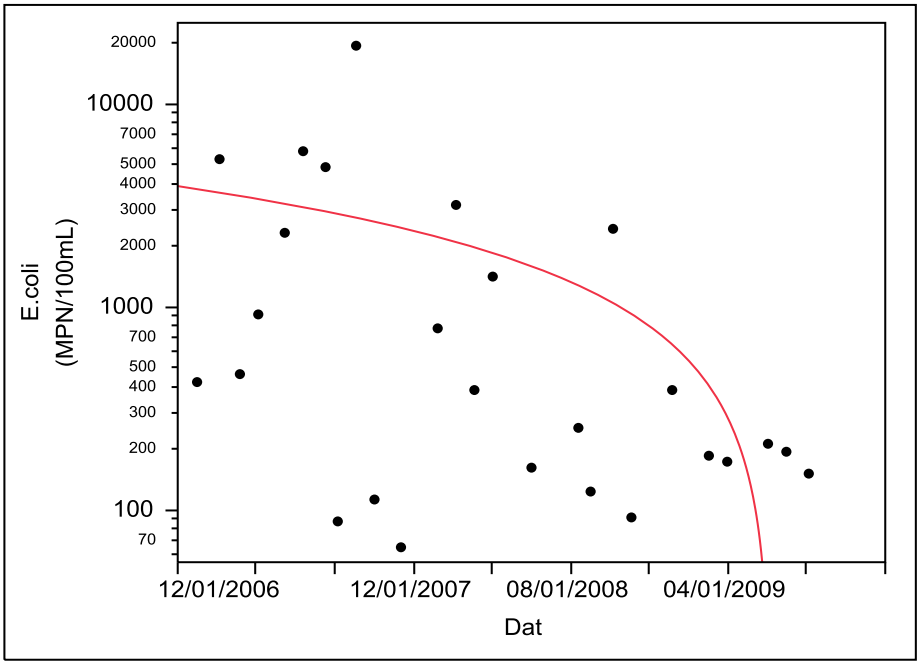
C.20 *E.coli* concentrations across time for monitoring station 11336 at Peach Creek on the SJR River watershed. The red line represents linear fit.



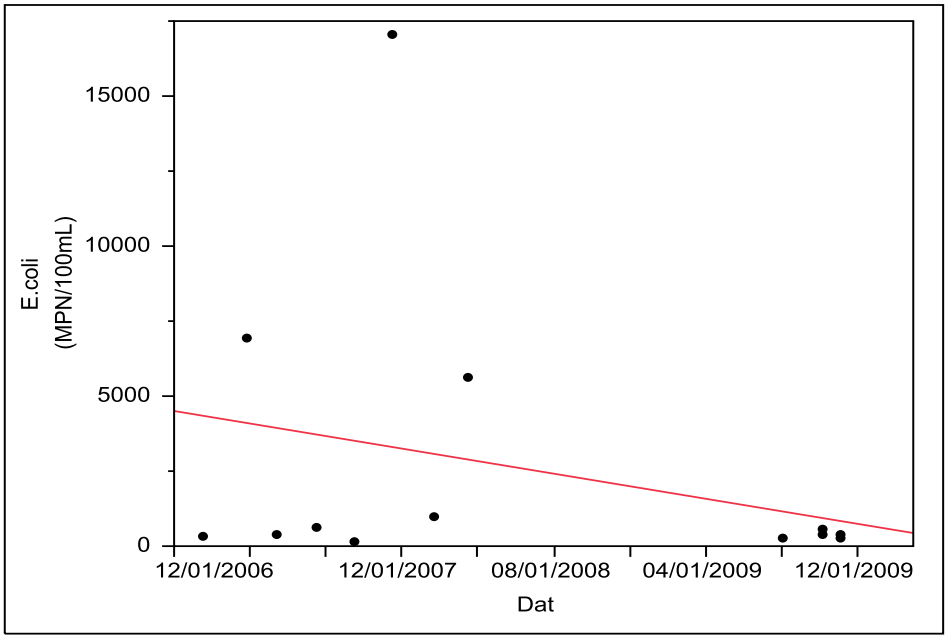
C.21 *E.coli* concentrations across time for monitoring station 17746 at Peach Creek on the SJR River watershed. The red line represents linear fit.



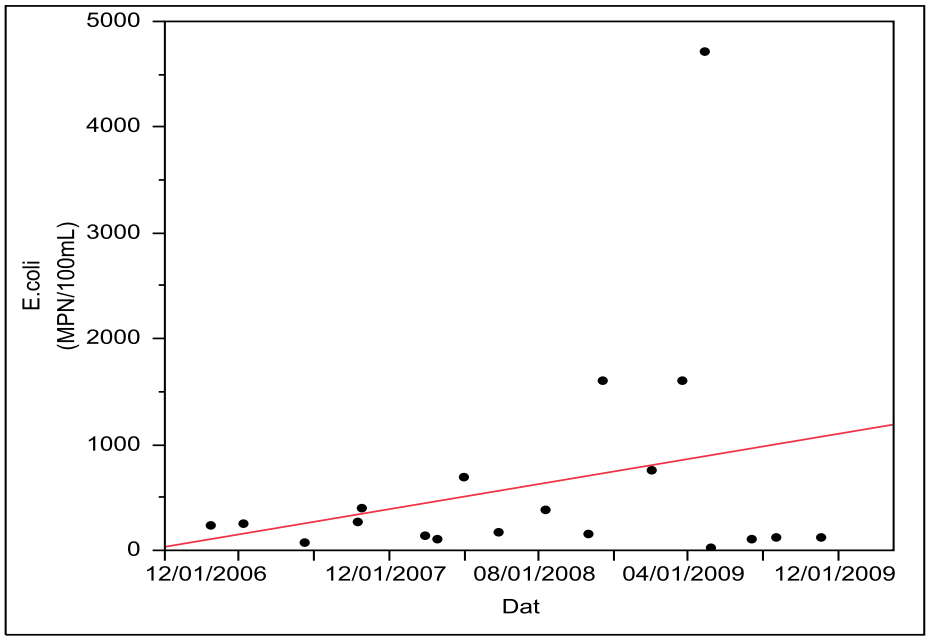
C.22 *E.coli* concentrations across time for monitoring station 11312 at Spring Creek on the SJR River watershed. The red line represents linear fit.



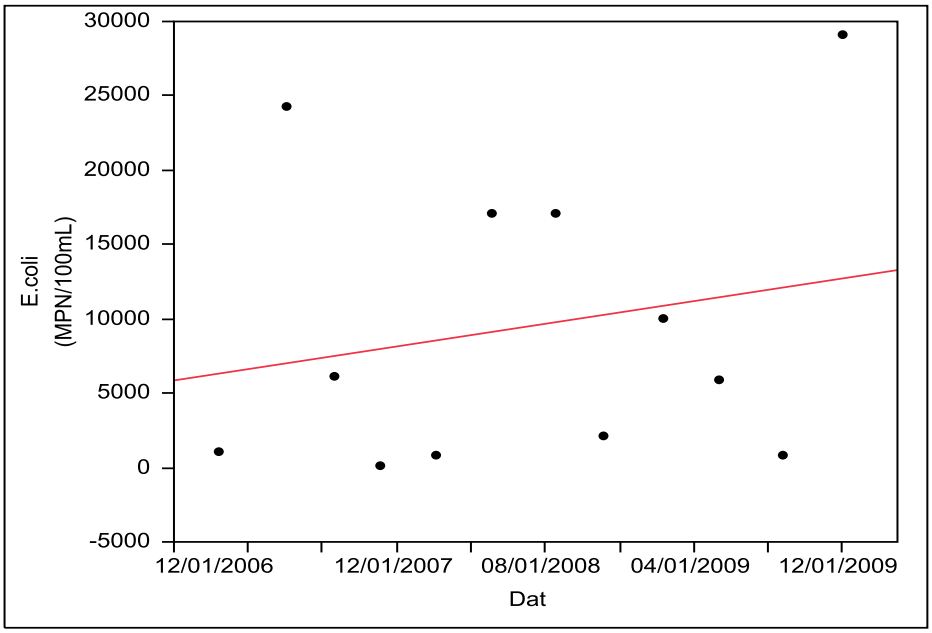
C.23 *E.coli* concentrations across time for monitoring station 11314 at Spring Creek on the SJR River watershed. The red line represents linear fit.



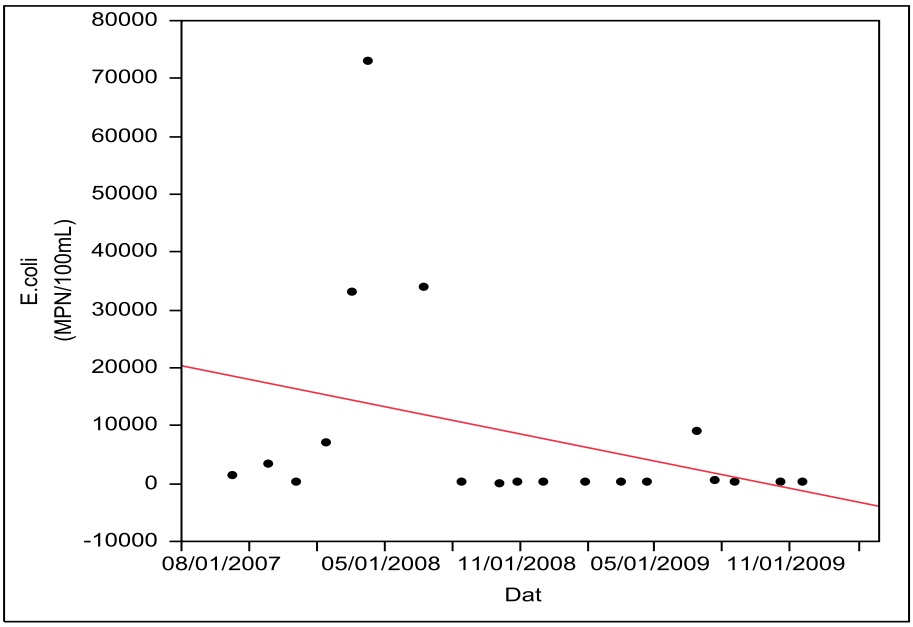
C.24 *E.coli* concentrations across time for monitoring station 11250 at West Fork San Jacinto River on the SJR River watershed. The red line represents linear fit.



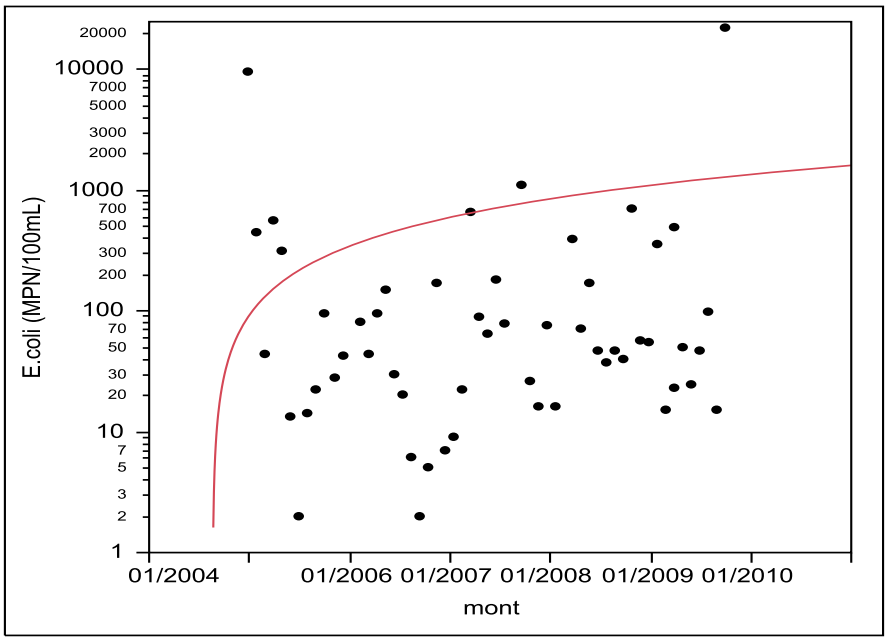
C.25 *E.coli* concentrations across time for monitoring station 11387 at White Oak Bayou on the SJR River watershed. The red line represents linear fit.



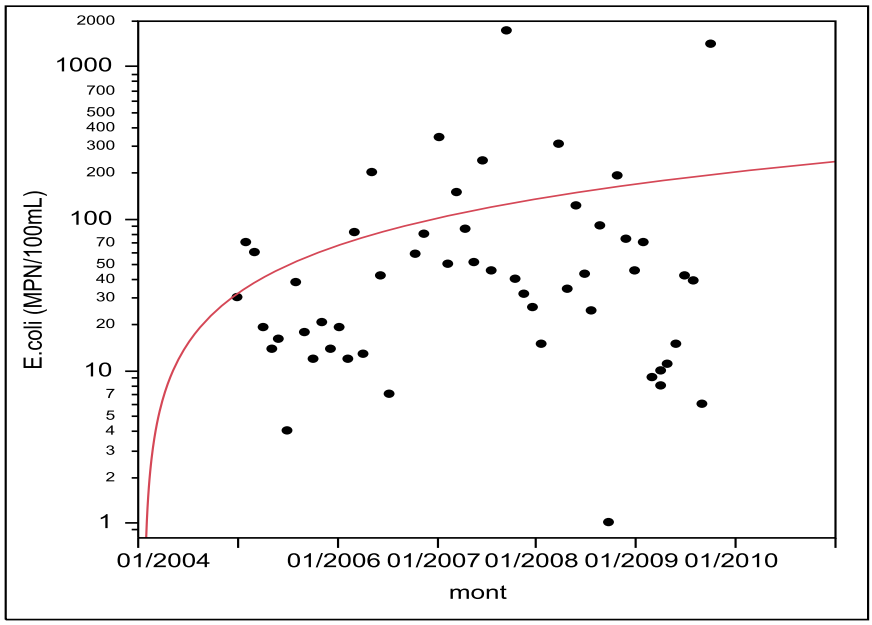
C.26 *E.coli* concentrations across time for monitoring station 11394 at White Oak Bayou on the SJR River watershed. The red line represents linear fit.



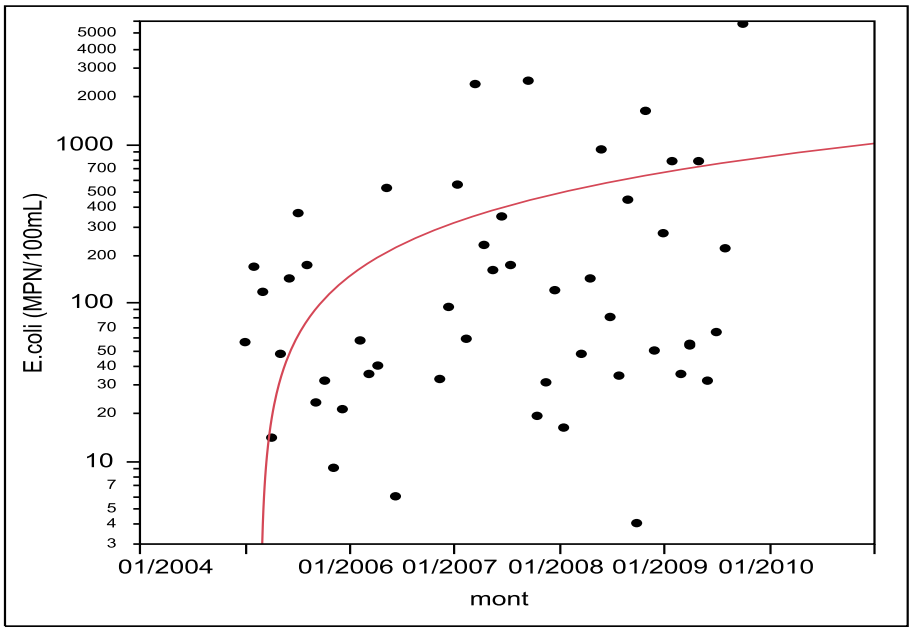
C.27 *E.coli* concentrations across time for monitoring station 11954 at North Bosque River on the Bosque River watershed. The red line represents linear fit.



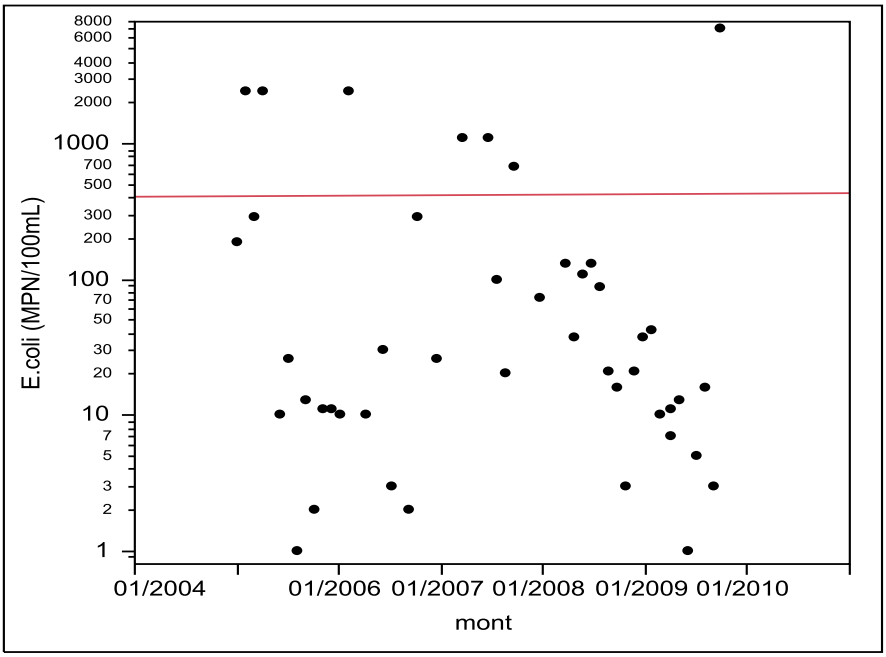
C.28 *E.coli* concentrations across time for monitoring station 11956 at North Bosque River on the Bosque River watershed. The red line represents linear fit.



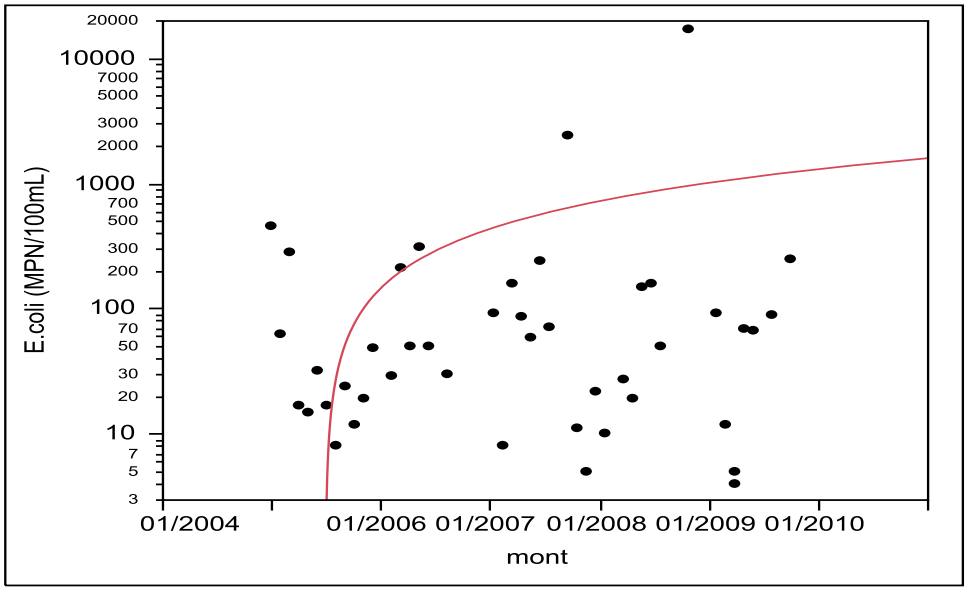
C.29 *E.coli* concentrations across time for monitoring station 11961 at North Bosque River on the Bosque River watershed. The red line represents linear fit.



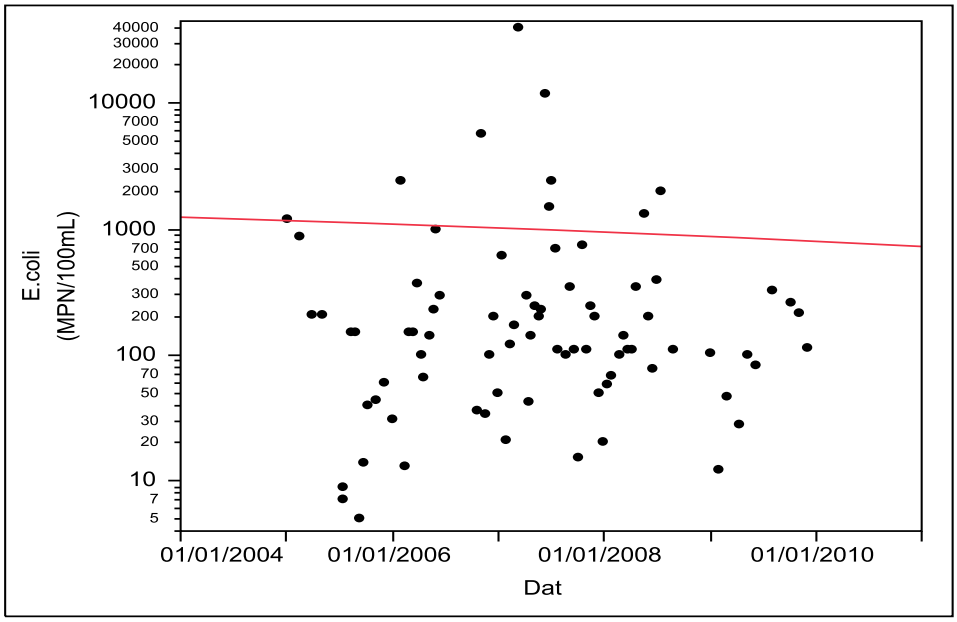
C.30 *E.coli* concentrations across time for monitoring station 17500 at North Bosque River on the Bosque River watershed. The red line represents linear fit.



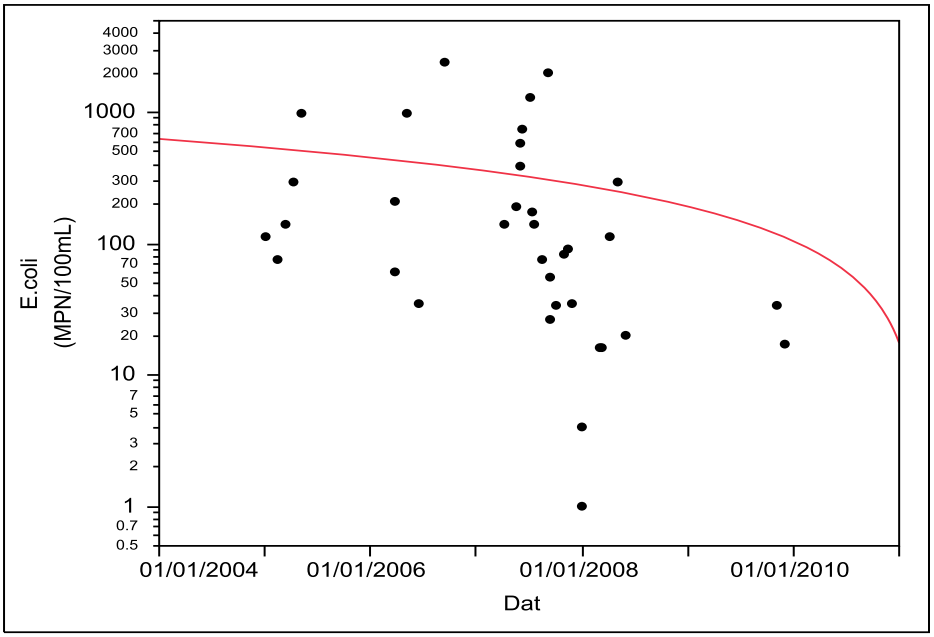
C.31 *E.coli* concentrations across time for monitoring station 18003 at North Bosque River on the Bosque River watershed. The red line represents linear fit.



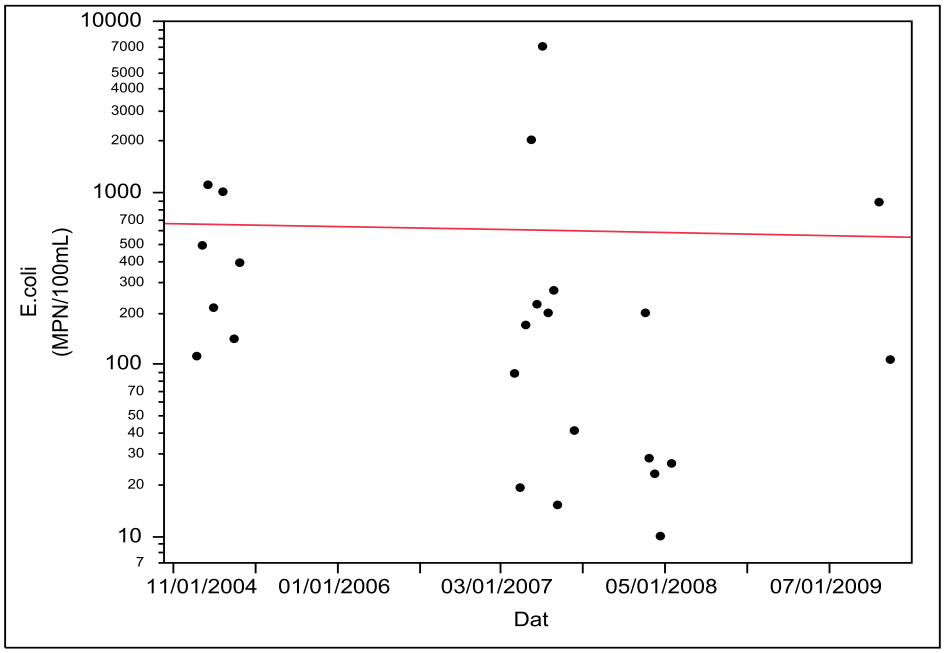
C.32 *E.coli* concentrations across time for monitoring station 17607 at Duffau Creek on the Bosque River watershed. The red line represents linear fit.



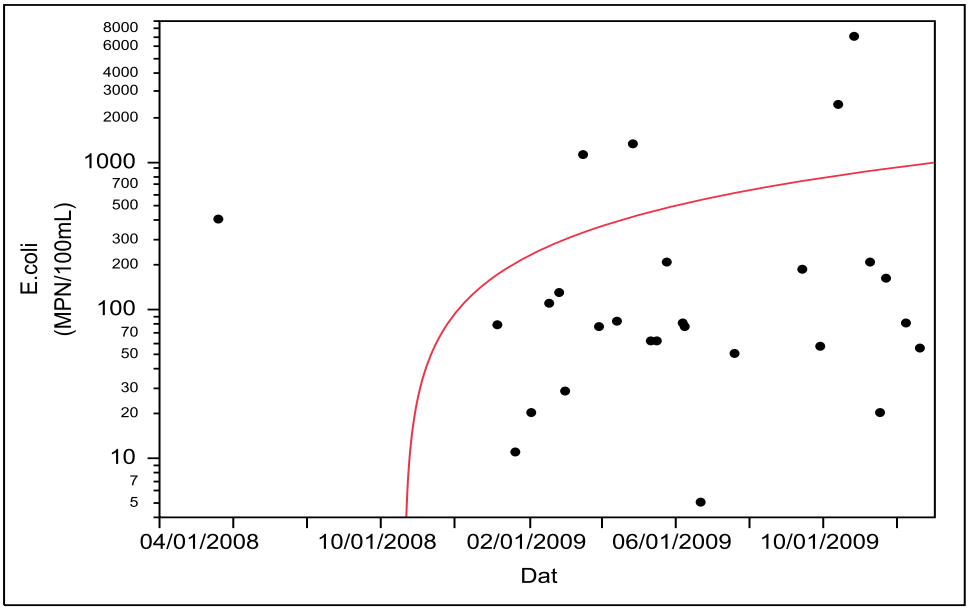
C.33 *E.coli* concentrations across time for monitoring station 13486 at Green Creek on the Bosque River watershed. The red line represents linear fit.



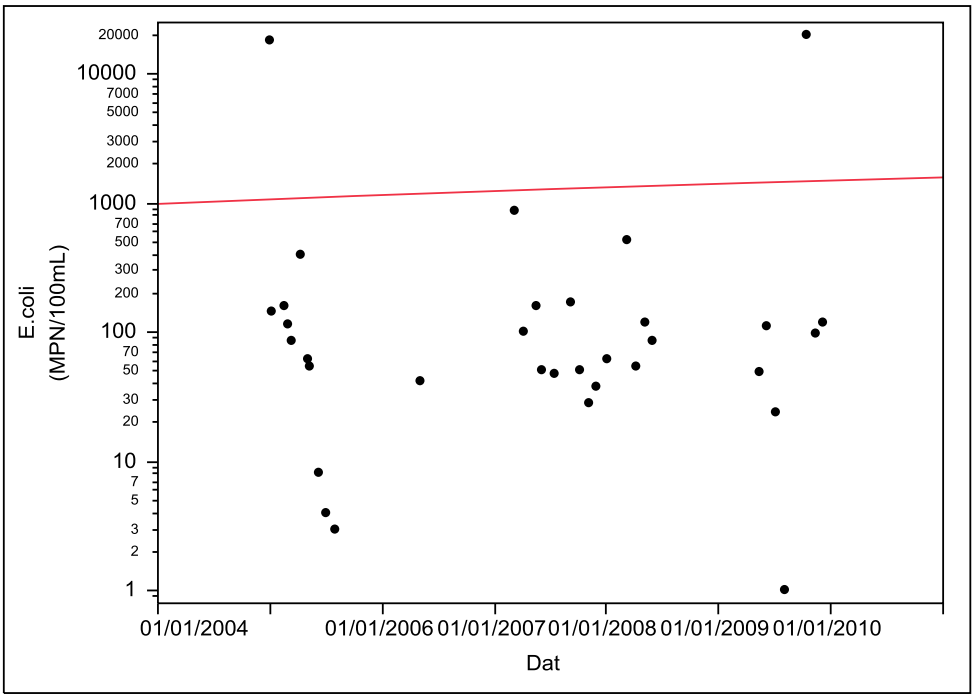
C.34 *E.coli* concentrations across time for monitoring station 17235 at Indian Creek on the Bosque River watershed. The red line represents linear fit.



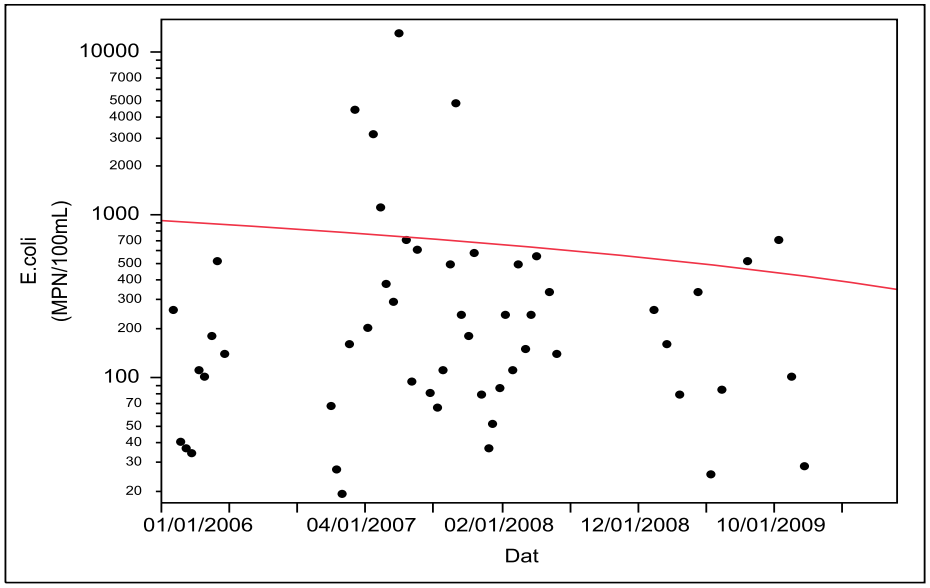
C.35 *E.coli* concentrations across time for monitoring station 20308 at Middle/South Bosque River on the Bosque River watershed. The red line represents linear fit.



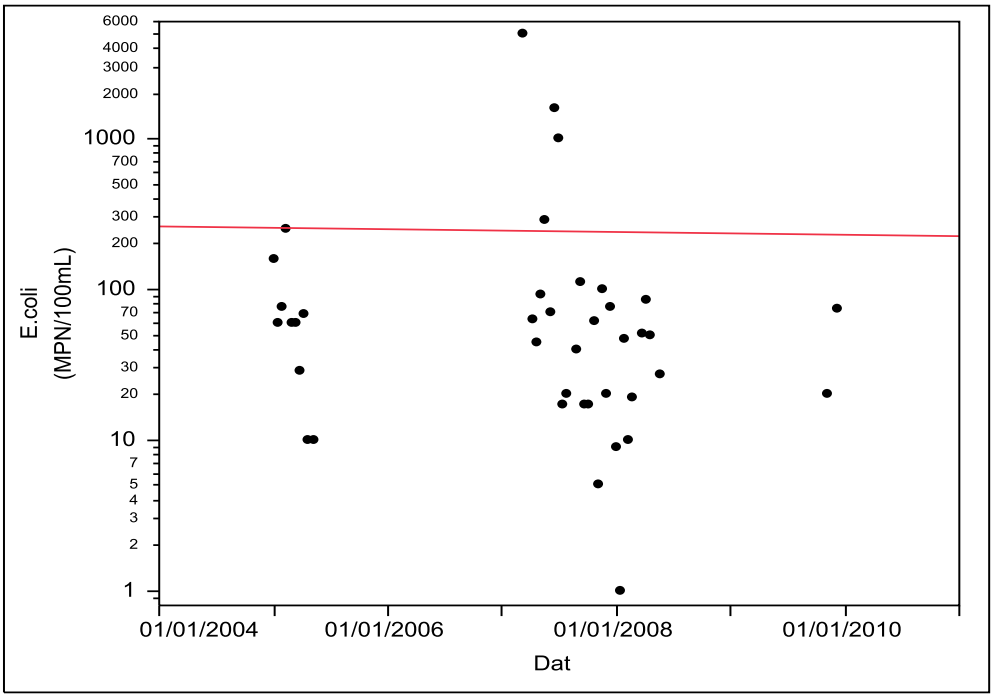
C.36 *E.coli* concentrations across time for monitoring station 11826 at Neils Creek on the Bosque River watershed. The red line represents linear fit.



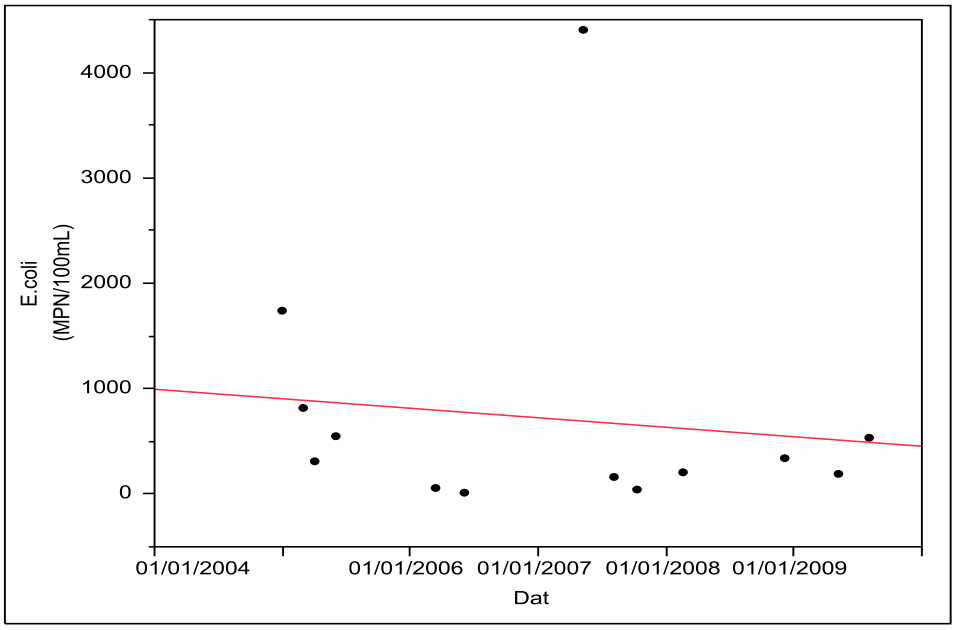
C.37 *E.coli* concentrations across time for monitoring station 17240 at Sims Creek on the Bosque River watershed. The red line represents linear fit.



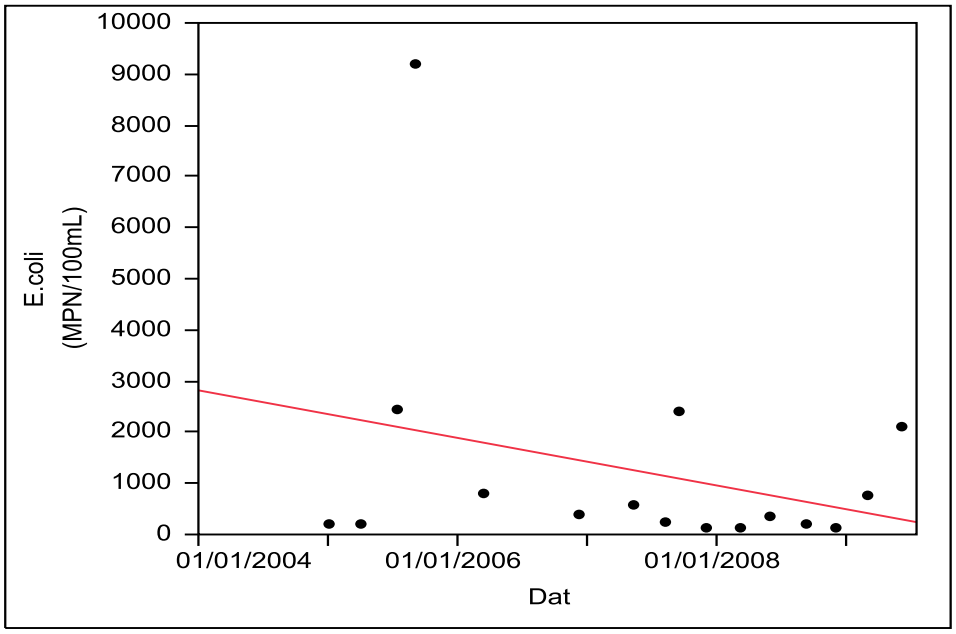
C.38 *E.coli* concentrations across time for monitoring station 17242 at Spring Creek on the Bosque River watershed. The red line represents linear fit.



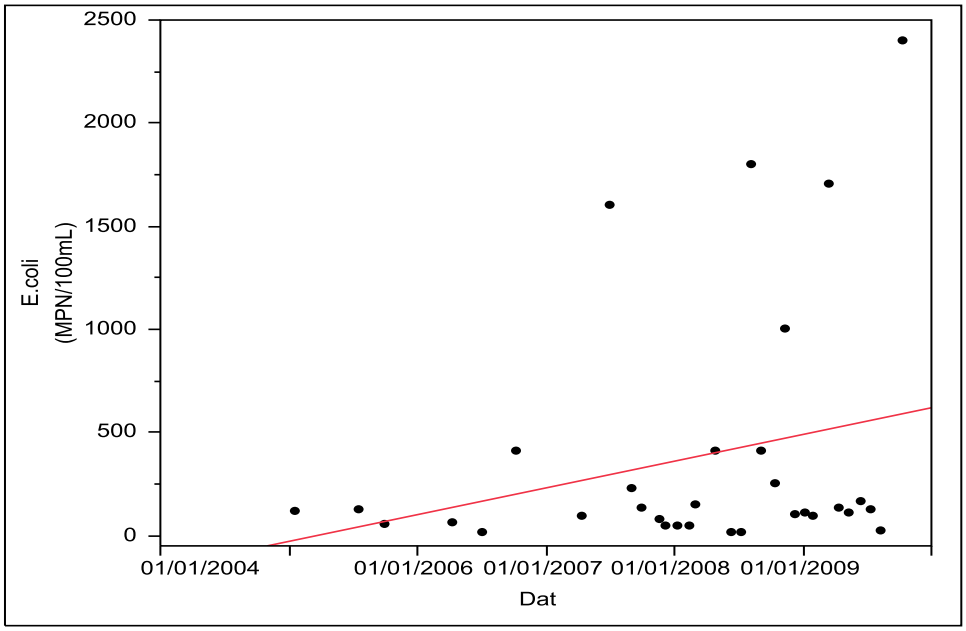
C.39 *E.coli* concentrations across time for monitoring station 11938 at Leon River below Leon River on the Leon River watershed. The red line represents linear fit.



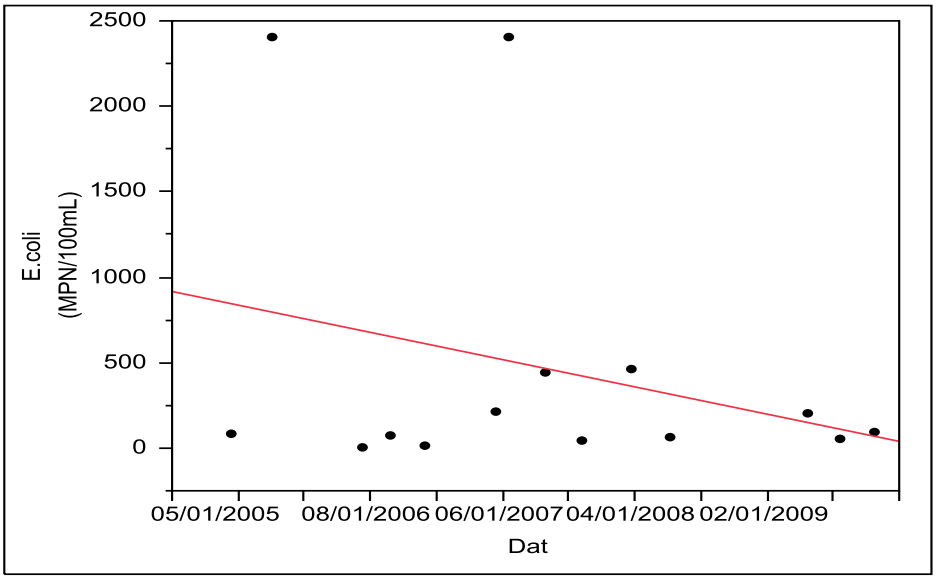
C.40 *E.coli* concentrations across time for monitoring station 11938 at Duncan Creek on the Leon River watershed. The red line represents linear fit.



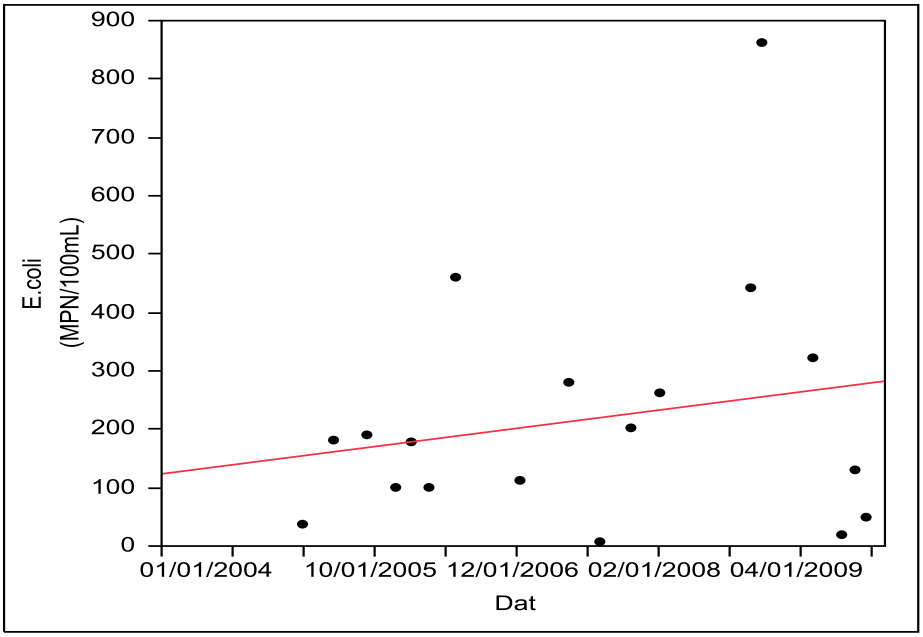
C.41 *E.coli* concentrations across time for monitoring station 11925 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



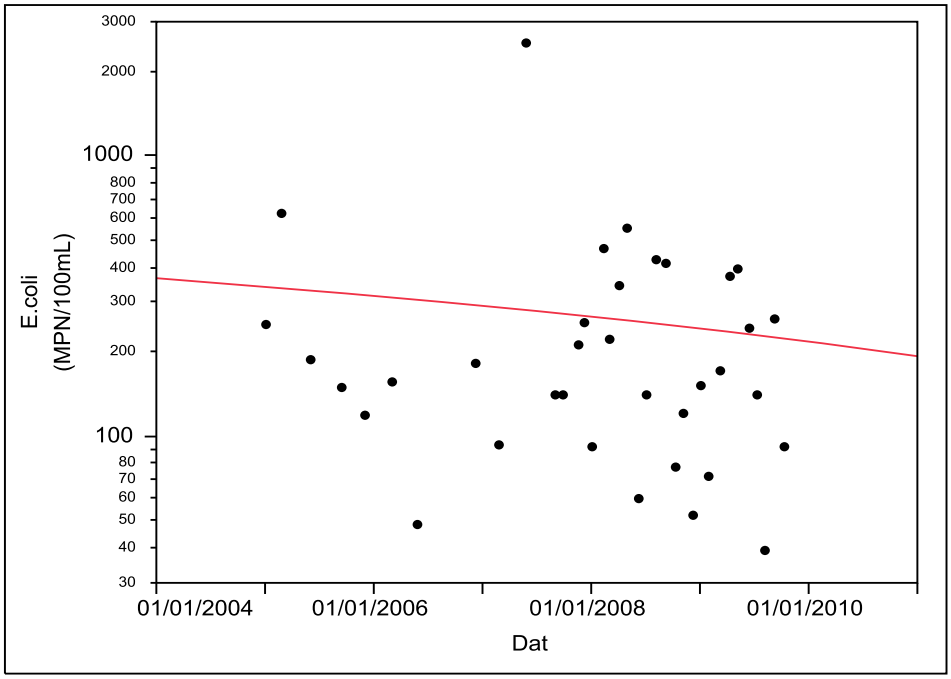
C.42 *E.coli* concentrations across time for monitoring station 11930 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



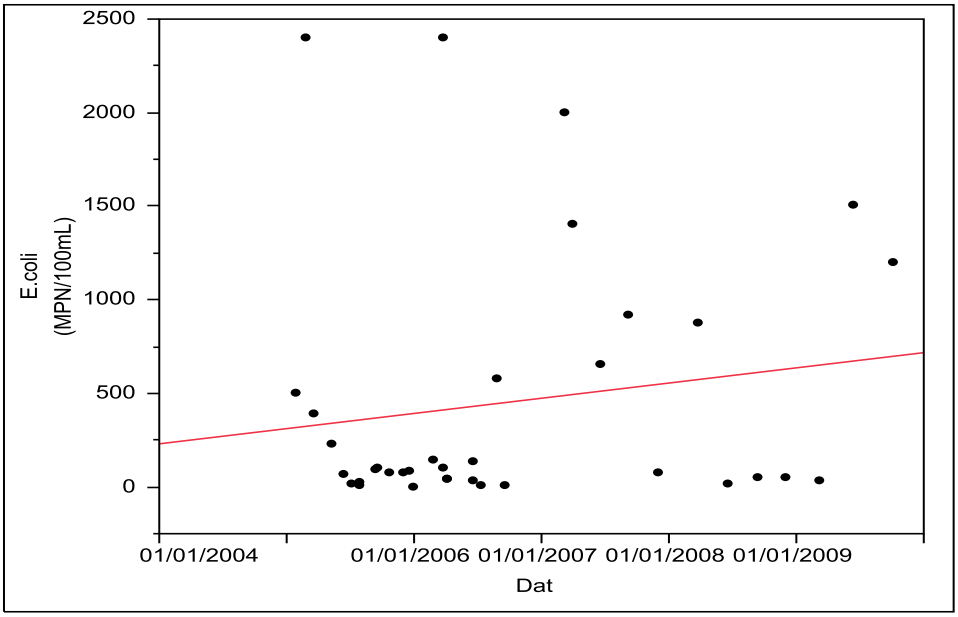
C.43 *E.coli* concentrations across time for monitoring station 11934 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



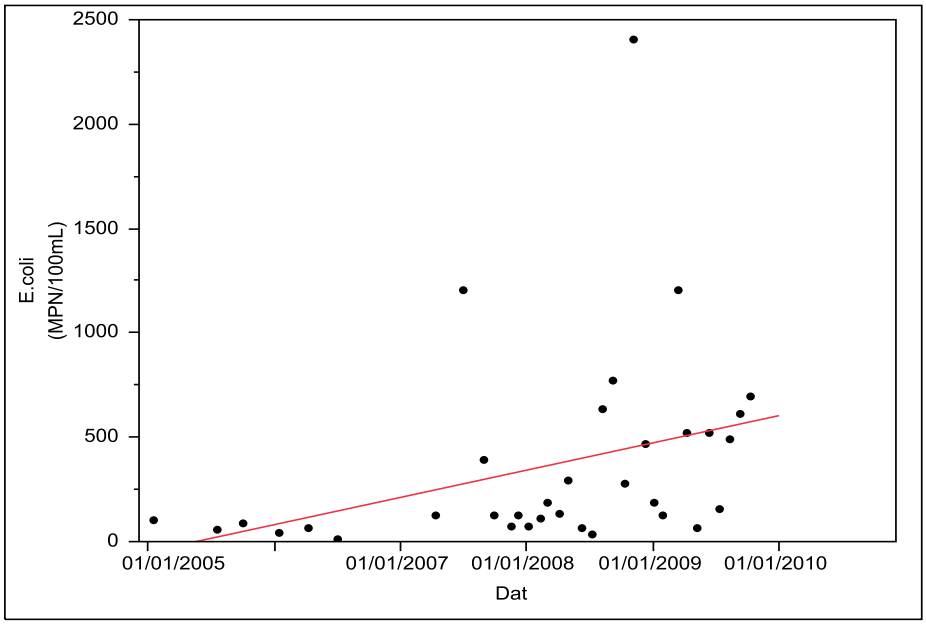
C.44 *E.coli* concentrations across time for monitoring station 15769 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



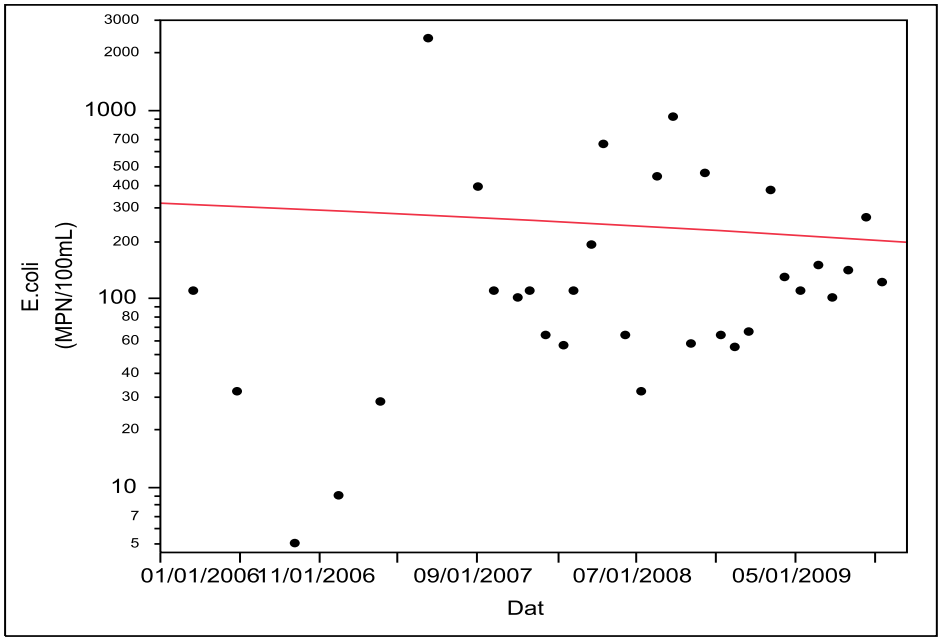
C.45 *E.coli* concentrations across time for monitoring station 17501 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



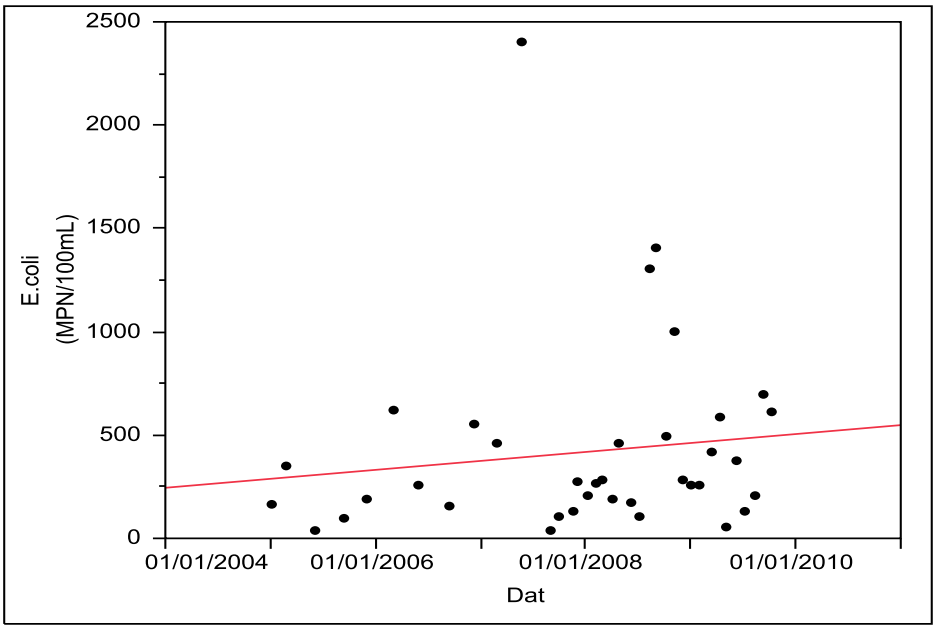
C.46 *E.coli* concentrations across time for monitoring station 17545 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



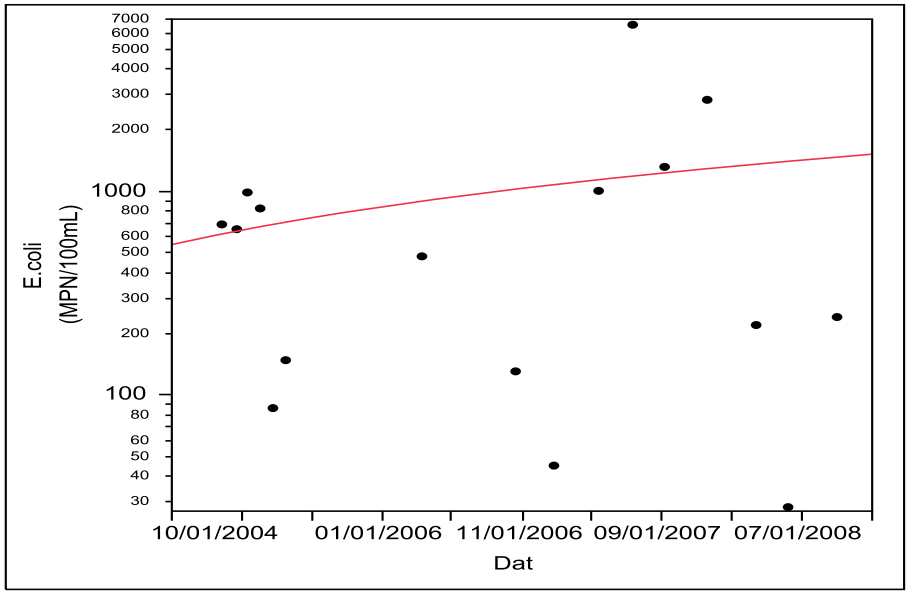
C.47 *E.coli* concentrations across time for monitoring station 18781 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



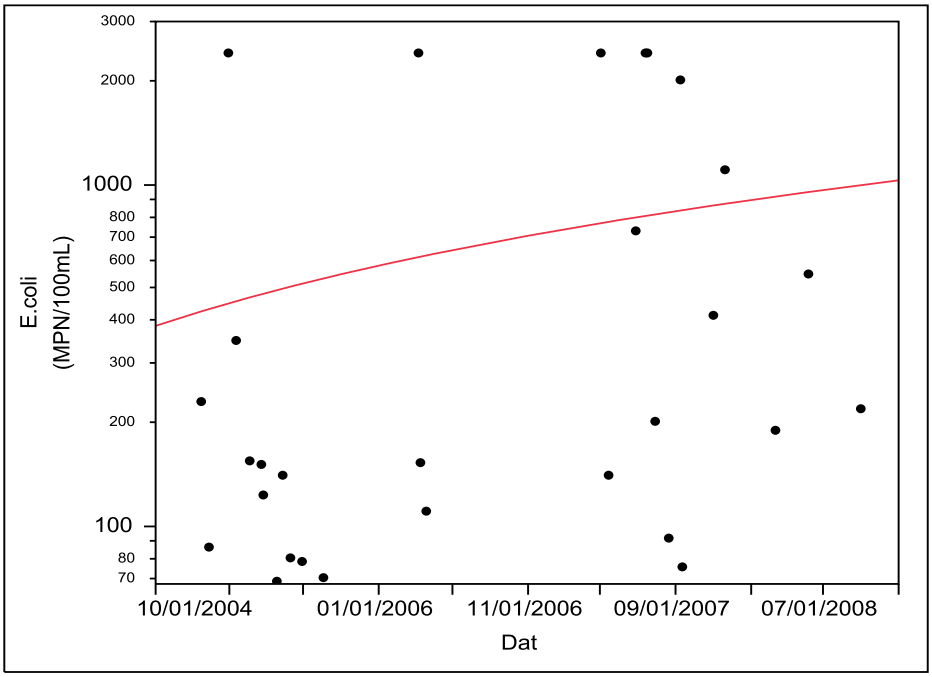
C.48 *E.coli* concentrations across time for monitoring station 17591 at Leon River below Proctor Lake on the Leon River watershed. The red line represents linear fit.



C.49 *E.coli* concentrations across time for monitoring station 17376 at Resley Creek on the Leon River watershed. The red line represents linear fit.

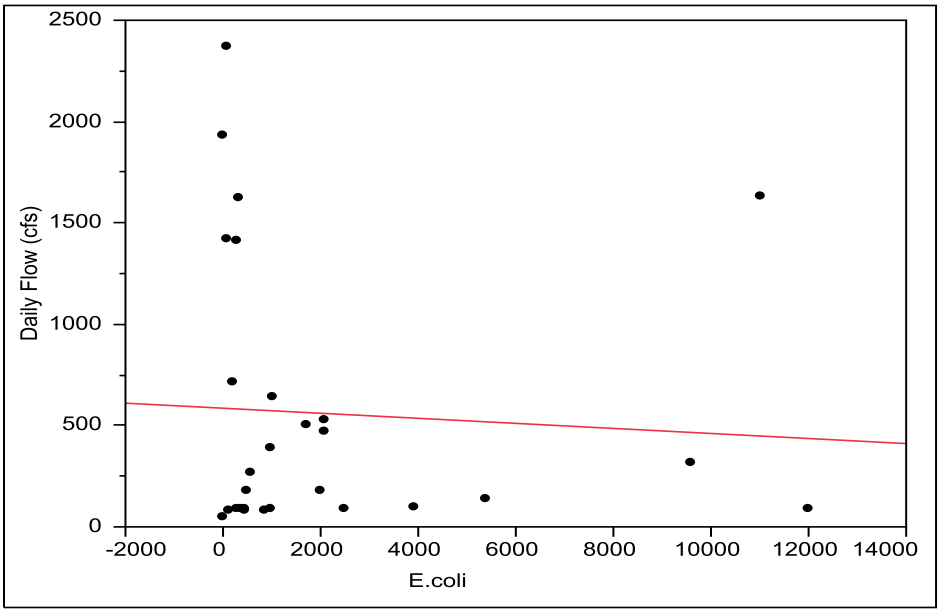


C.50 *E.coli* concentrations across time for monitoring station 17377 at Resley Creek on the Leon River watershed. The red line represents linear fit.

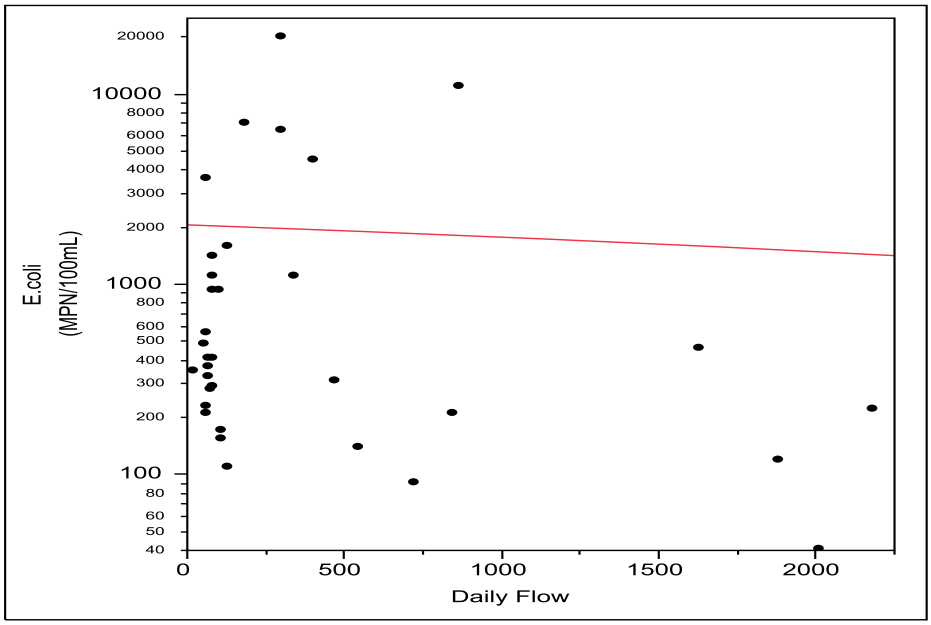


APPENDIX D

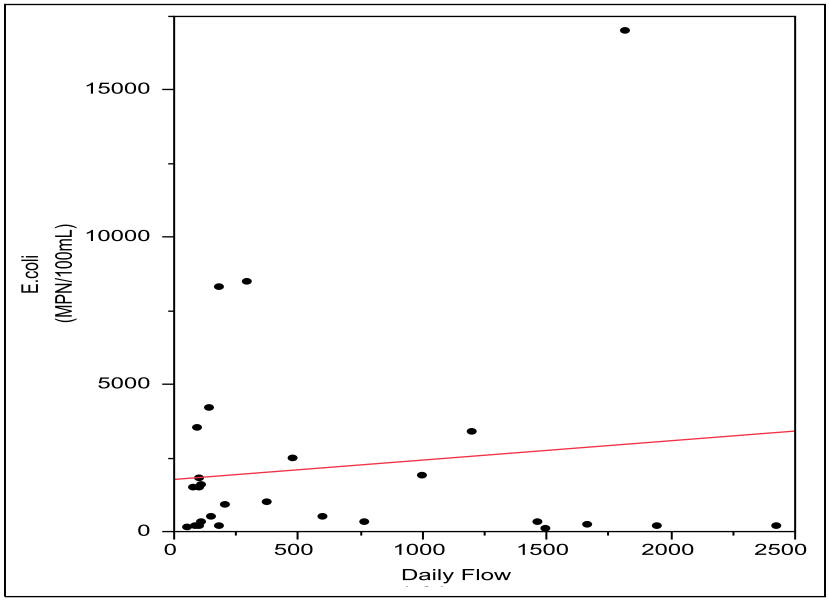
D.1 *E.coli* concentrations as a function of daily mean flow for monitoring station 11360 at Buffalo Bayou above Tidal on the SJR watershed. The Red line represents linear fit.



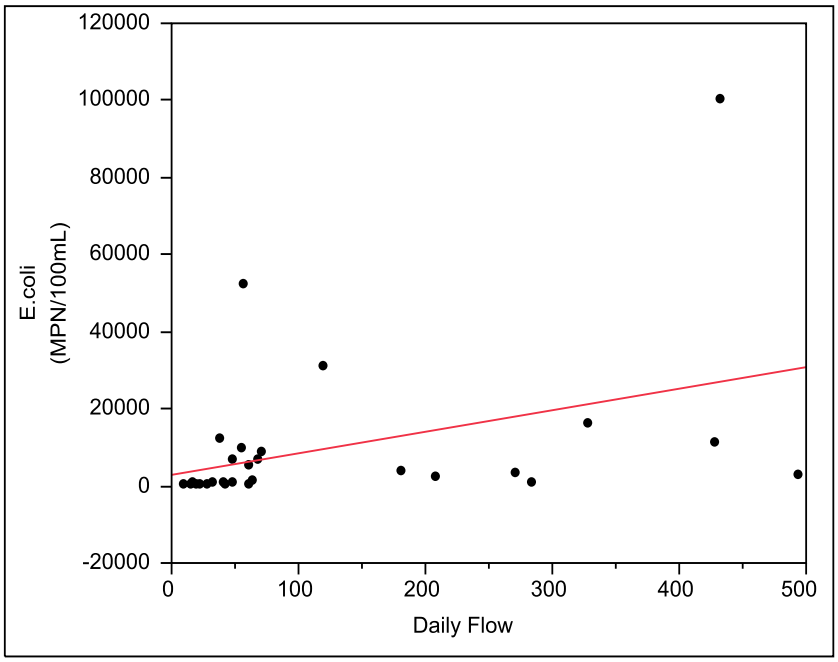
D.2 *E.coli* concentrations as a function of daily mean flow for monitoring station 11362 at Buffalo Bayou above Tidal on the SJR watershed. The Red line represents linear fit.



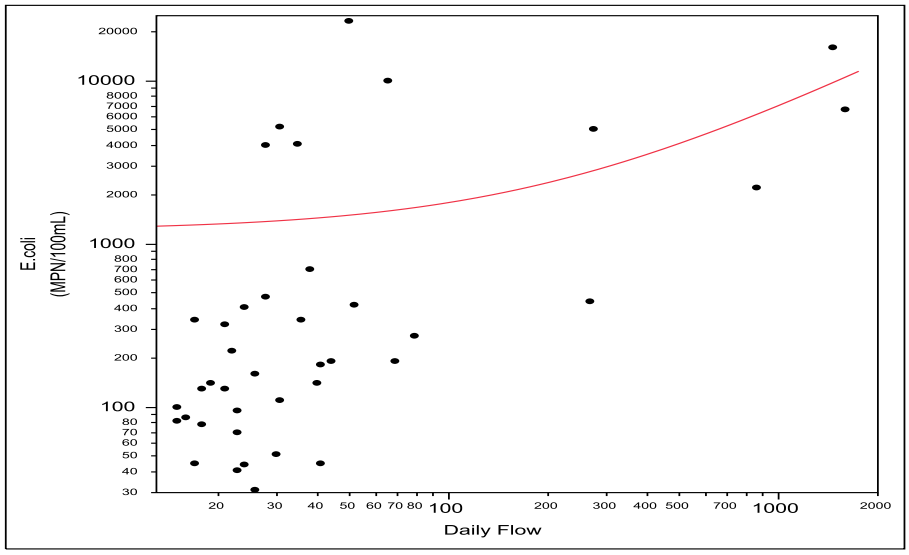
D.3 *E.coli* concentrations as a function of daily mean flow for monitoring station 15846 at Buffalo Bayou above Tidal on the SJR watershed. The Red line represents linear fit.



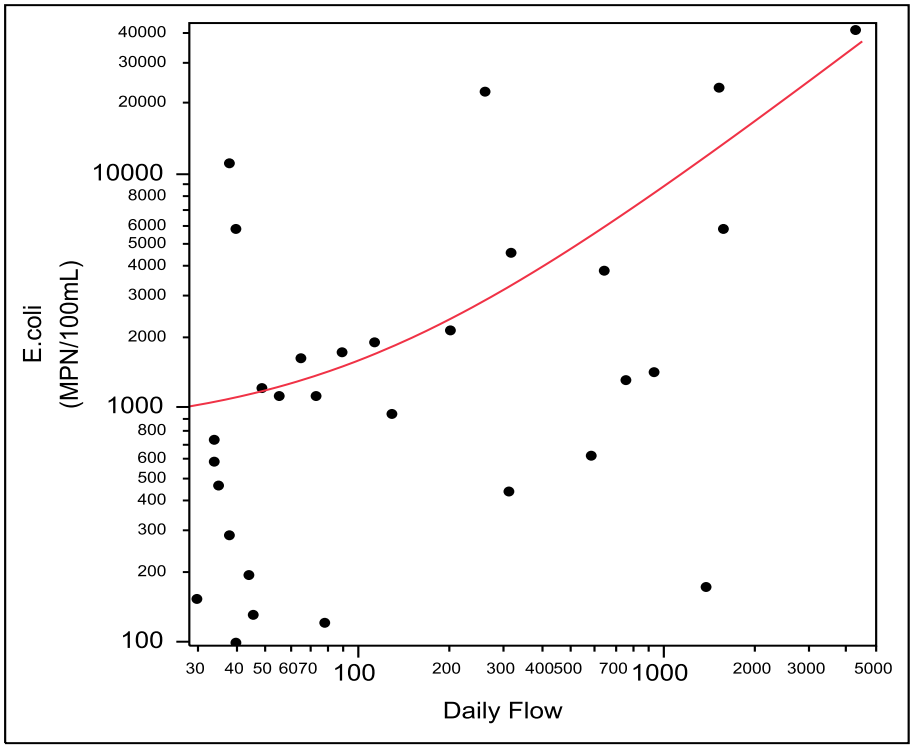
D.4 *E.coli* concentrations as a function of daily mean flow for monitoring station 16648 at Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



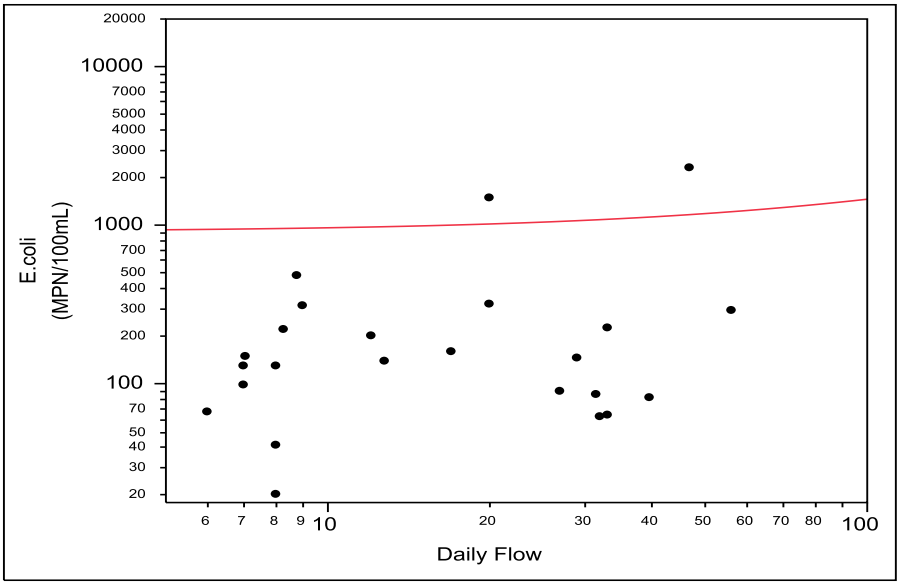
D.5 *E.coli* concentrations as a function of daily mean flow for monitoring station 11334 at Caney Creek on the SJR watershed. The Red line represents linear fit.



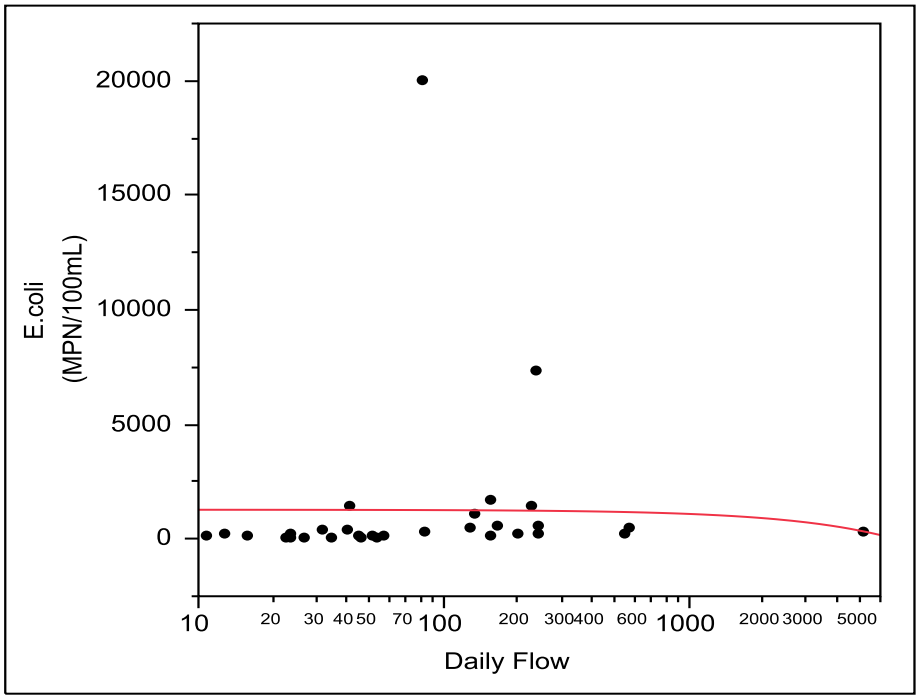
D.6 *E.coli* concentrations as a function of daily mean flow for monitoring station 11328 at Cypress Creek on the SJR watershed. The Red line represents linear fit.



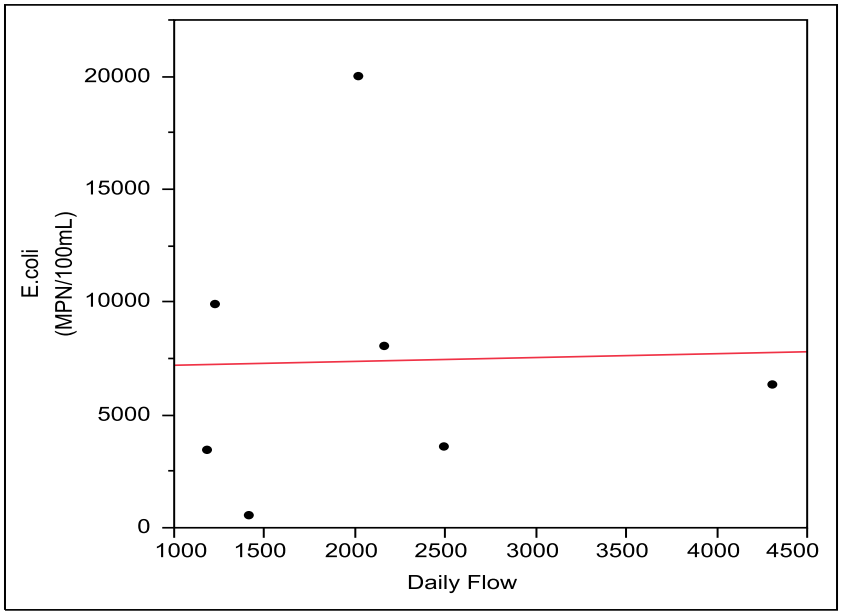
D.7 *E.coli* concentrations as a function of daily mean flow for monitoring station 11332 at Cypress Creek on the SJR watershed. The Red line represents linear fit.



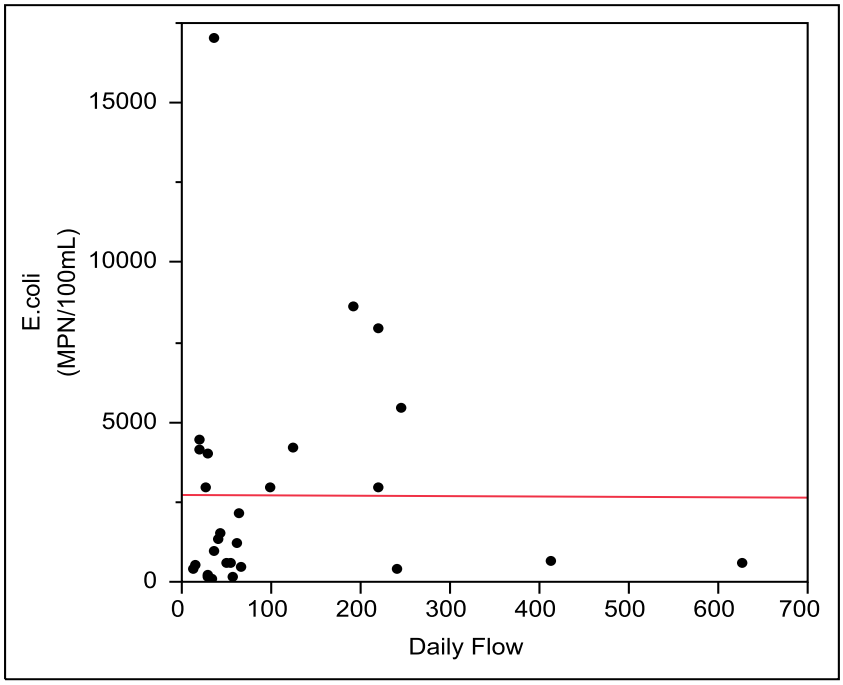
D.8 *E.coli* concentrations as a function of daily mean flow for monitoring station 11235 at East Fork San Jacinto on the SJR watershed. The Red line represents linear fit.



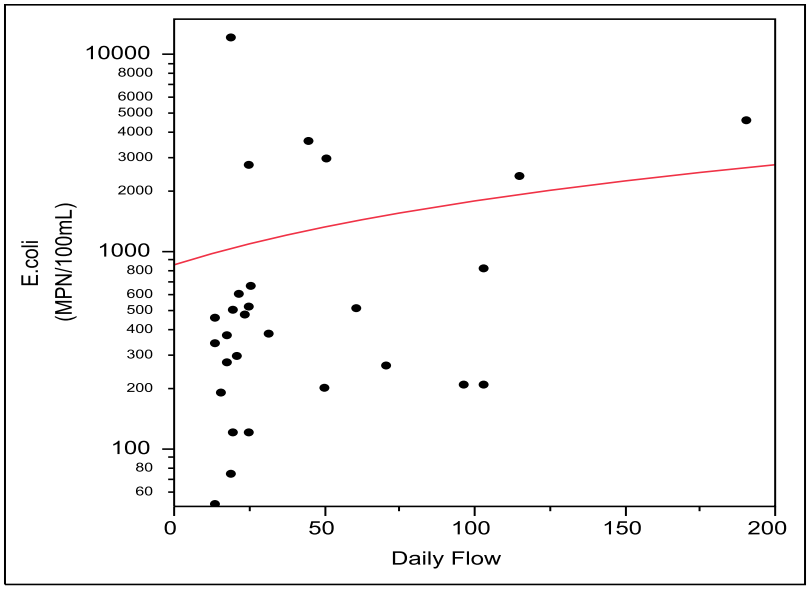
D.9 *E.coli* concentrations as a function of daily mean flow for monitoring station 11369 at Greens Bayou on the SJR watershed. The Red line represents linear fit.



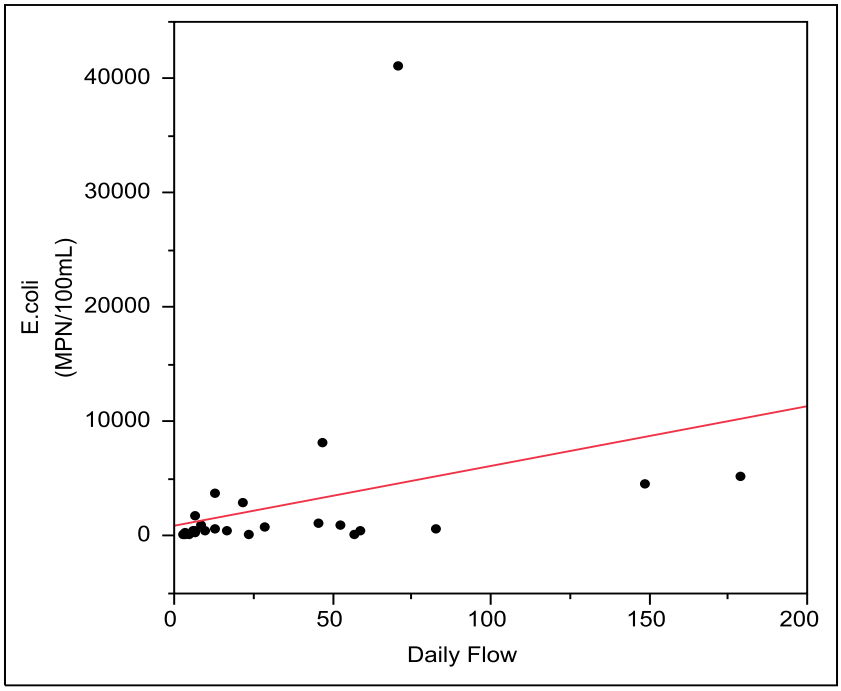
D.10 *E.coli* concentrations as a function of daily mean flow for monitoring station 11371 at Greens Bayou on the SJR watershed. The Red line represents linear fit.



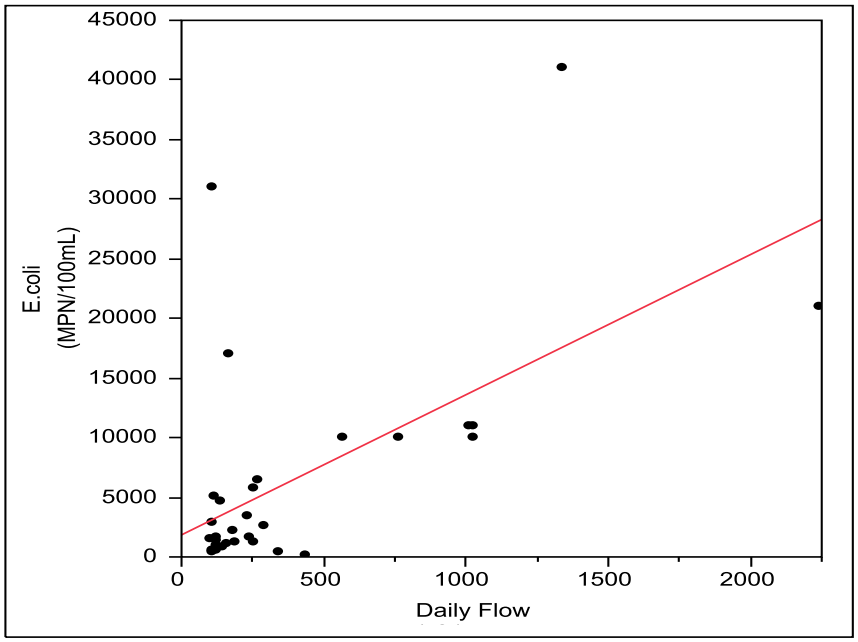
D.11 *E.coli* concentrations as a function of daily mean flow for monitoring station 11925 at Cypress Creek on the SJR watershed. The Red line represents linear fit.



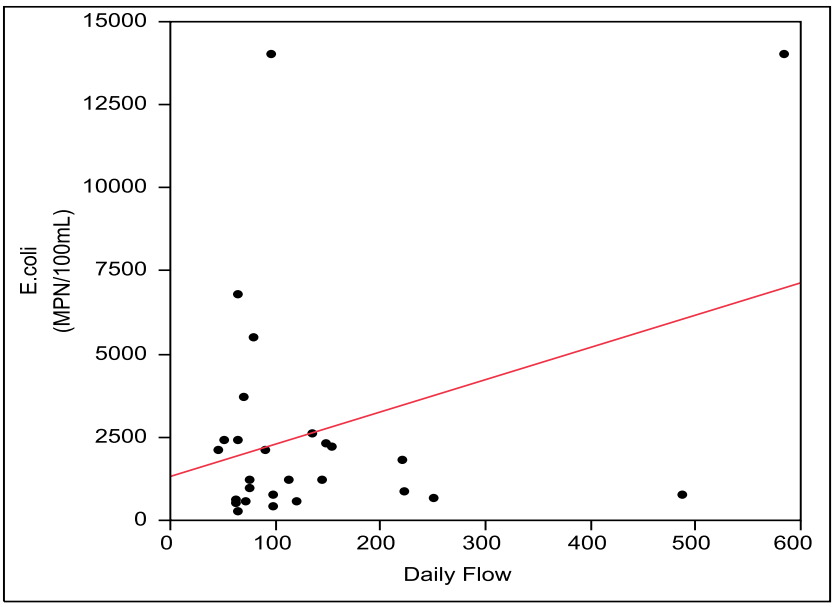
D.12 *E.coli* concentrations as a function of daily mean flow for monitoring station 11135 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



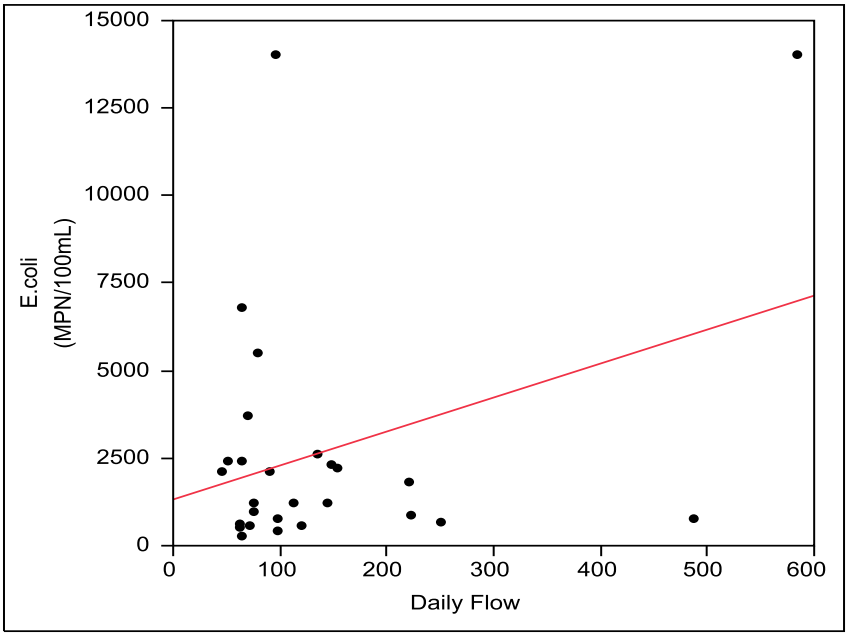
D.13 *E.coli* concentrations as a function of daily mean flow for monitoring station 11139 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



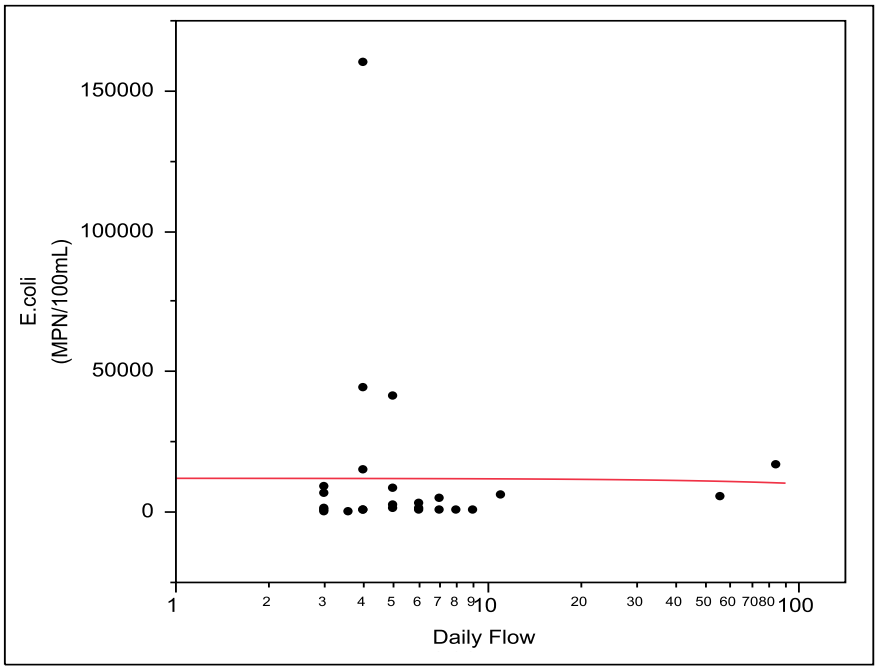
D.14 *E.coli* concentrations as a function of daily mean flow for monitoring station 11140 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



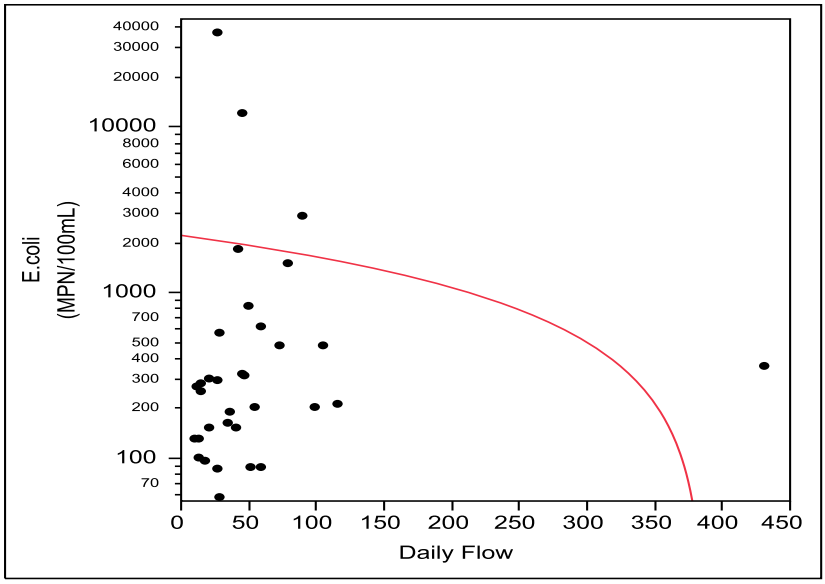
D.15 *E.coli* concentrations as a function of daily mean flow for monitoring station 15851 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



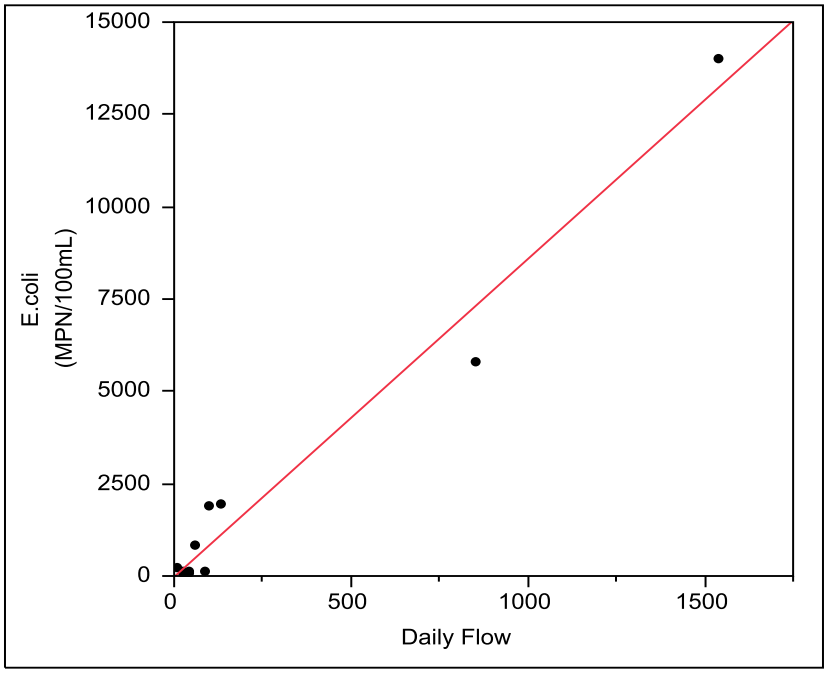
D. 16 *E.coli* concentrations as a function of daily mean flow for monitoring station 16661 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed. The Red line represents linear fit.



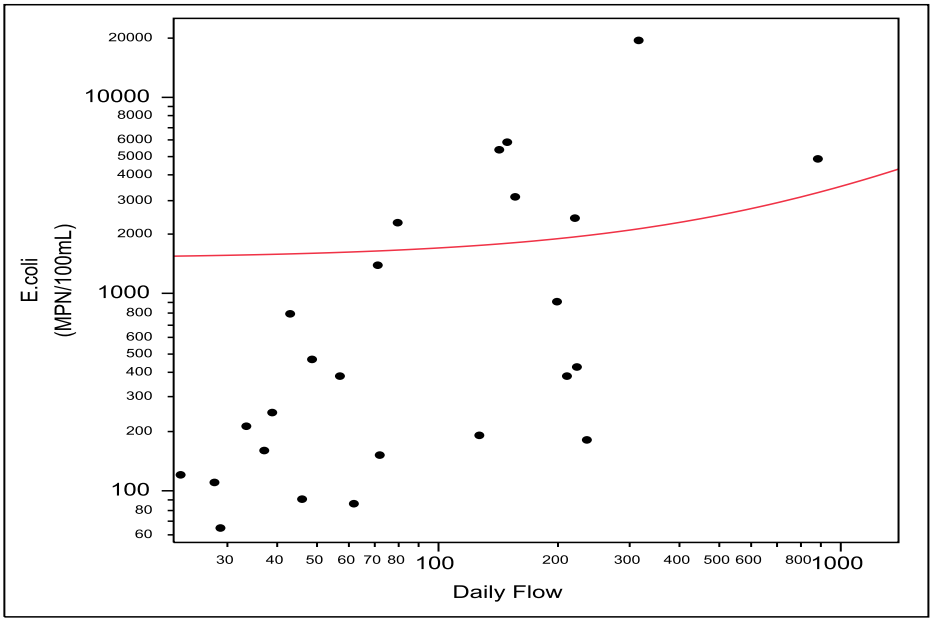
D.17 *E.coli* concentrations as a function of daily mean flow for monitoring station 11336 at Peach Creek on the SJR watershed. The Red line represents linear fit.



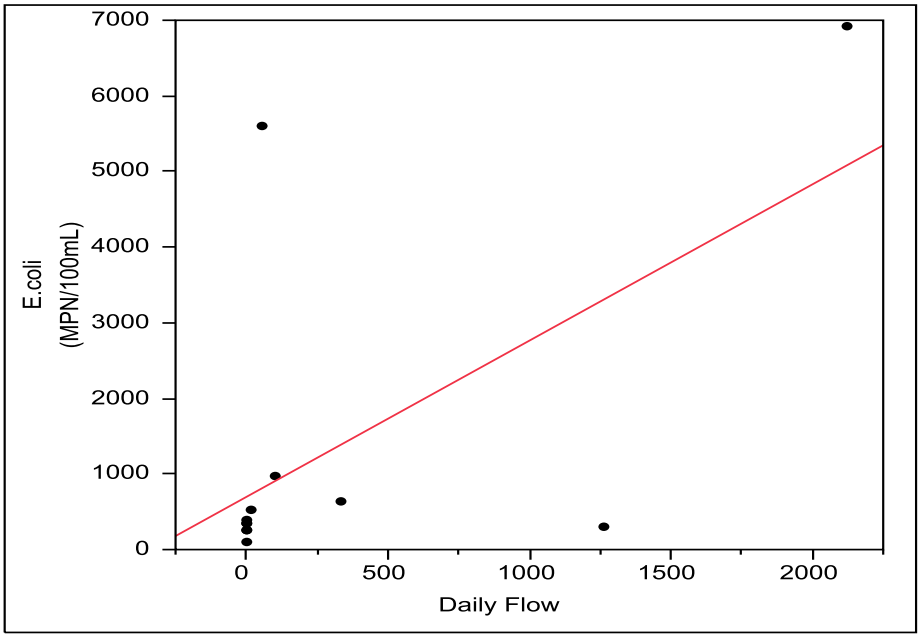
D.18 *E.coli* concentrations as a function of daily mean flow for monitoring station 11336 at Peach Creek on the SJR watershed. The Red line represents linear fit.



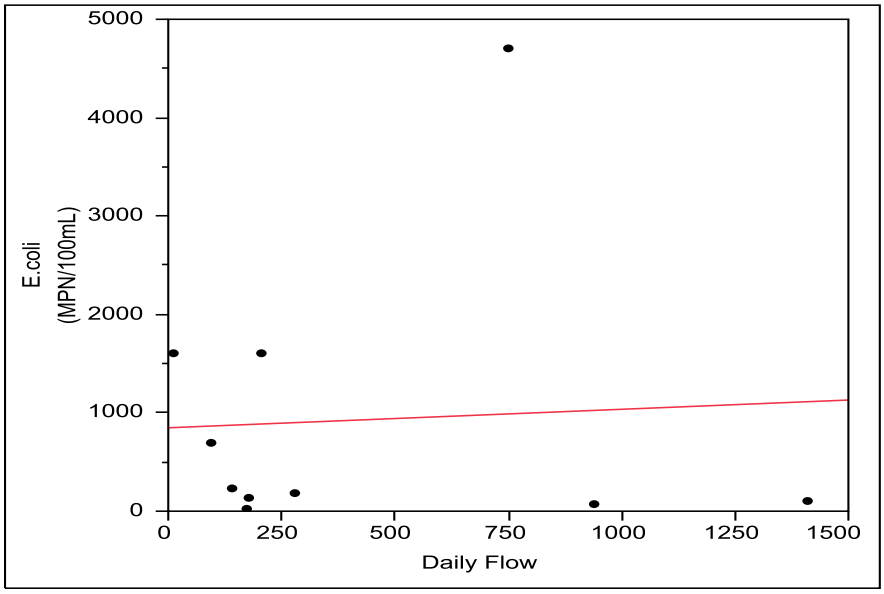
D.19 *E.coli* concentrations as a function of daily mean flow for monitoring station 11312 at Spring Creek on the SJR watershed. The Red line represents linear fit.



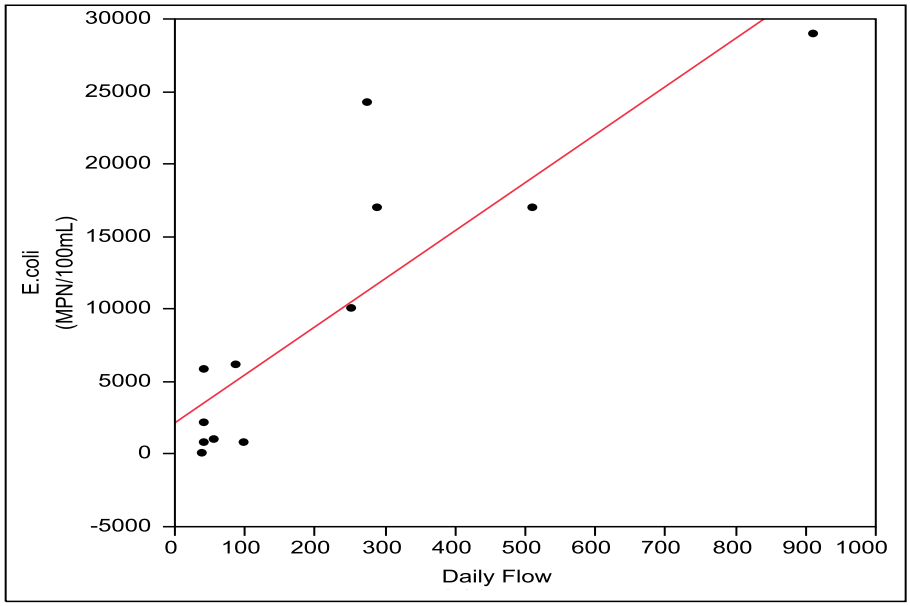
D.20 *E.coli* concentrations as a function of daily mean flow for monitoring station 11314 at Spring Creek on the SJR watershed. The Red line represents linear fit.



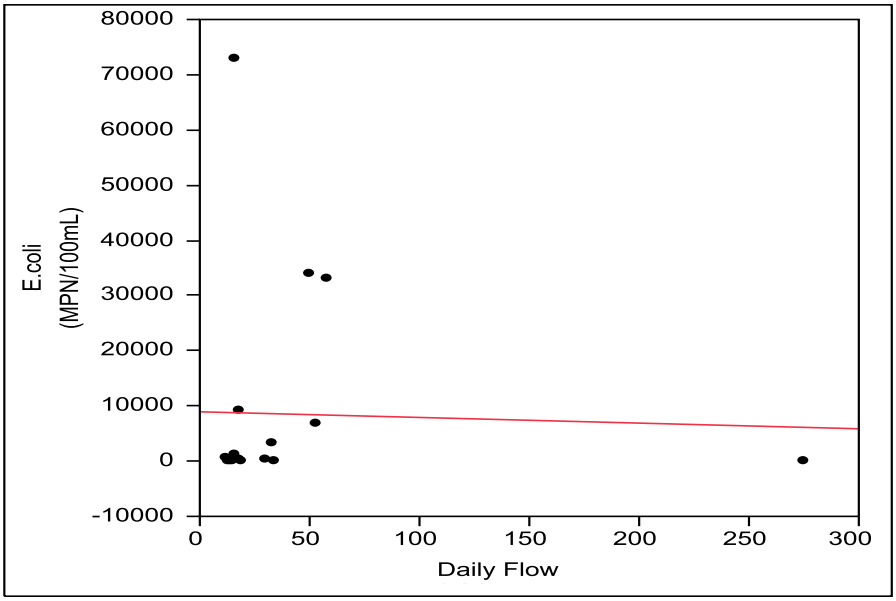
D.21 *E.coli* concentrations as a function of daily mean flow for monitoring station 11250 at West Fork San Jacinto on the SJR watershed. The Red line represents linear fit.



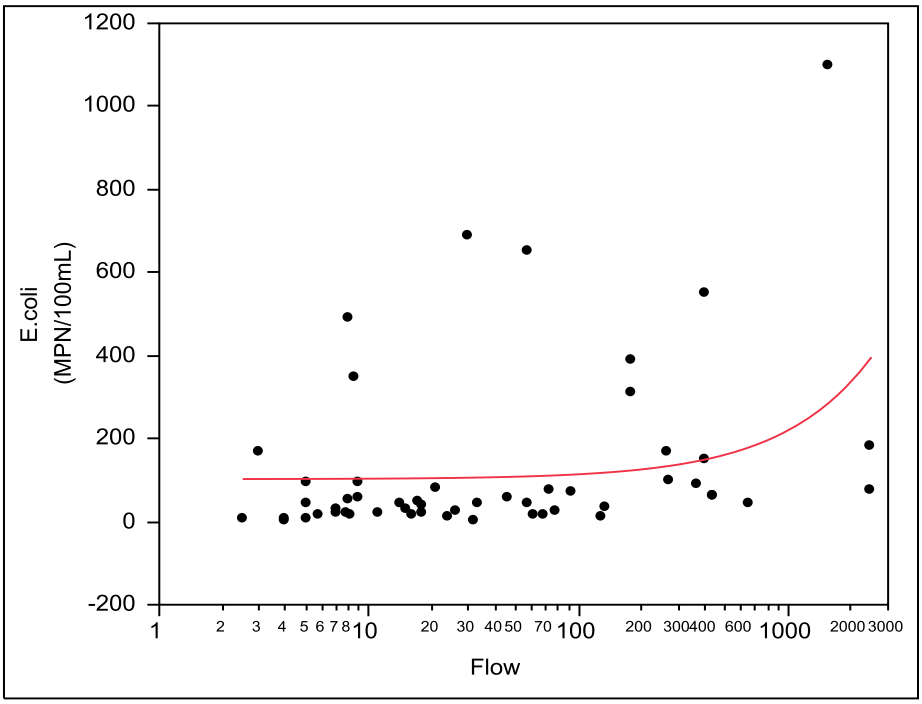
D.22 *E.coli* concentrations as a function of daily mean flow for monitoring station 11387 at White Oak Bayou on the SJR watershed. The Red line represents linear fit.



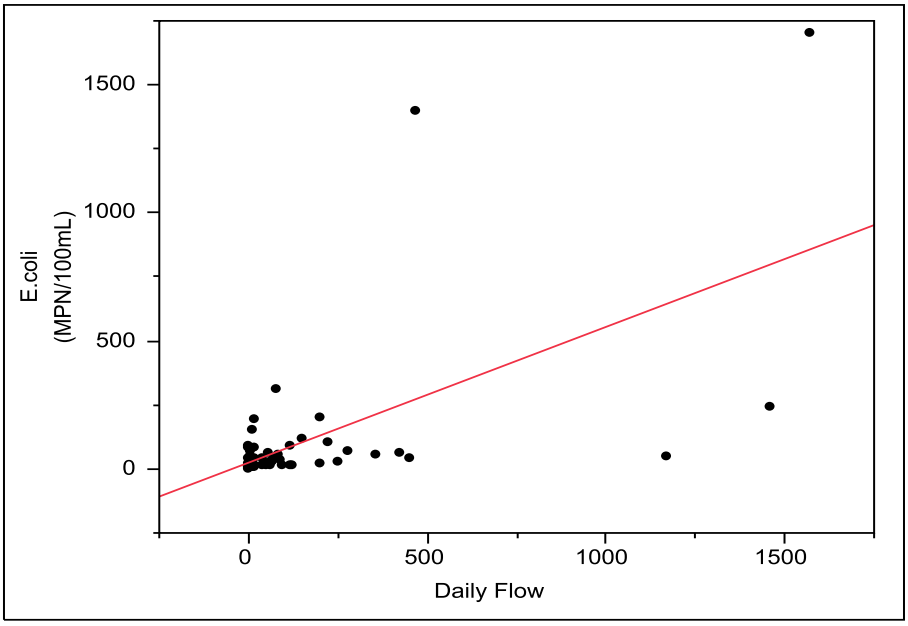
D.23 *E.coli* concentrations as a function of daily mean flow for monitoring station 11394 at White Oak Bayou on the SJR watershed. The Red line represents linear fit.



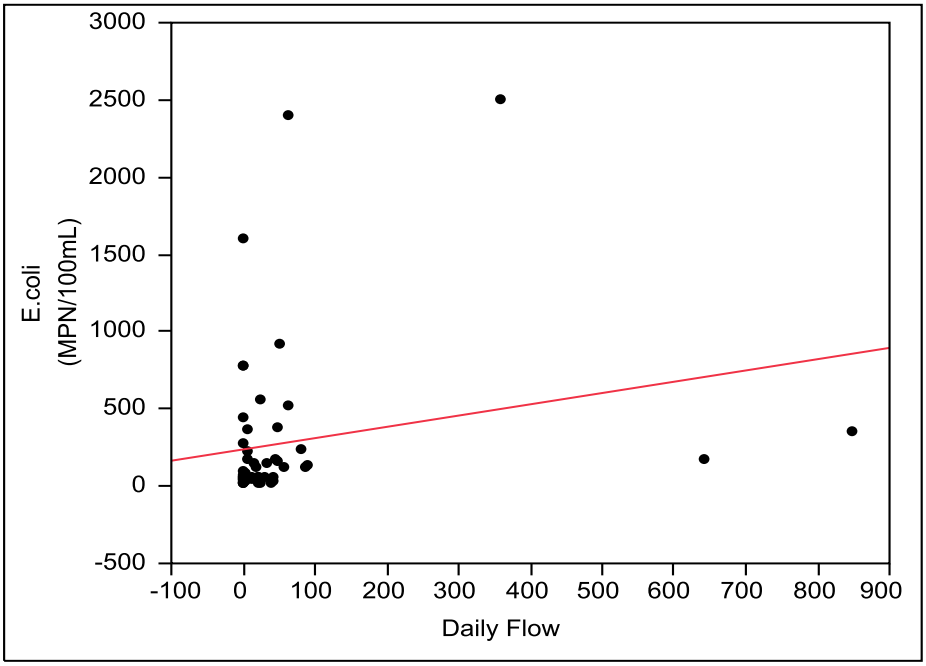
D.24 *E.coli* concentrations as a function of daily mean flow for monitoring station 11954 at North Bosque River on the Bosque River watershed. The Red line represents linear fit.



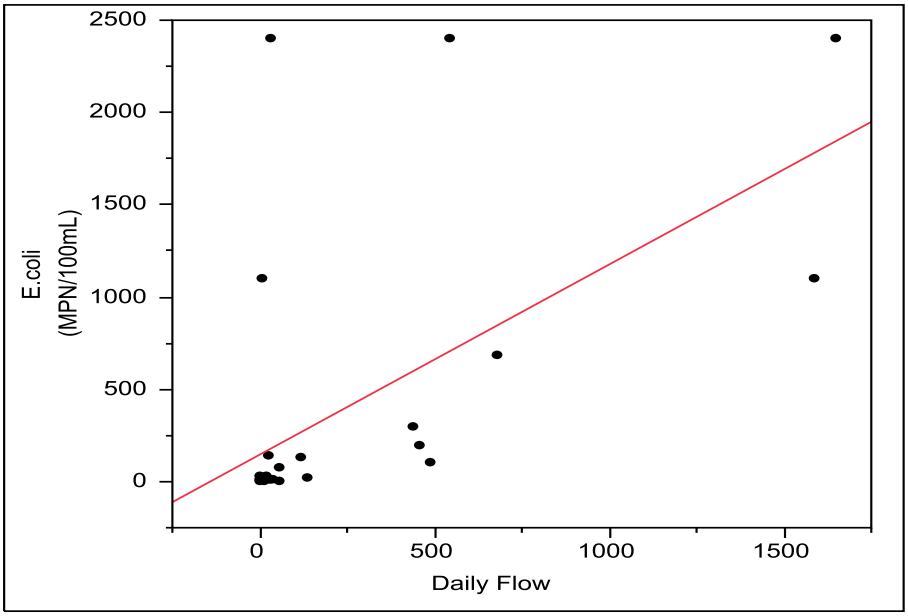
D.25 *E.coli* concentrations as a function of daily mean flow for monitoring station 11956 at North Bosque River on the Bosque River watershed. The Red line represents linear fit.



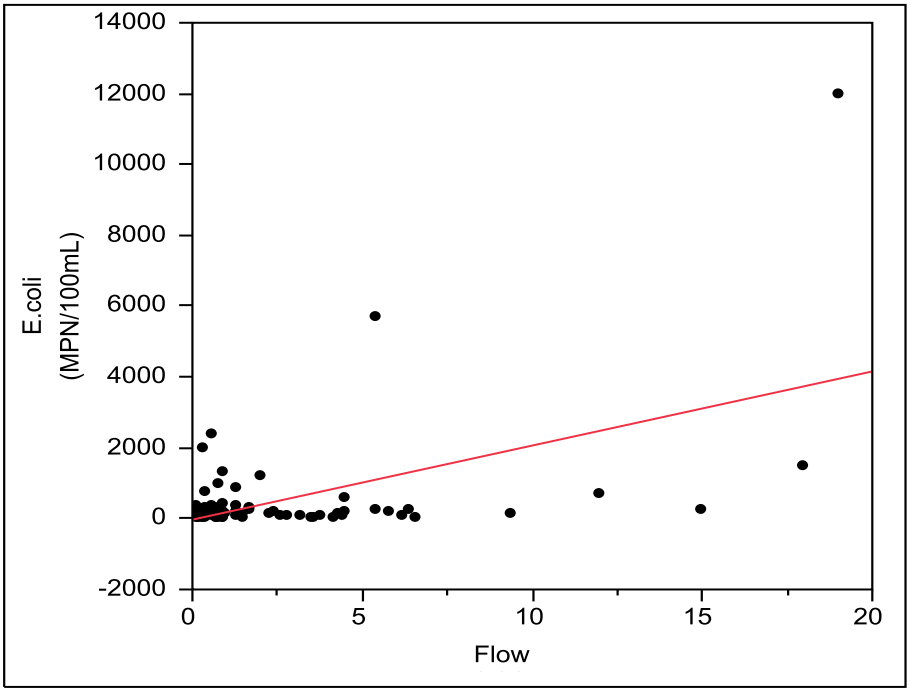
D.26 *E.coli* concentrations as a function of daily mean flow for monitoring station 11961 at North Bosque River on the Bosque River watershed. The Red line represents linear fit.



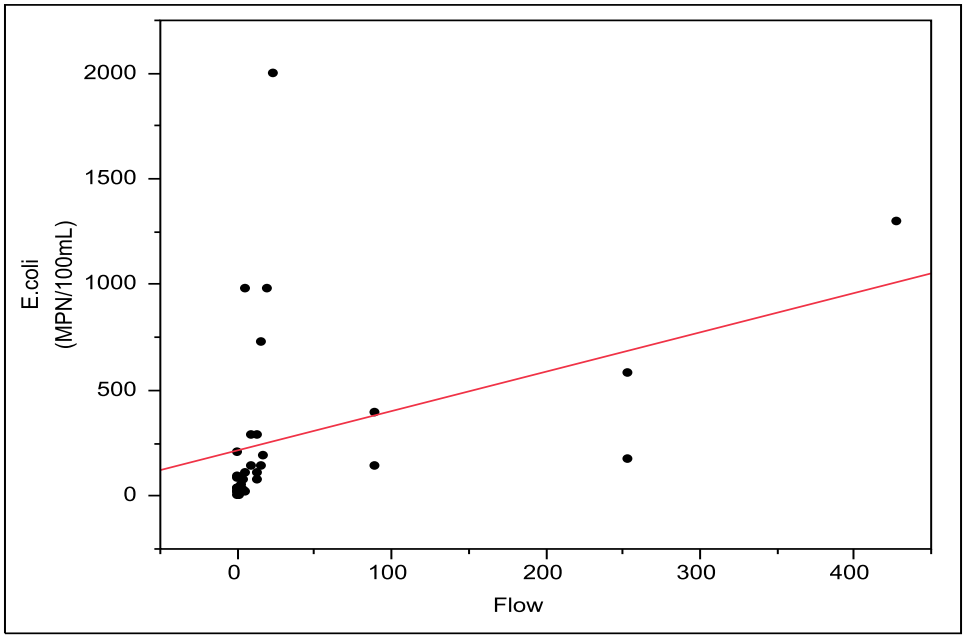
D.27 *E.coli* concentrations as a function of daily mean flow for monitoring station 17500 at North Bosque River on the Bosque River watershed. The Red line represents linear fit.



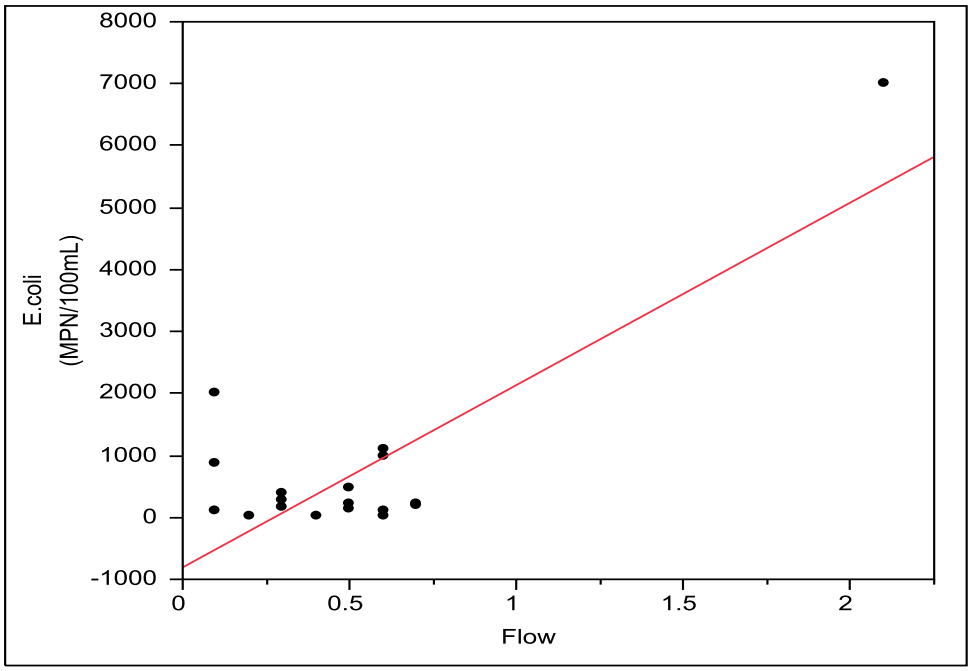
D.28 *E.coli* concentrations as a function of daily mean flow for monitoring station 17607 at Duffau Creek on the Bosque River watershed. The Red line represents linear fit.



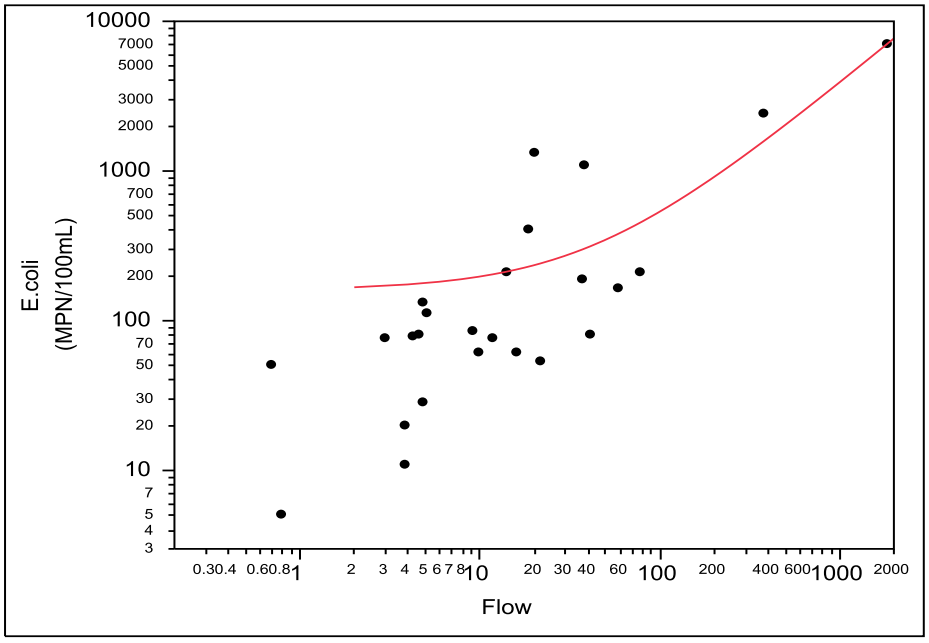
D.29 *E.coli* concentrations as a function of daily mean flow for monitoring station 13486 at Green Creek on the Bosque River watershed. The Red line represents linear fit.



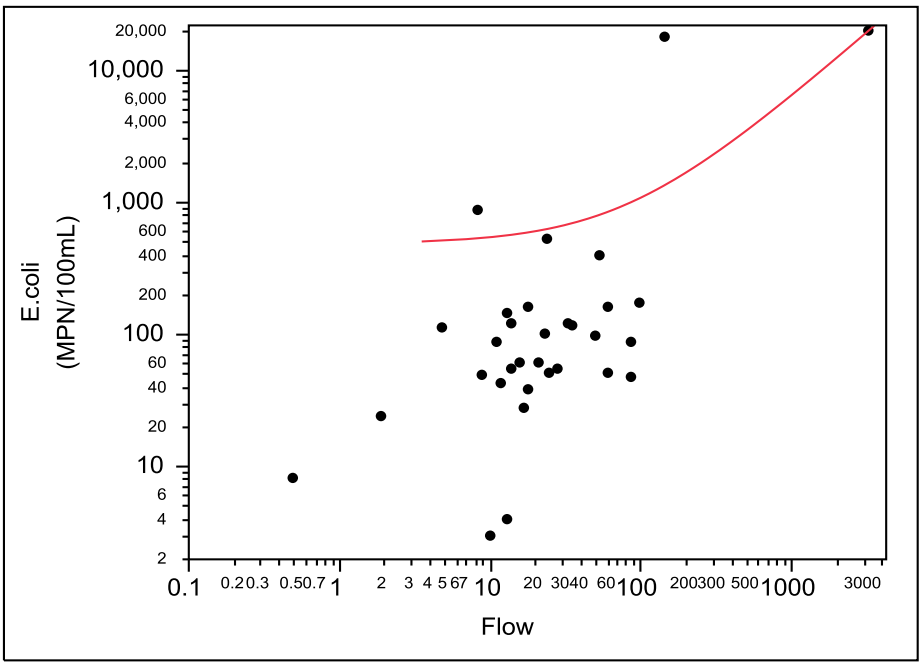
D.30 *E.coli* concentrations as a function of daily mean flow for monitoring station 17235 at Indian Creek on the Bosque River watershed. The Red line represents linear fit.



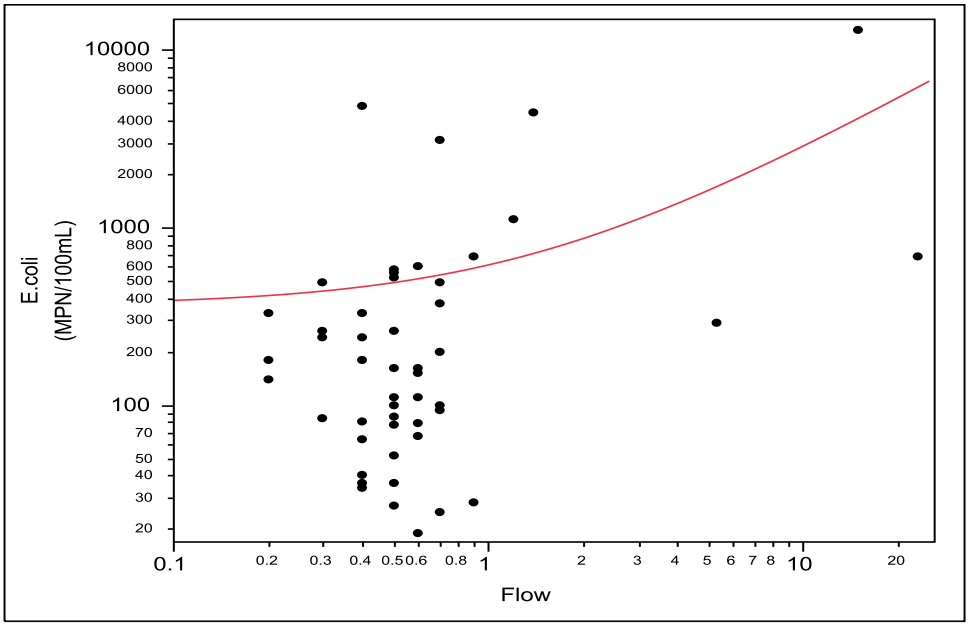
D.31 *E.coli* concentrations as a function of daily mean flow for monitoring station 20308 at Middle/South Bosque River on the Bosque River watershed. The Red line represents linear fit.



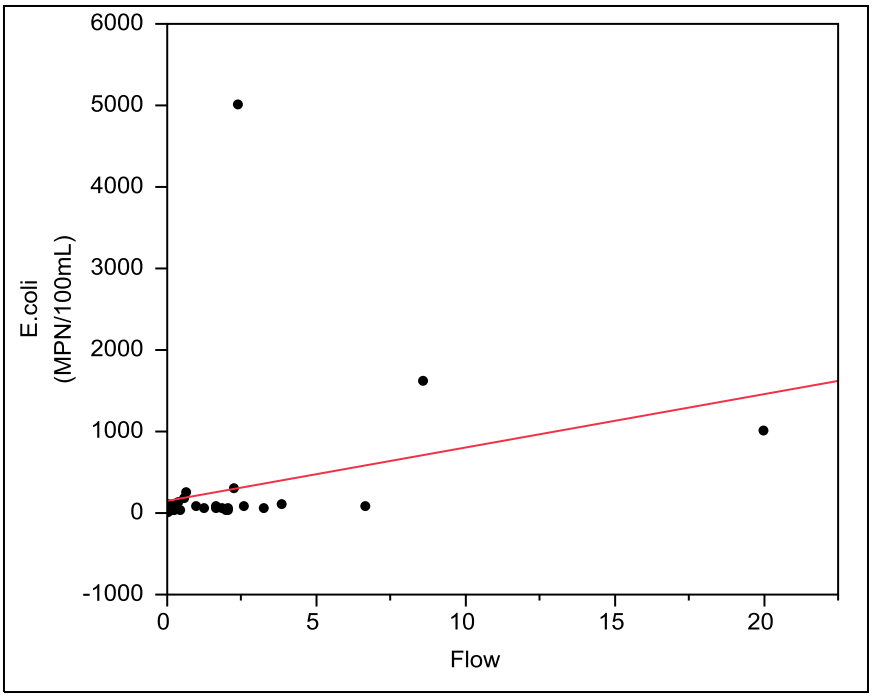
D.32 *E.coli* concentrations as a function of daily mean flow for monitoring station 11826 at Neils Creek on the Bosque River watershed. The Red line represents linear fit.



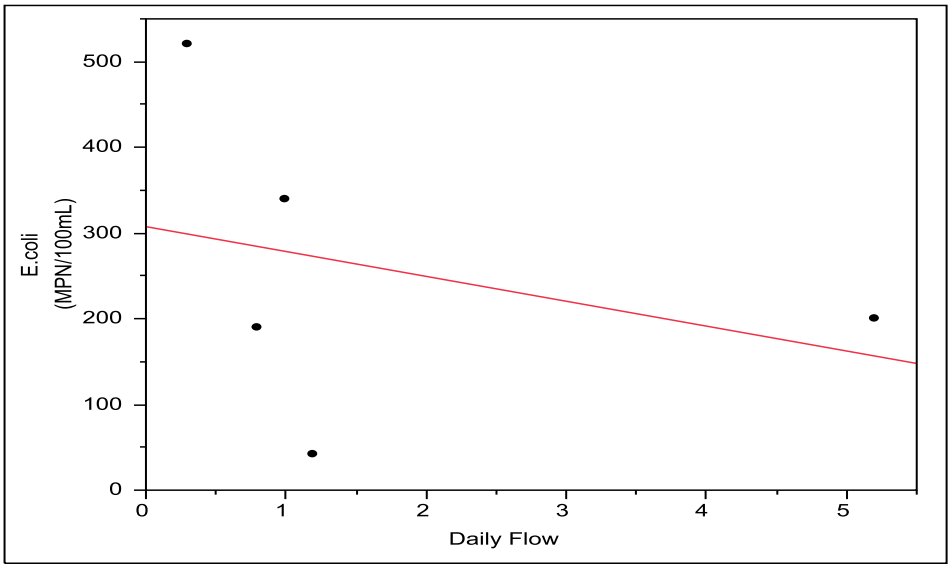
D.33 *E.coli* concentrations as a function of daily mean flow for monitoring station 17240 at Sims Creek on the Bosque River watershed. The Red line represents linear fit.



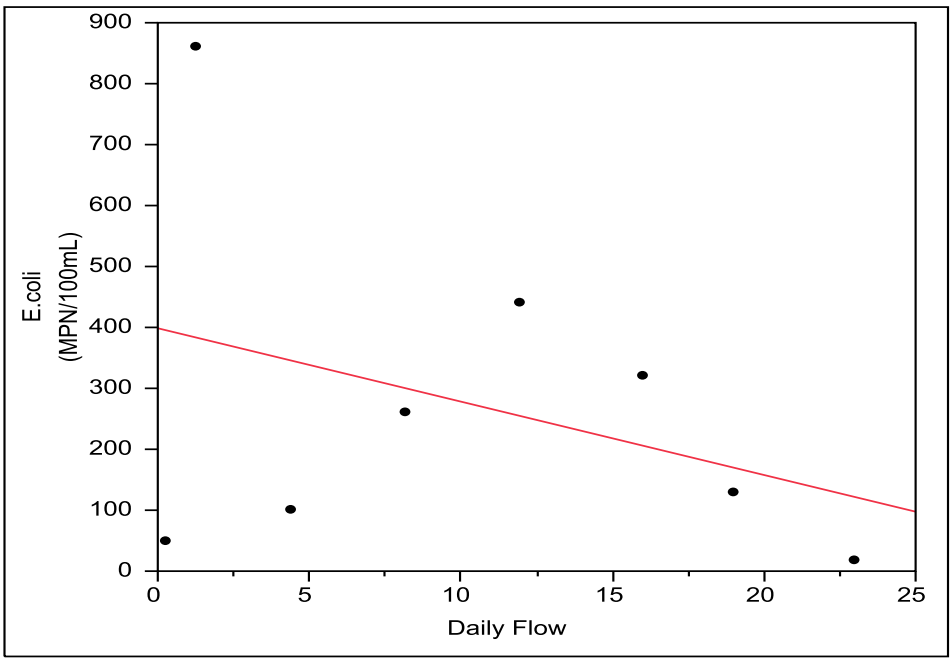
D.34 *E.coli* concentrations as a function of daily mean flow for monitoring station 17242 at Spring Creek on the Bosque River watershed. The Red line represents linear fit.



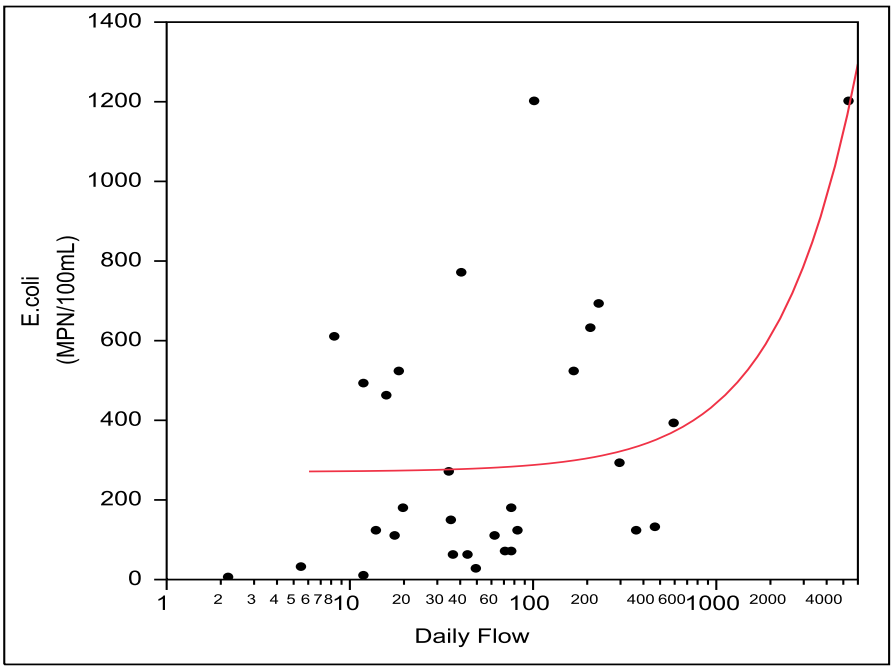
D.35 *E.coli* concentrations as a function of daily mean flow for monitoring station 11938 at Leon River below Leon Reservoir on the Leon River watershed. The Red line represents linear fit.



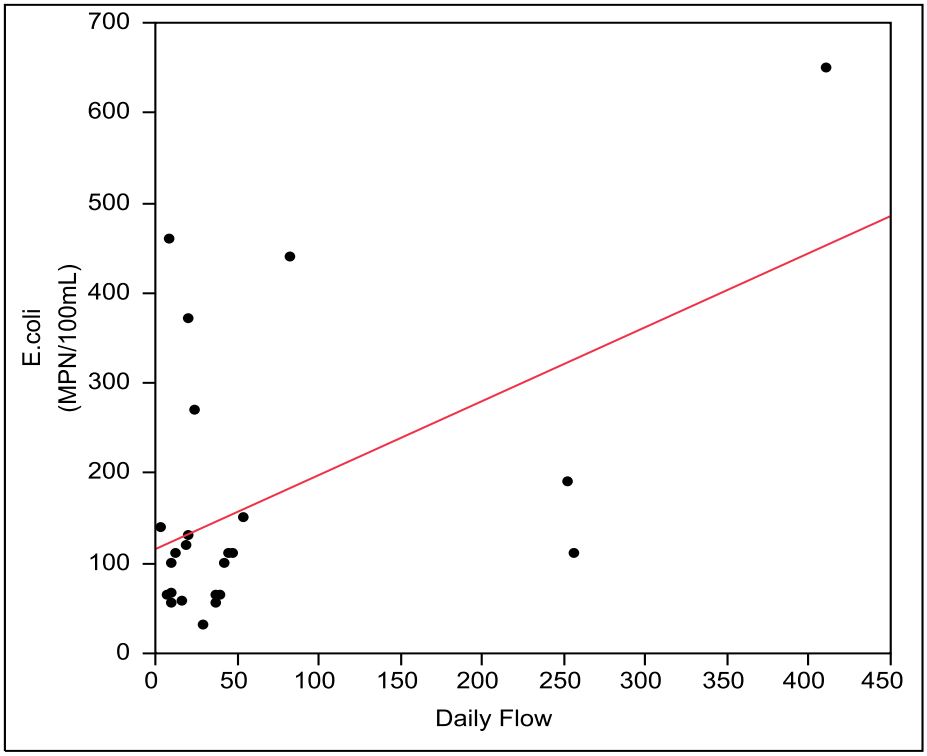
D.36 *E.coli* concentrations as a function of daily mean flow for monitoring station 11934 at Leon River below Proctor Lake on the Leon River watershed. The Red line represents linear fit.



D.37 *E.coli* concentrations as a function of daily mean flow for monitoring station 17545 at Leon River below Proctor Lake on the Leon River watershed. The Red line represents linear fit.

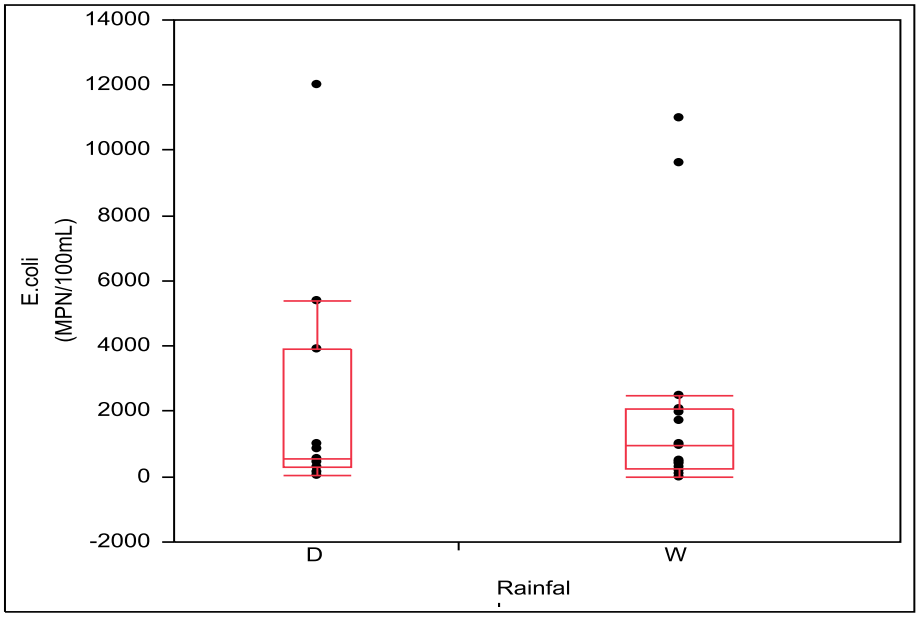


D.38 *E.coli* concentrations as a function of daily mean flow for monitoring station 18781 at Leon River below Proctor Lake on the Leon River watershed. The Red line represents linear fit.

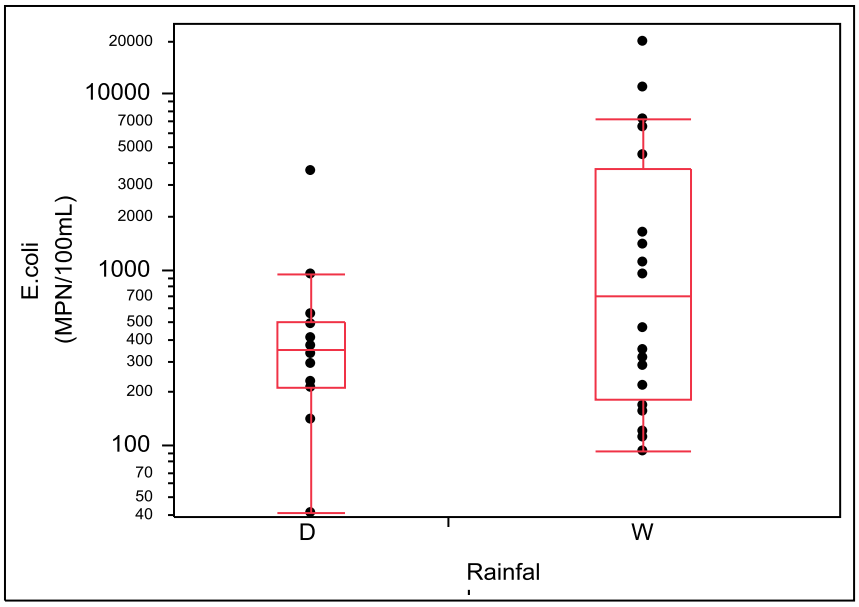


APPENDIX E

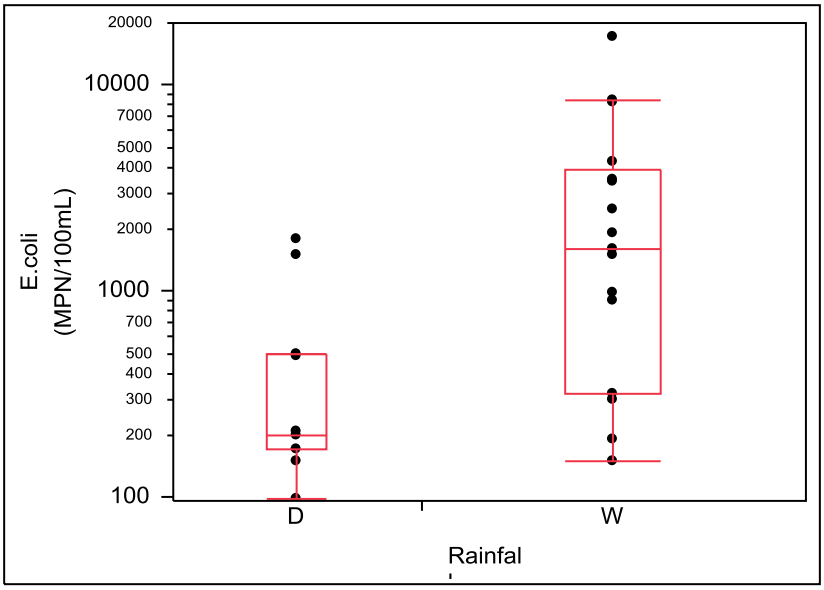
E.1 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11360 at Buffalo Bayou above Tidal on the San Jacinto River Watershed.



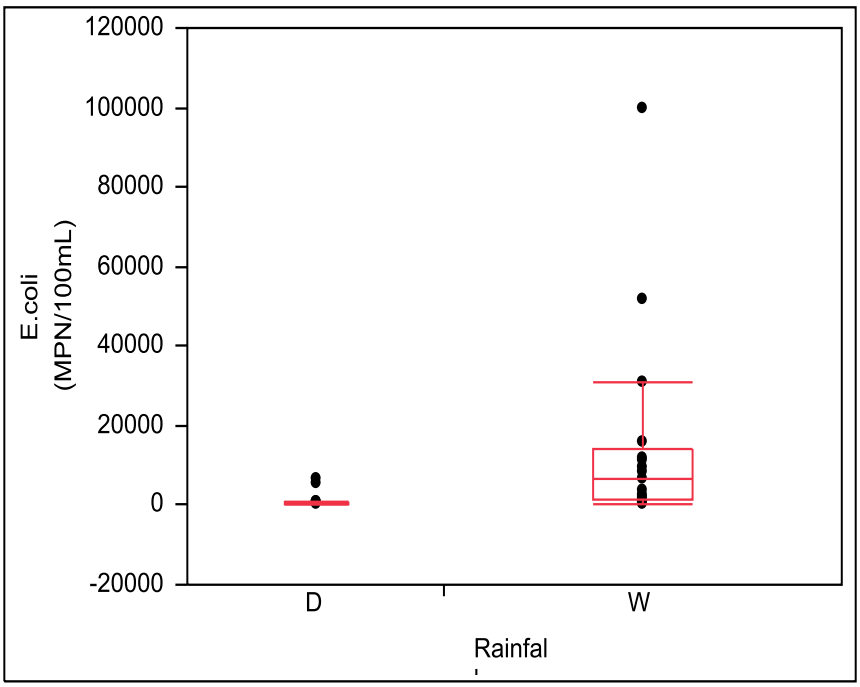
E.2 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11362 at Buffalo Bayou above Tidal on the San Jacinto River Watershed.



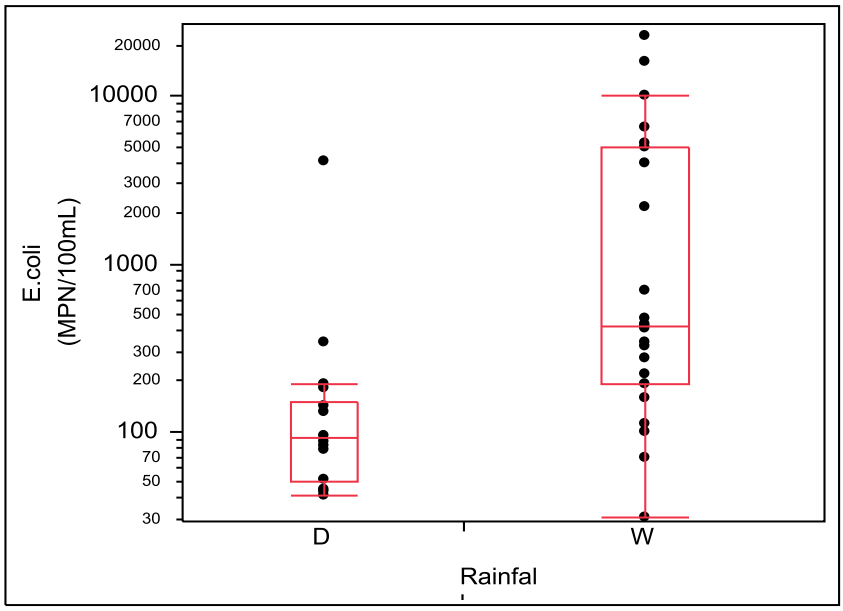
E.3 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 15846 at Buffalo Bayou above Tidal on the San Jacinto River Watershed.



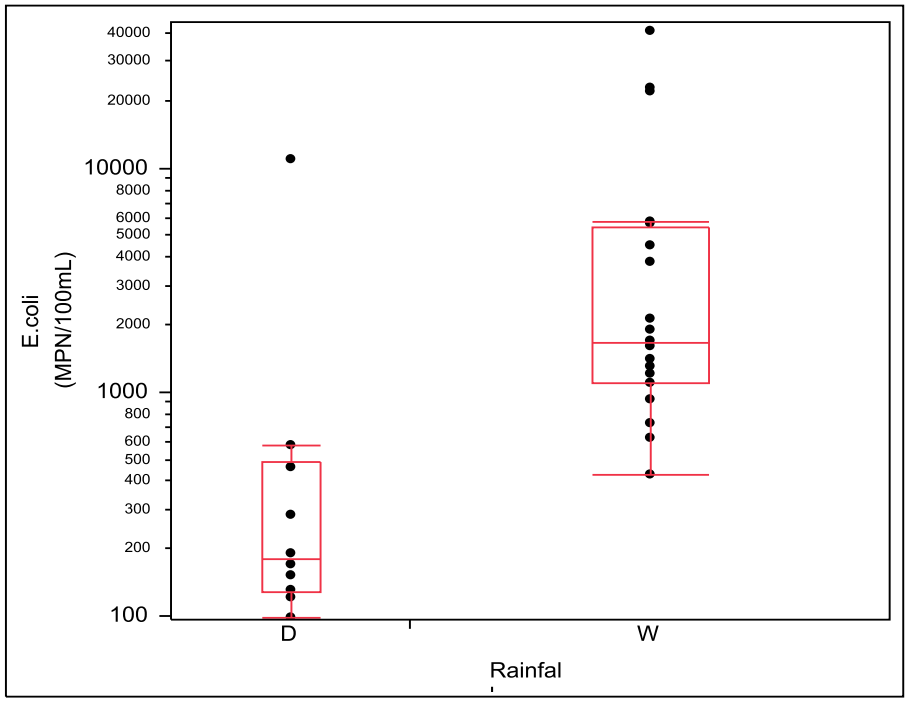
E.4 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 16648 at Buffalo Bayou Tidal on the San Jacinto River Watershed.



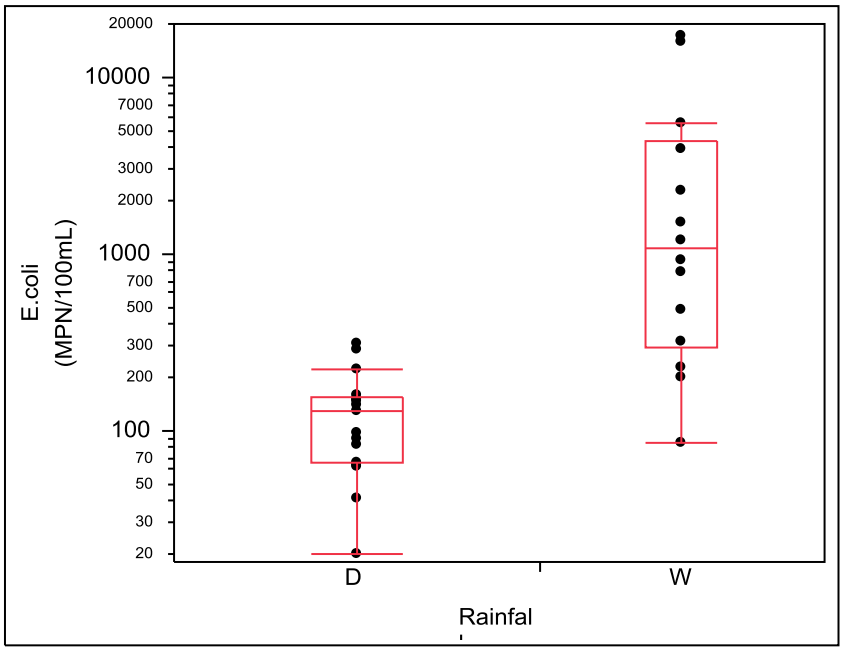
E.5 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11334 at Caney Creek on the San Jacinto River Watershed.



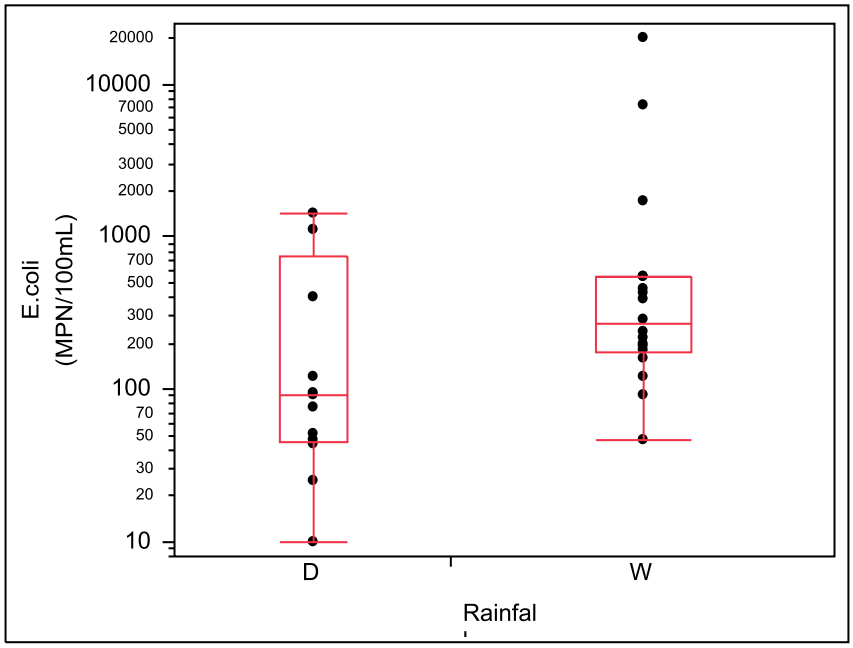
E.6 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11328 at Cpyress Creek on the San Jacinto River Watershed.



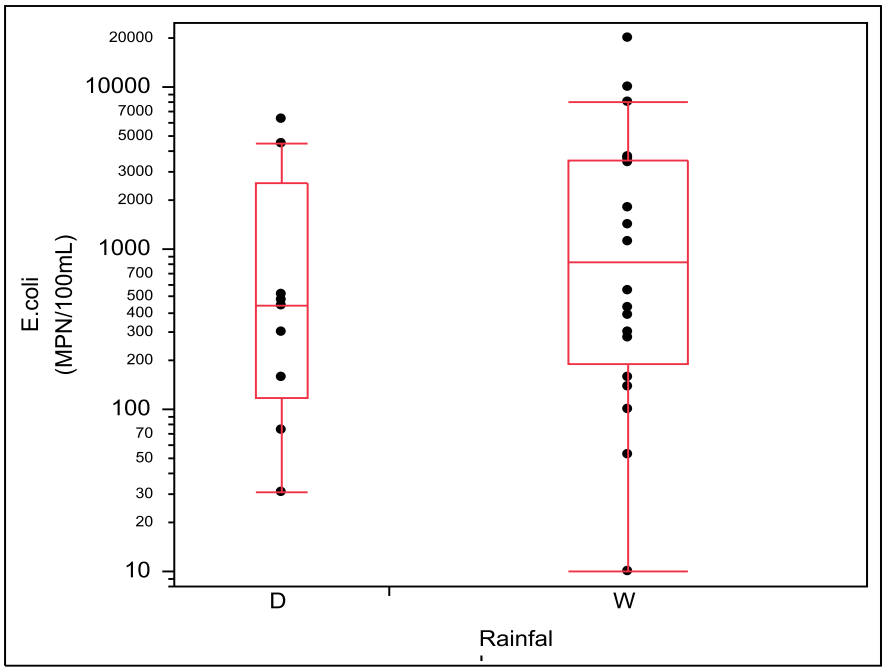
E.7 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11332 at Cypress Creek on the San Jacinto River Watershed.



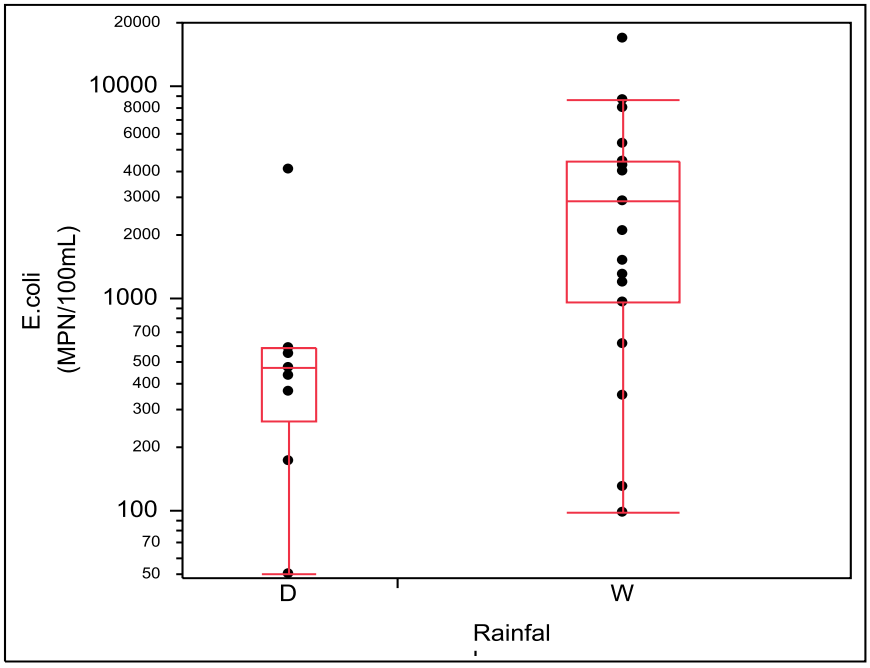
E.8 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11235 at East Fork San Jacinto River on the San Jacinto River Watershed.



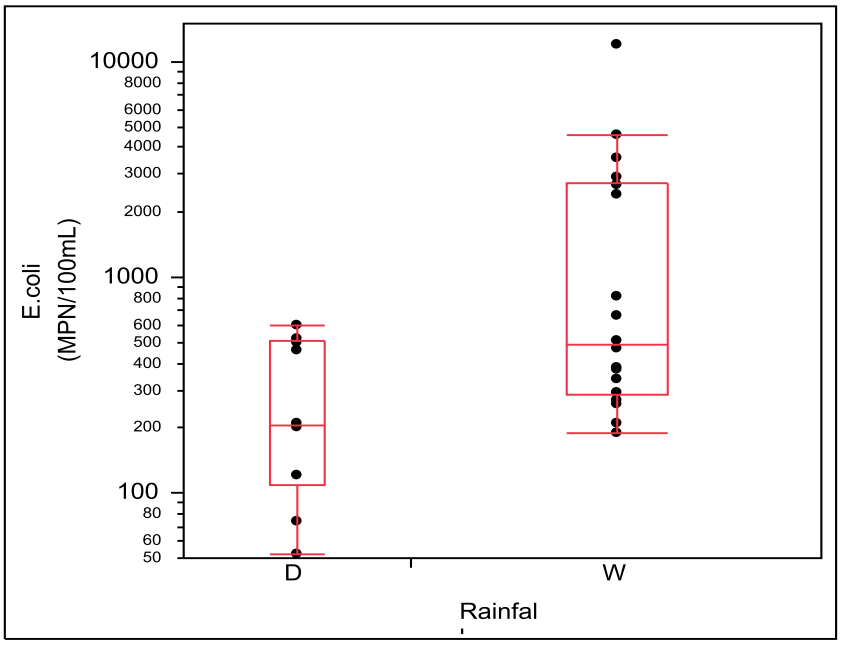
E.9 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11369 at Greens Bayou on the San Jacinto River Watershed.



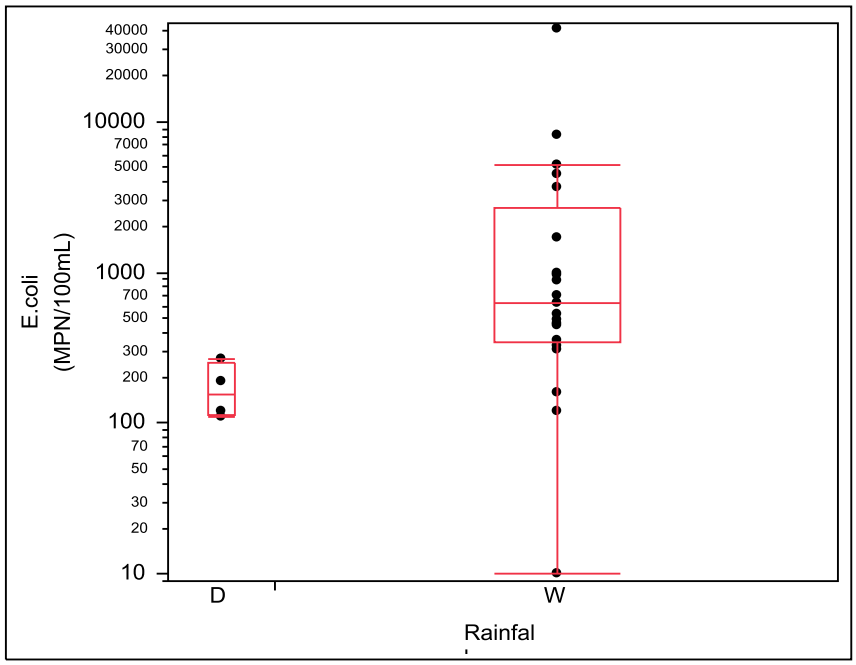
E.10 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11371 at Greens Bayou on the San Jacinto River Watershed.



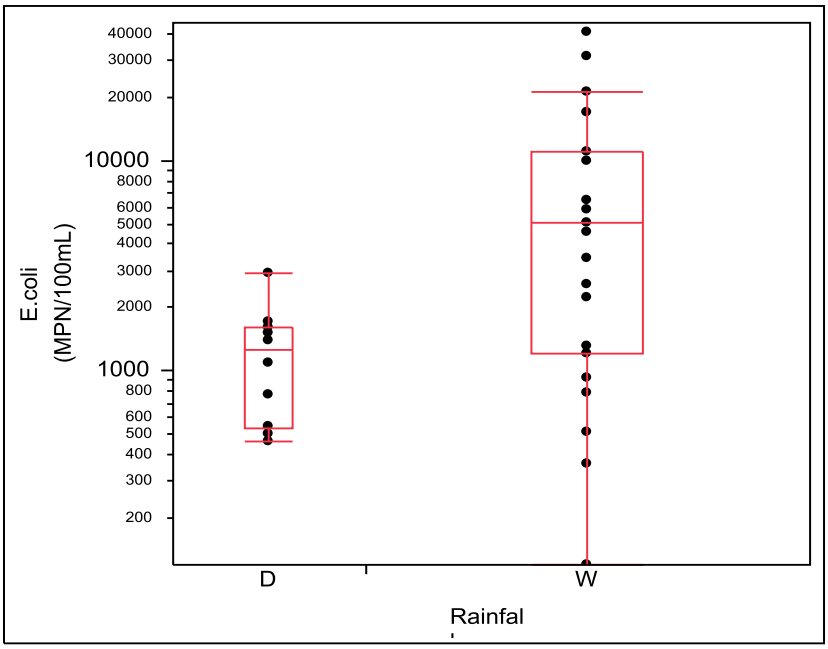
E.11 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11925 at Greens Bayou on the San Jacinto River Watershed.



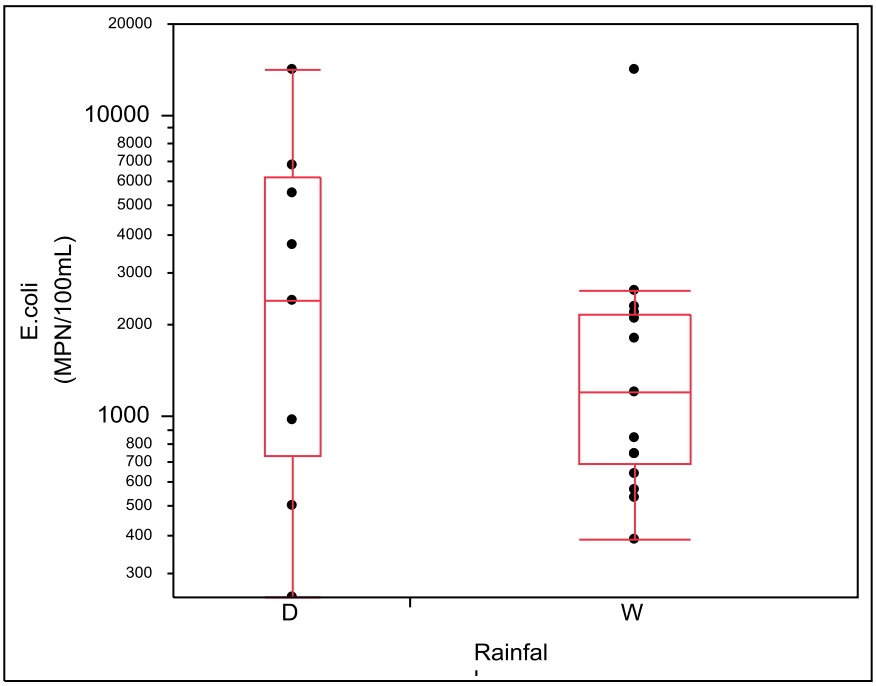
E.12 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11135 at Houston Ship Channel-Buffalo Bayou Tidal on the San Jacinto River Watershed.



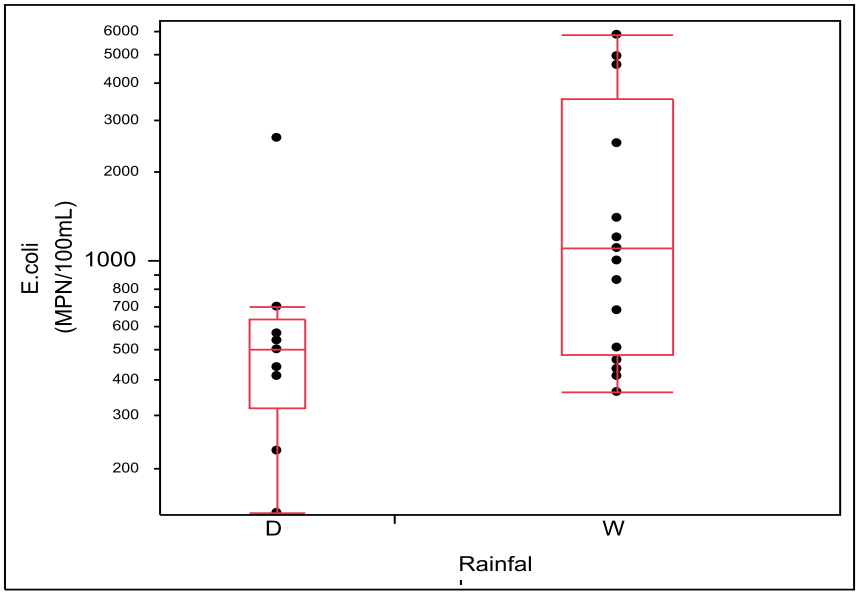
E.13 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11139 at Houston Ship Channel-Buffalo Bayou Tidal on the San Jacinto River Watershed.



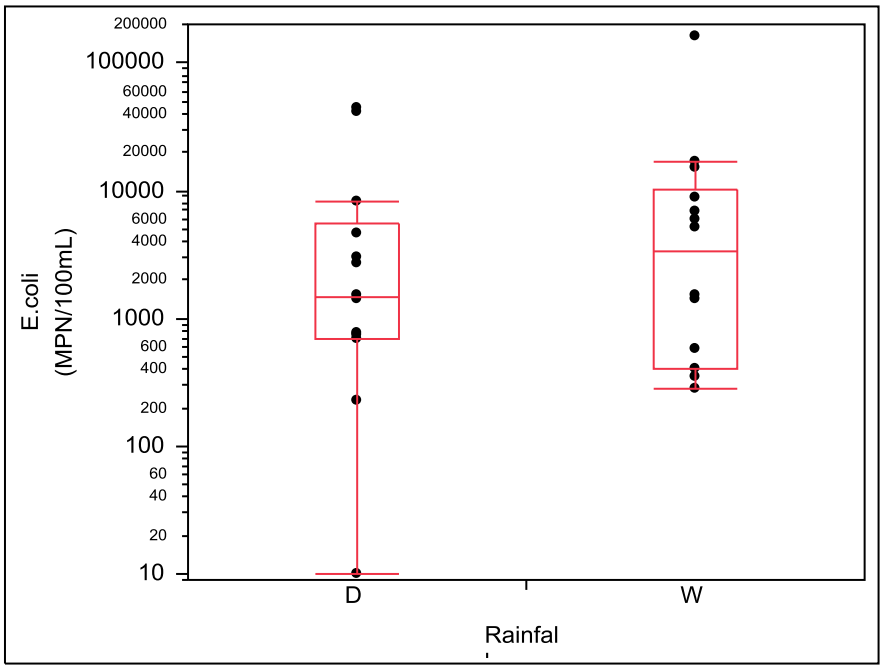
E.14 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11140 at Houston Ship Channel-Buffalo Bayou Tidal on the San Jacinto River Watershed.



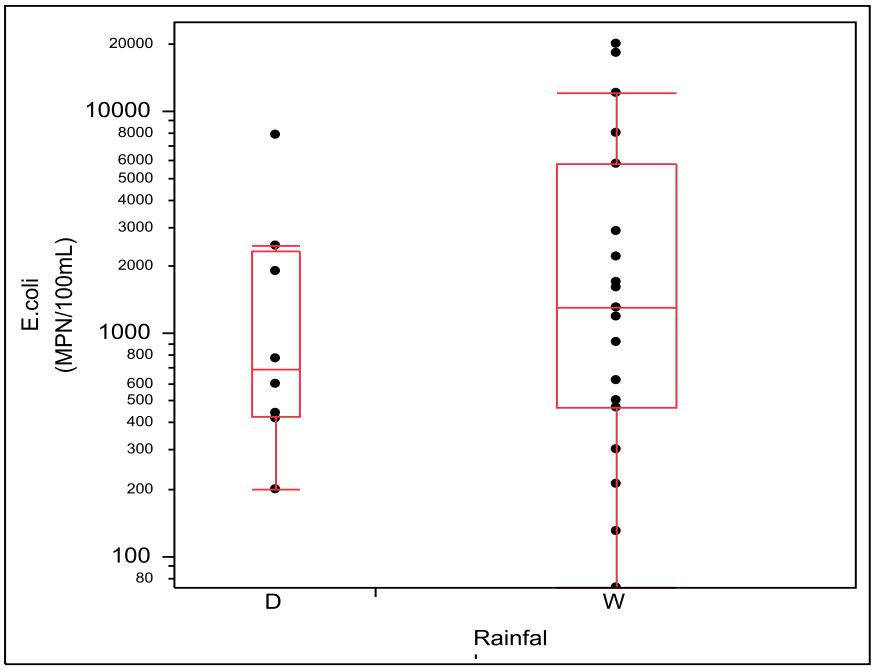
E.15 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 15851 at Houston Ship Channel-Buffalo Bayou Tidal on the San Jacinto River Watershed.



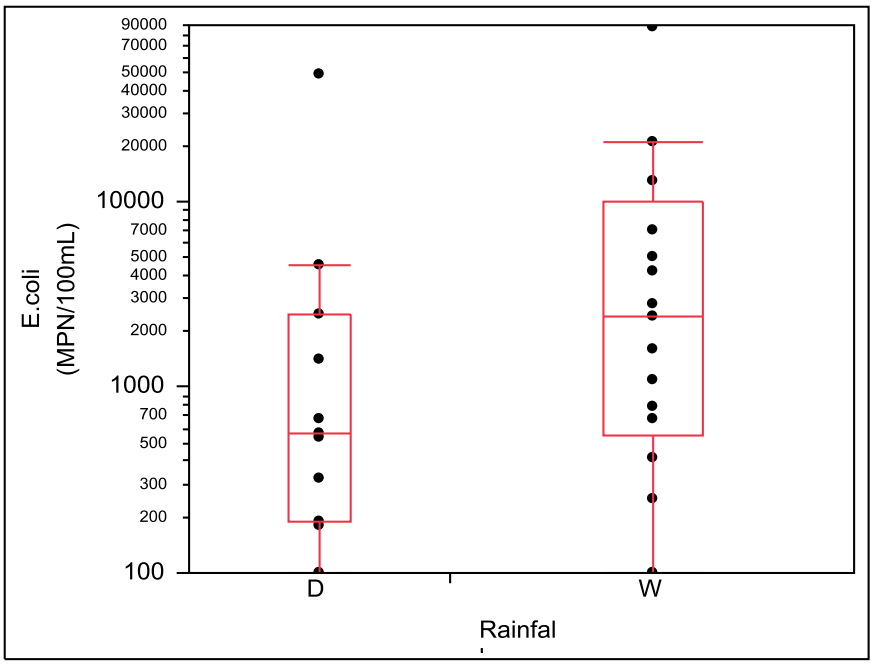
E.16 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 16661 at Houston Ship Channel-Buffalo Bayou TIdal on the San Jacinto River Watershed.



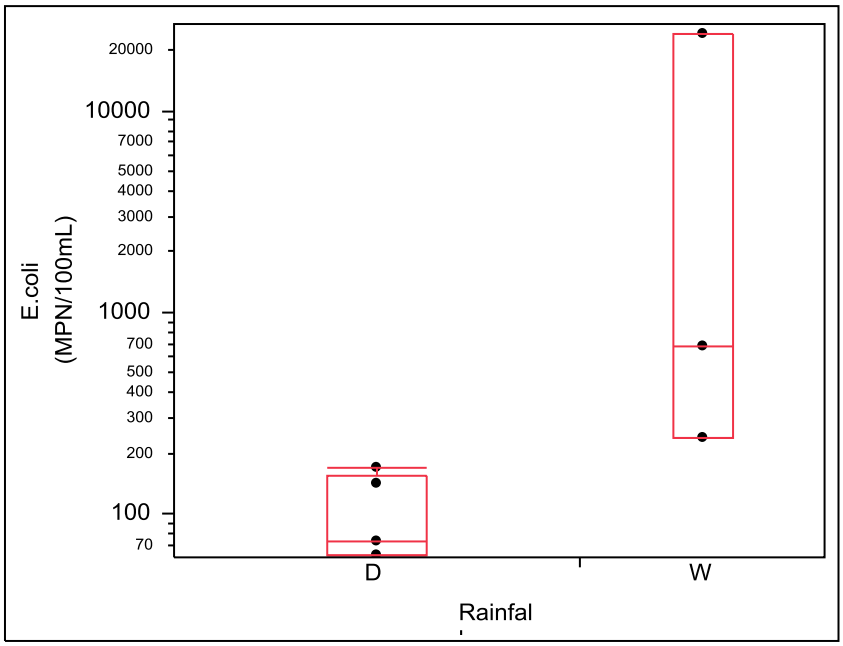
E.17 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11279 at Houston Ship Channel on the San Jacinto River Watershed.



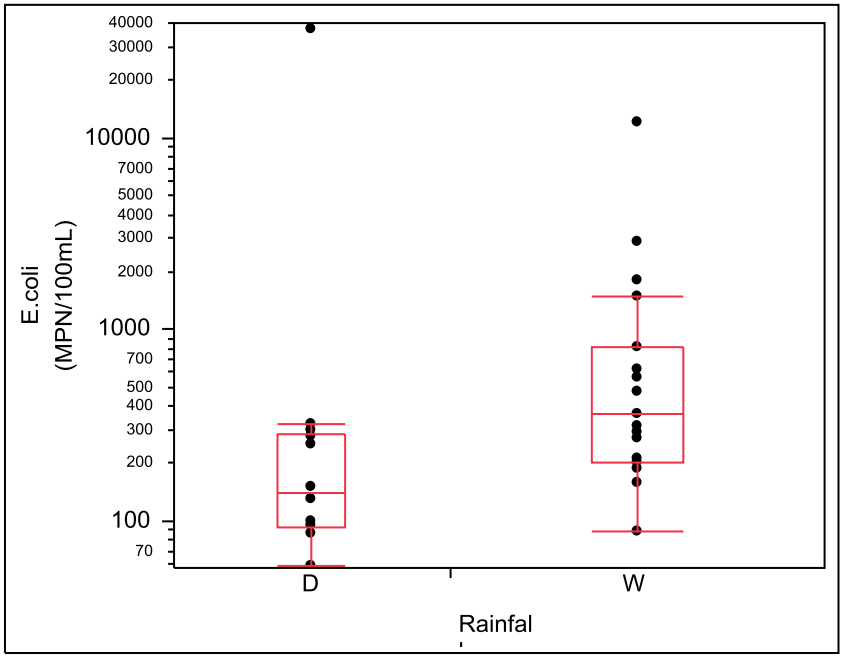
E.18 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 16665 at Houston Ship Channel on the San Jacinto River Watershed.



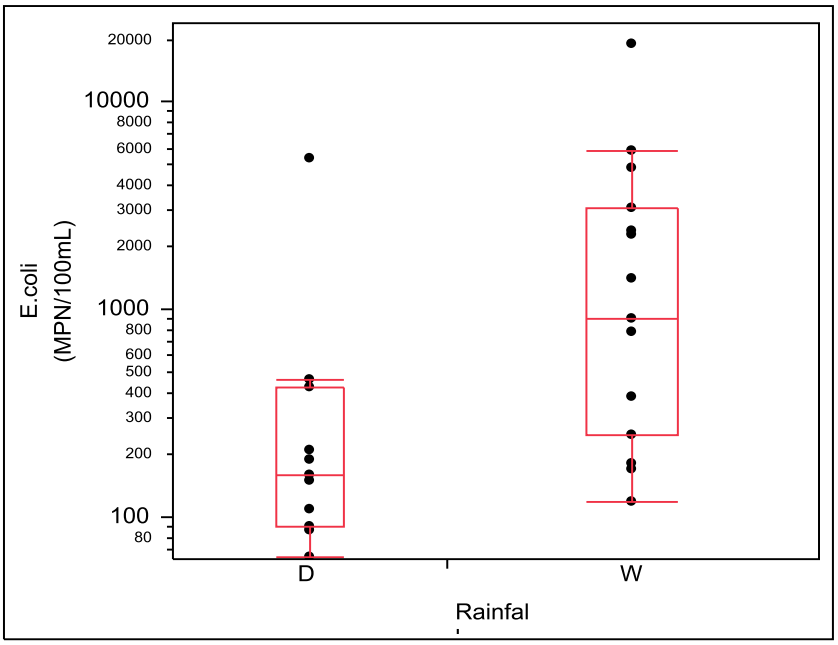
E.19 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 18191 at Lake Creek on the San Jacinto River Watershed.



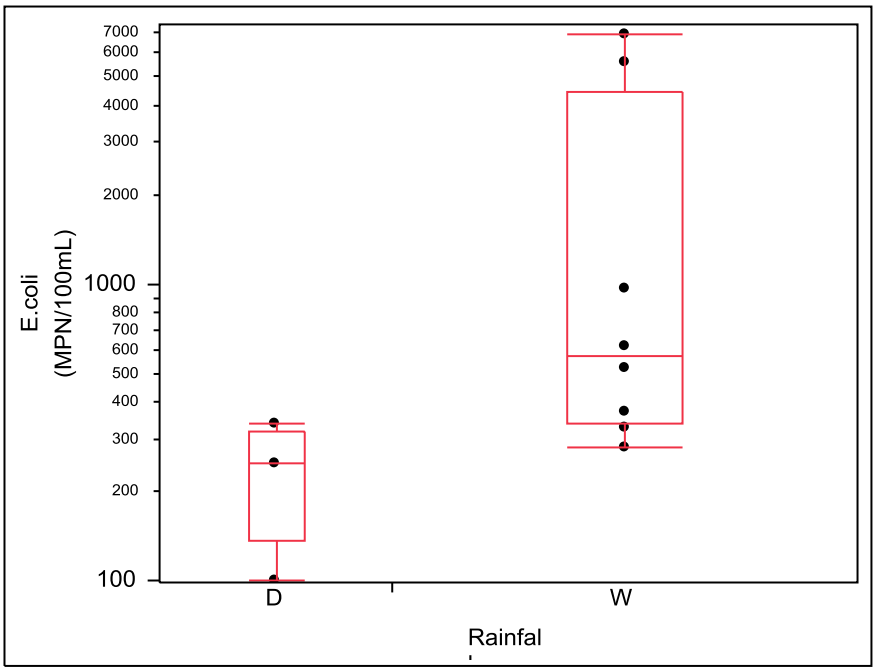
E.20 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11336 at Peach Creek on the San Jacinto River Watershed.



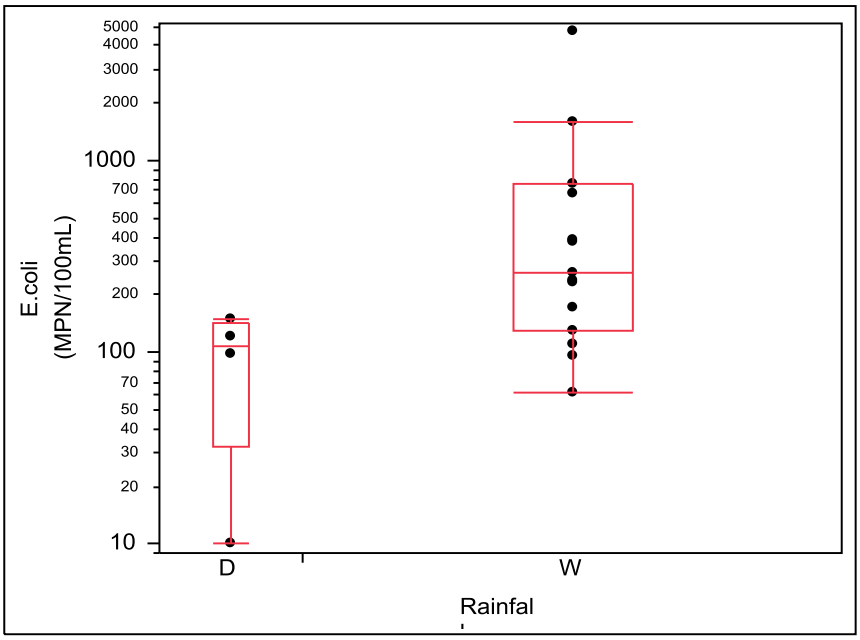
E.21 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11312 at Spring Creek on the San Jacinto River Watershed.



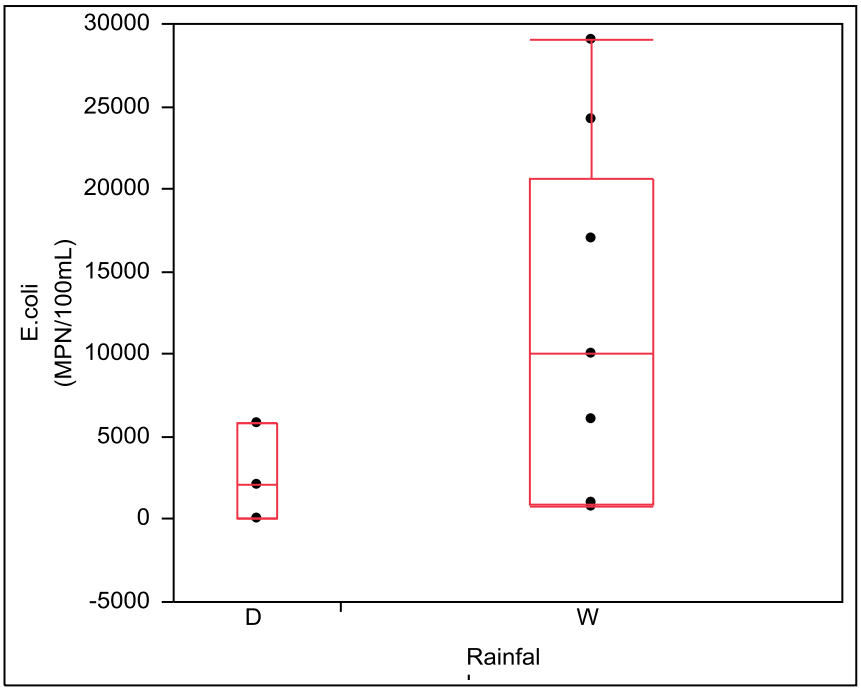
E.22 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11314 at Spring Creek on the San Jacinto River Watershed.



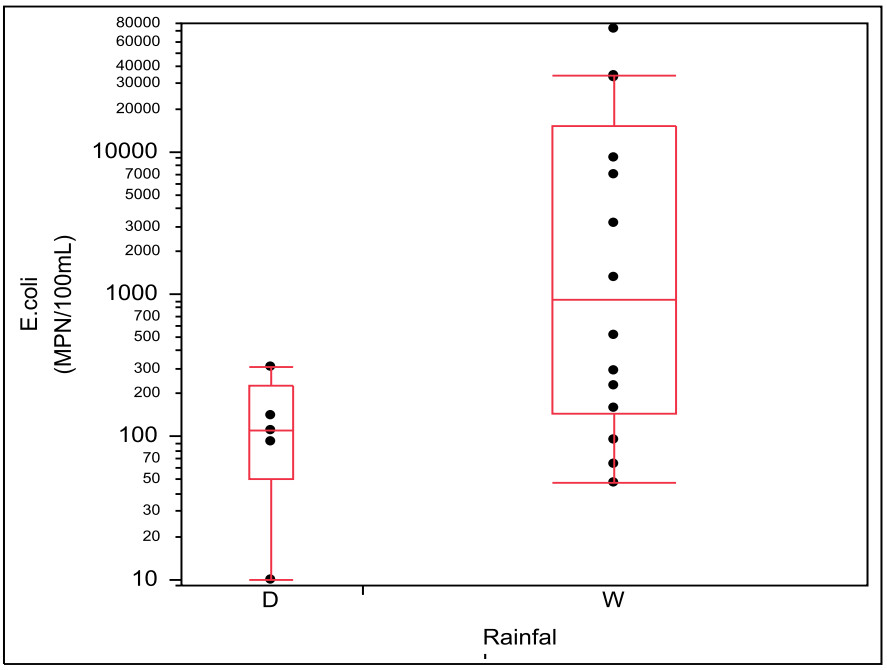
E.23 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11250 at West Fork San Jacinto River on the San Jacinto River Watershed.



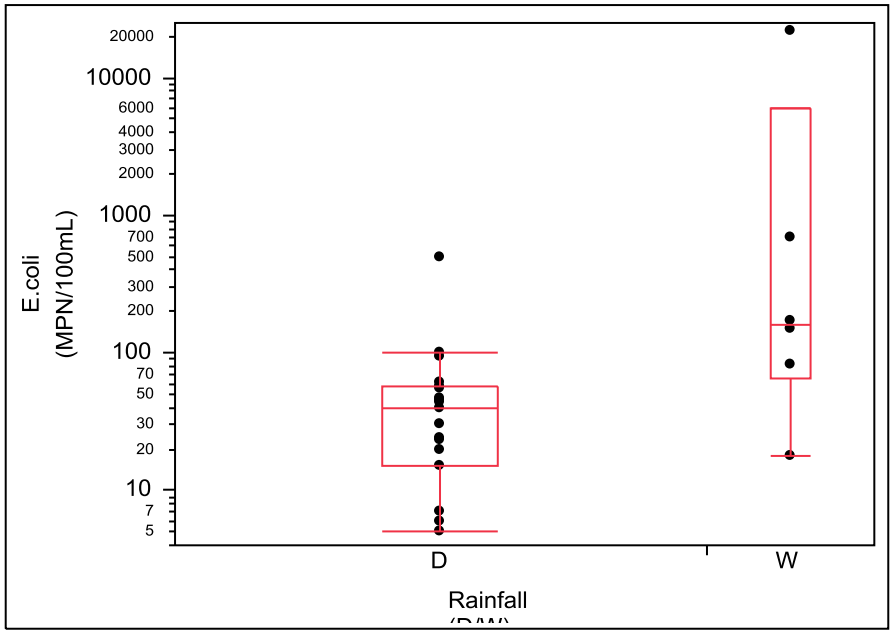
E.24 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11387 at White Oak Bayou on the San Jacinto River Watershed.



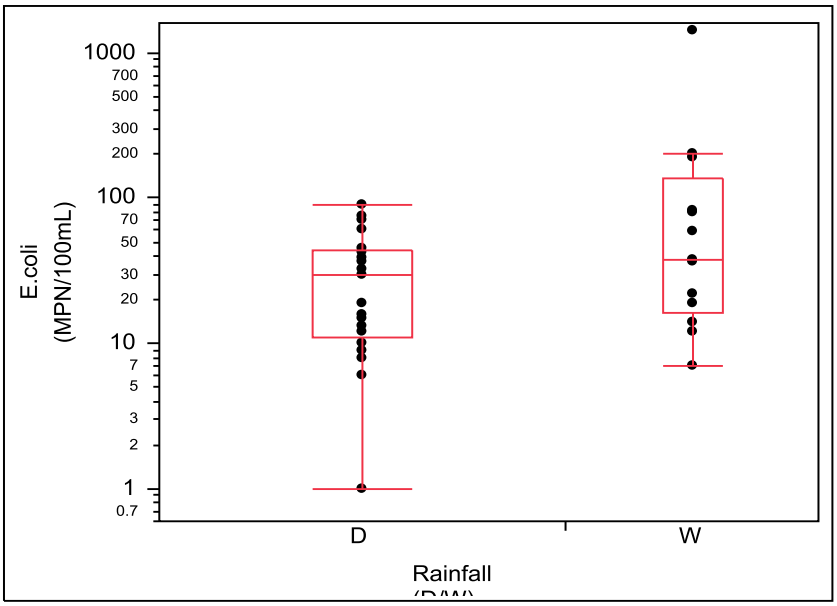
E.25 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11394 at Peach Creek on the San Jacinto River Watershed.



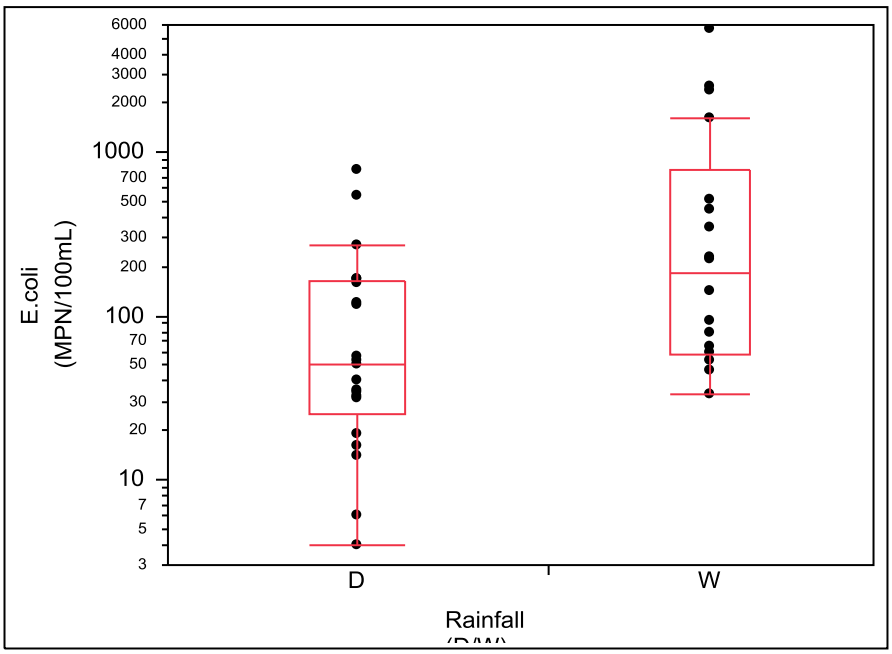
E.26 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11954 at North Bosque River on the Bosque River Watershed.



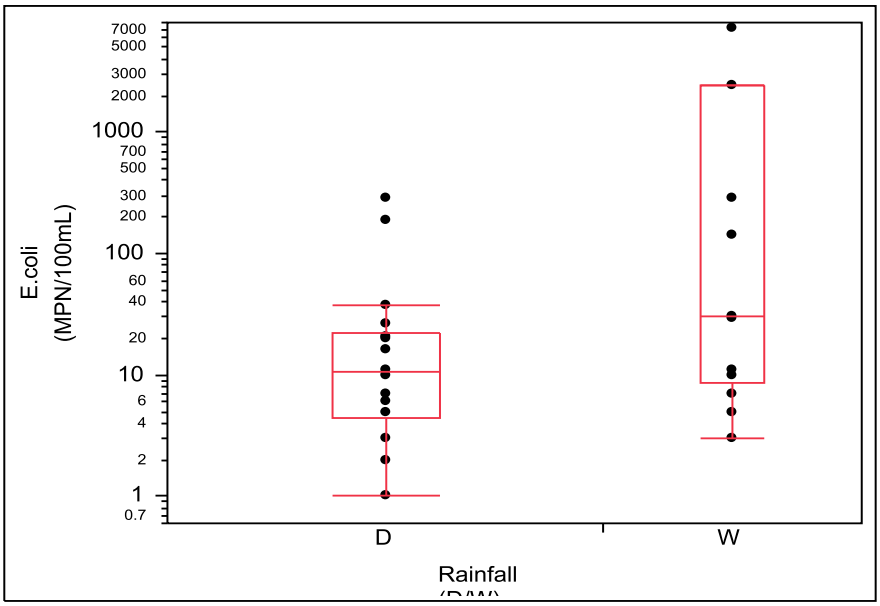
E.27 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11956 at North Bosque River on the Bosque River watershed.



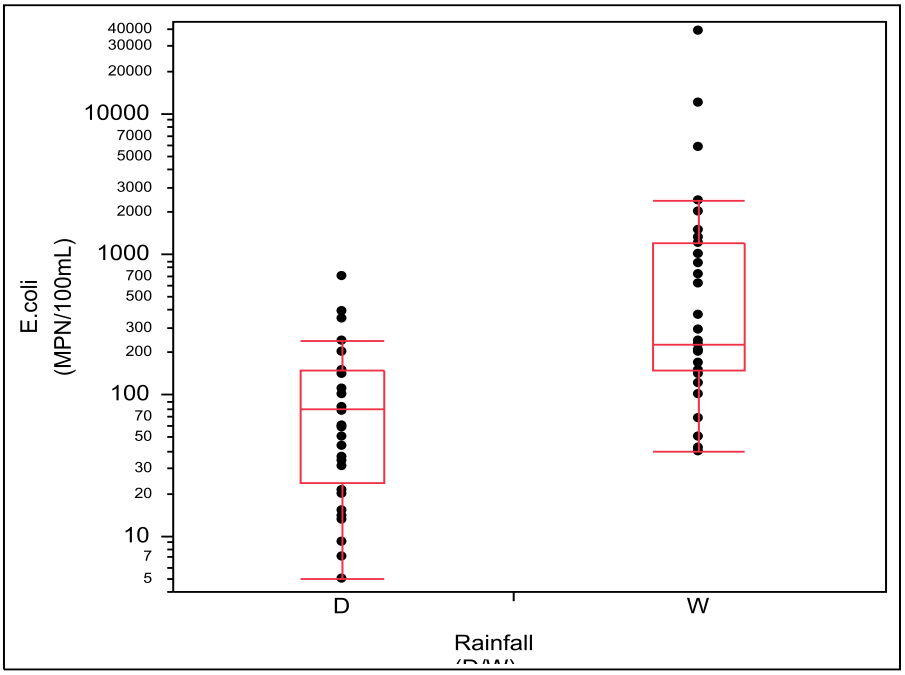
E.28 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11961 at North Bosque River on the Bosque River watershed.



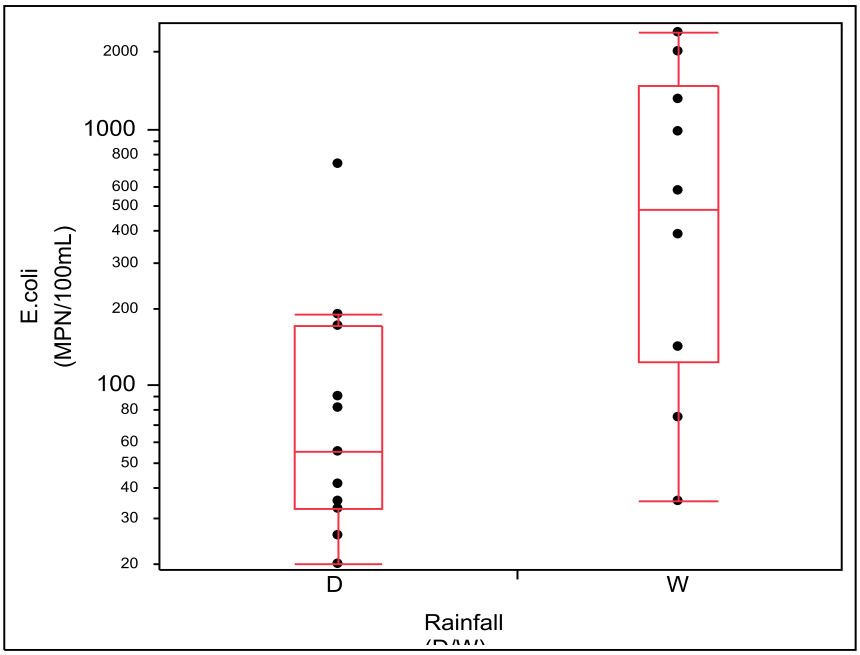
E.29 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17500 at North Bosque River on the Bosque River watershed.



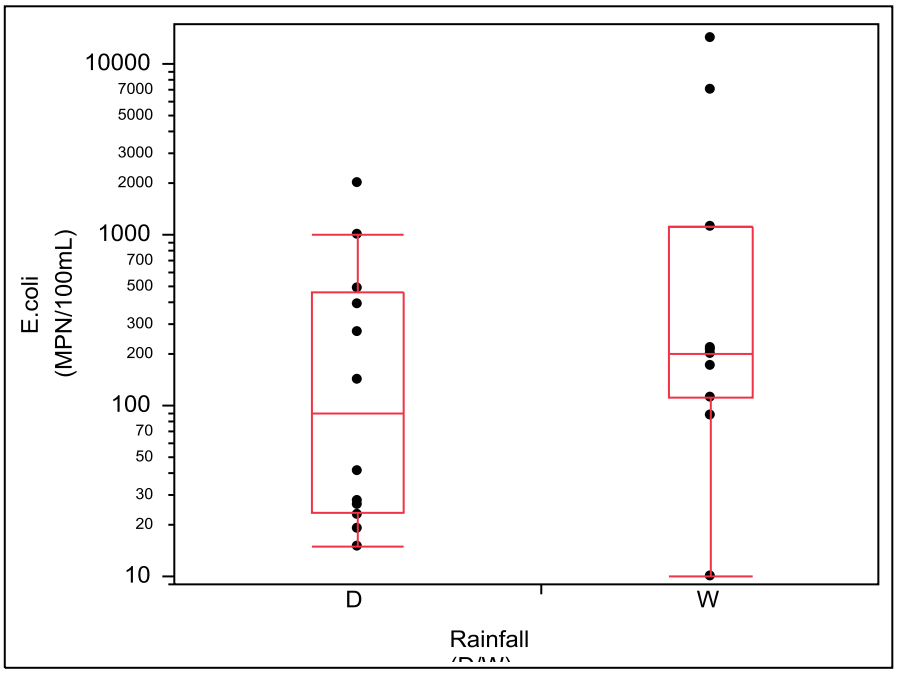
E.30 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17607 at Duffau Creek on the Bosque River watershed.



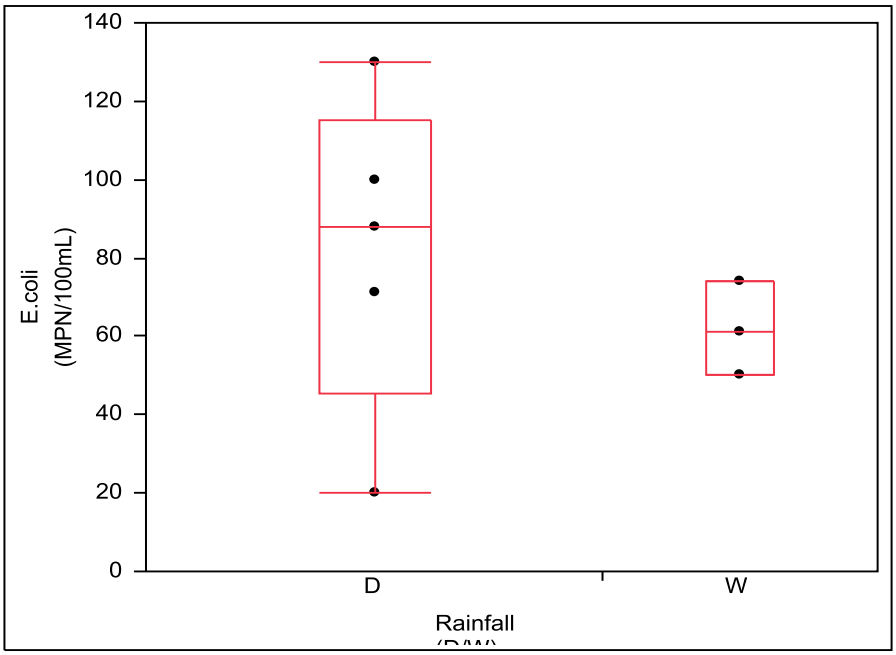
E.31 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 13486 at Green Creek on the Bosque River watershed.



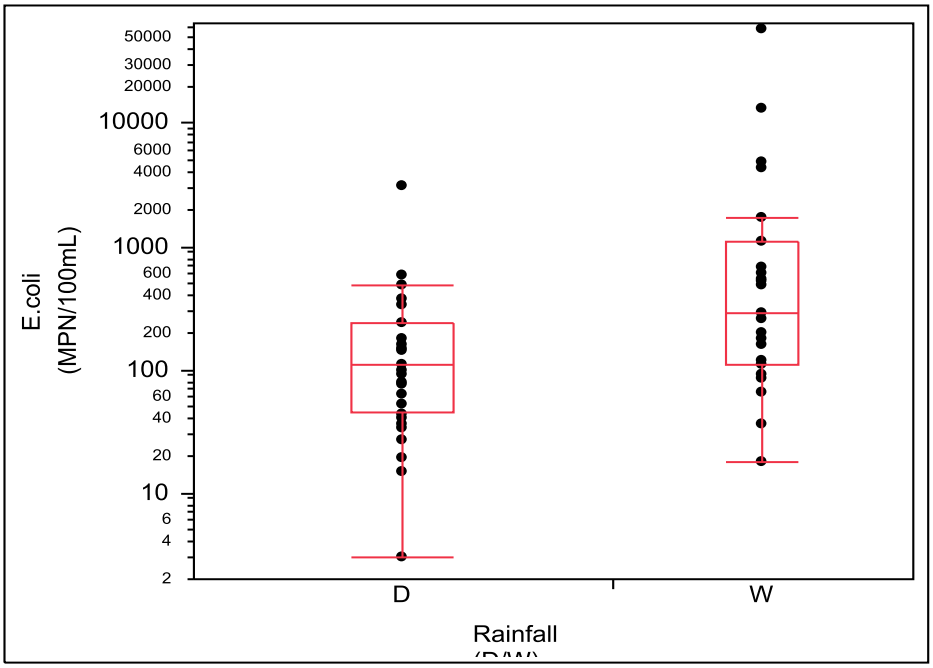
E.32 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17235 at Indian Creek on the Bosque River watershed.



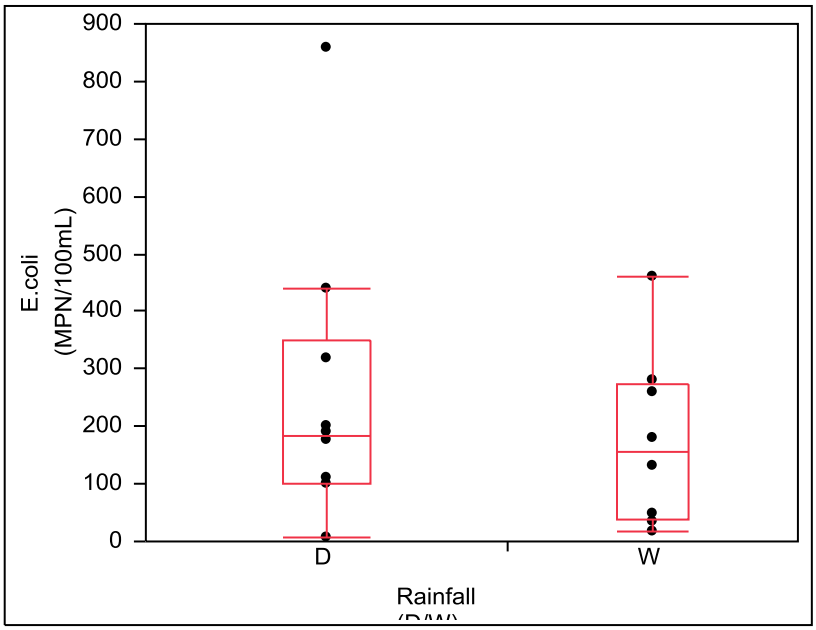
E.33 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 20308 at Middle/South Bosque River on the Bosque River watershed.



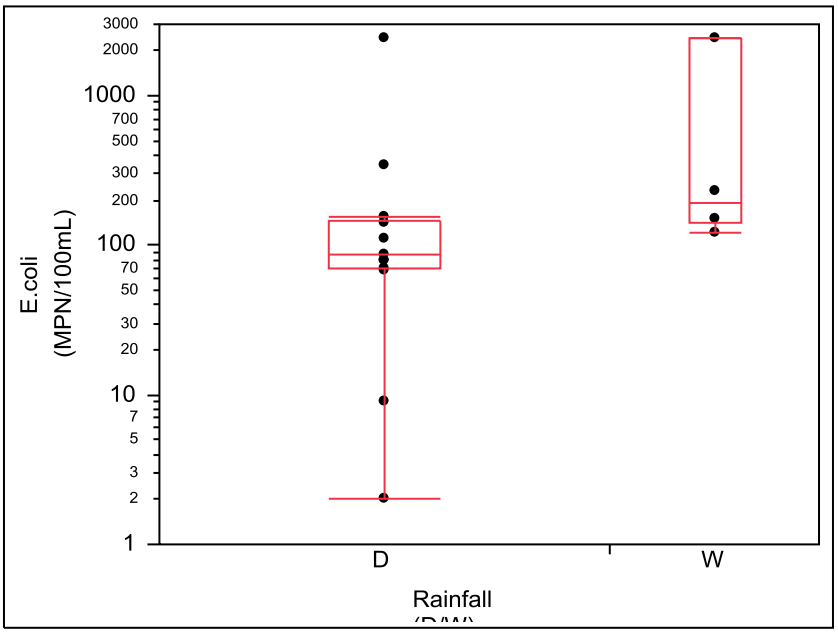
E.34 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17240 at Sims Creek on the Bosque River watershed.



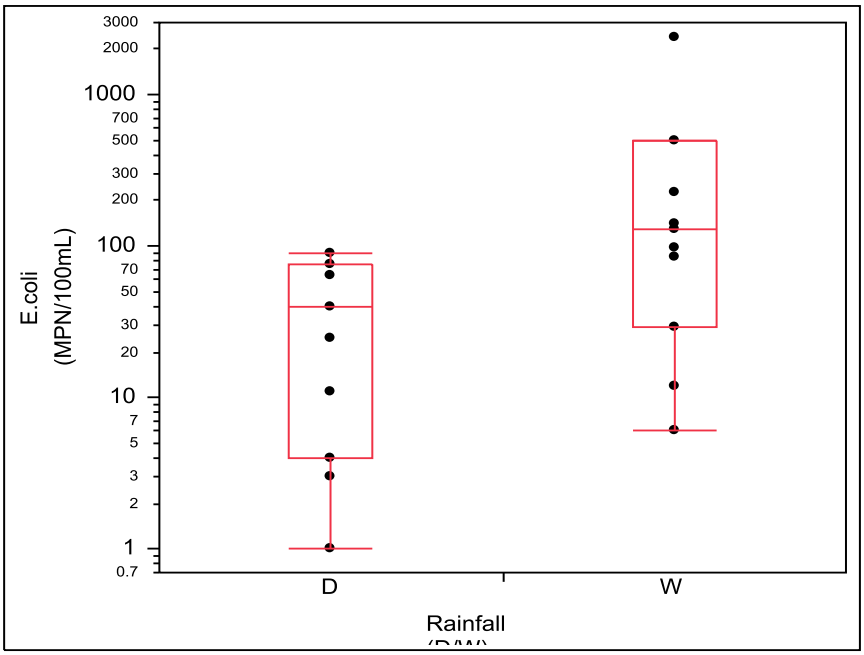
E.35 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 11934 at Leon River below Proctor Lake on the Leon River watershed.



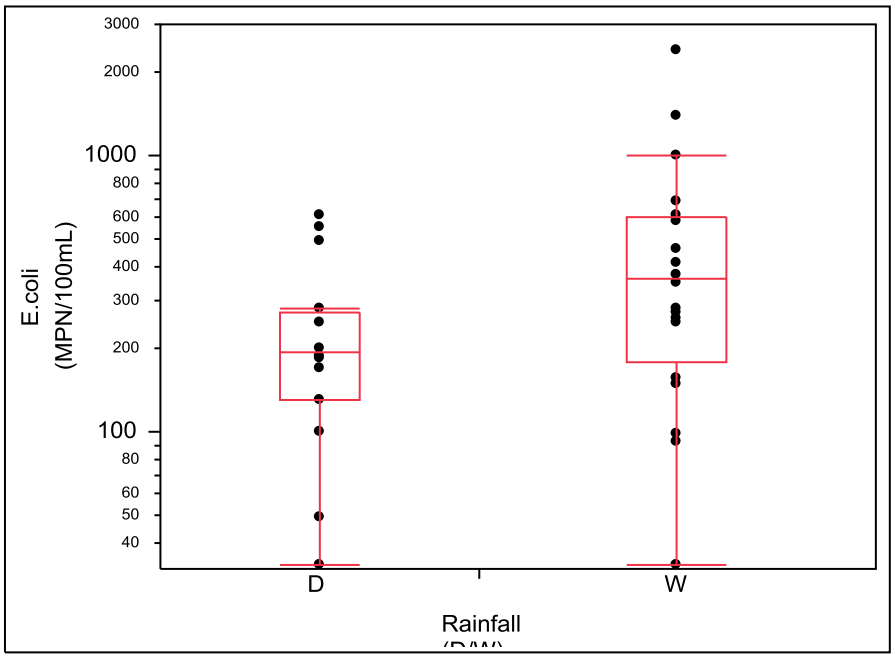
E.36 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17377 at Leon River below Proctor Lake on the Leon River watershed.



E.37 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17501 at Leon River below Proctor Lake on the Leon River watershed.

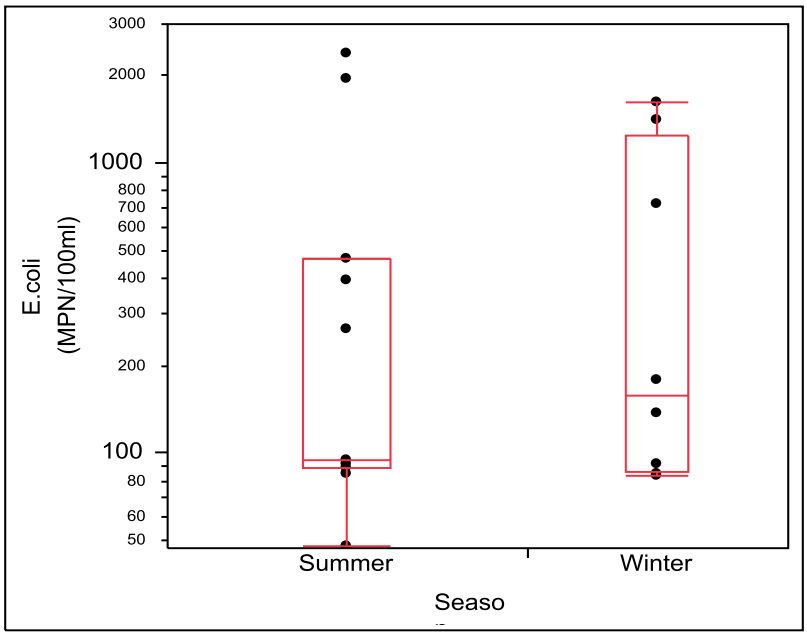


E.38 Box-Plots showing the difference in *E.coli* concentrations between dry and wet weather samples for monitoring station 17591 at Leon River below Proctor Lake on the Leon River watershed.

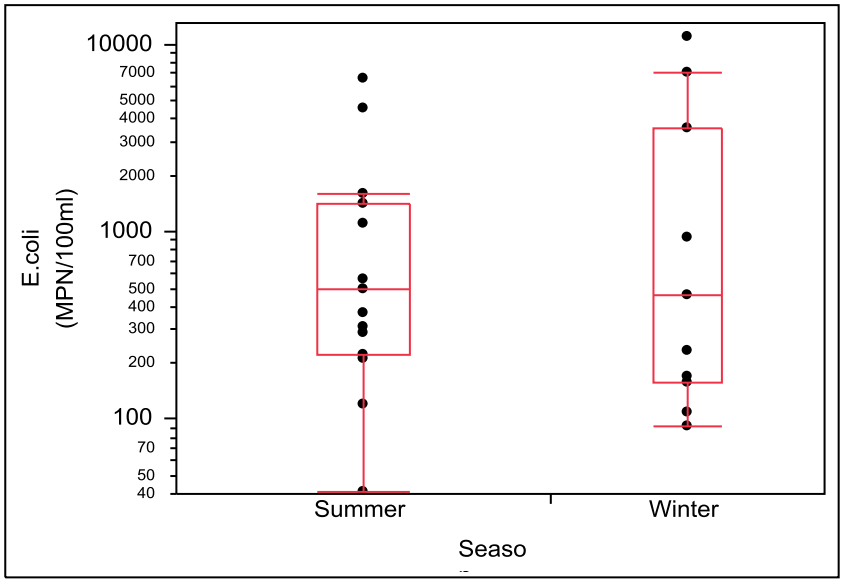


APPENDIX F

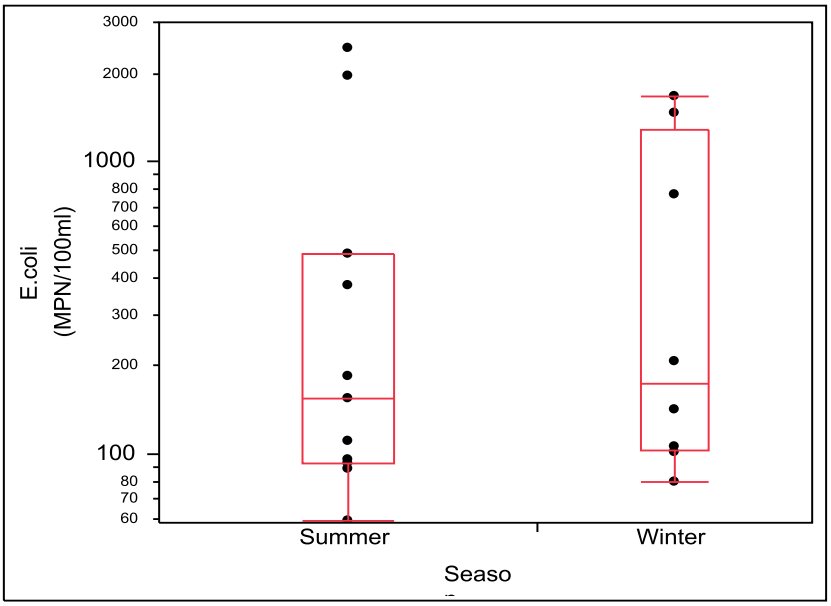
F.1 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11360 at Buffalo Bayou above Tidal on the SJR watershed.



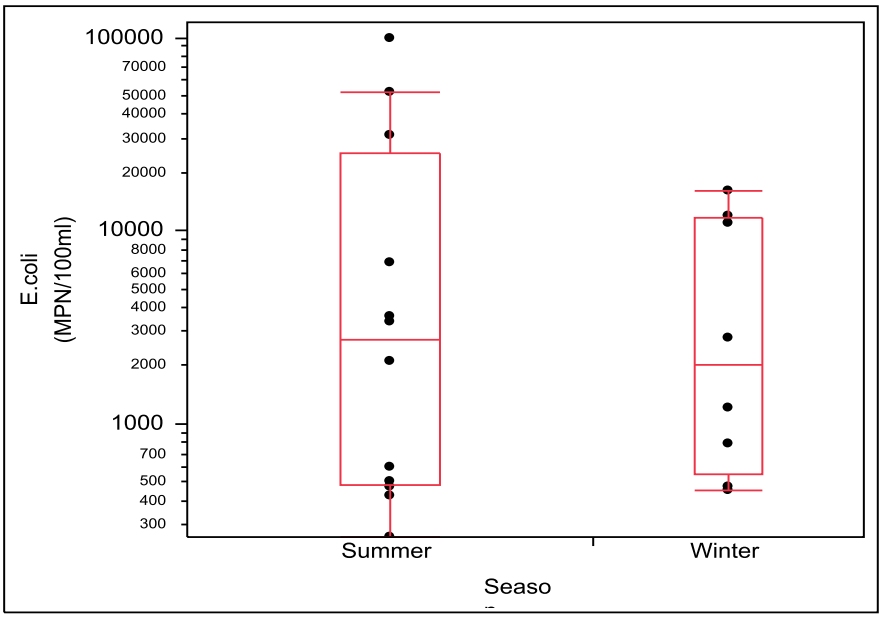
F.2 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11362 at Buffalo Bayou above Tidal on the SJR watershed.



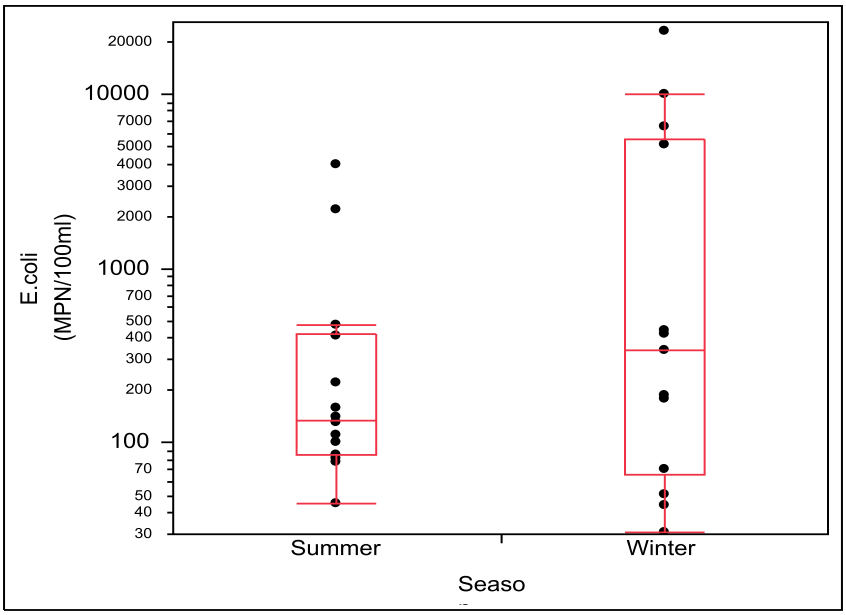
F.3 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 15846 at Buffalo Bayou above Tidal on the SJR watershed.



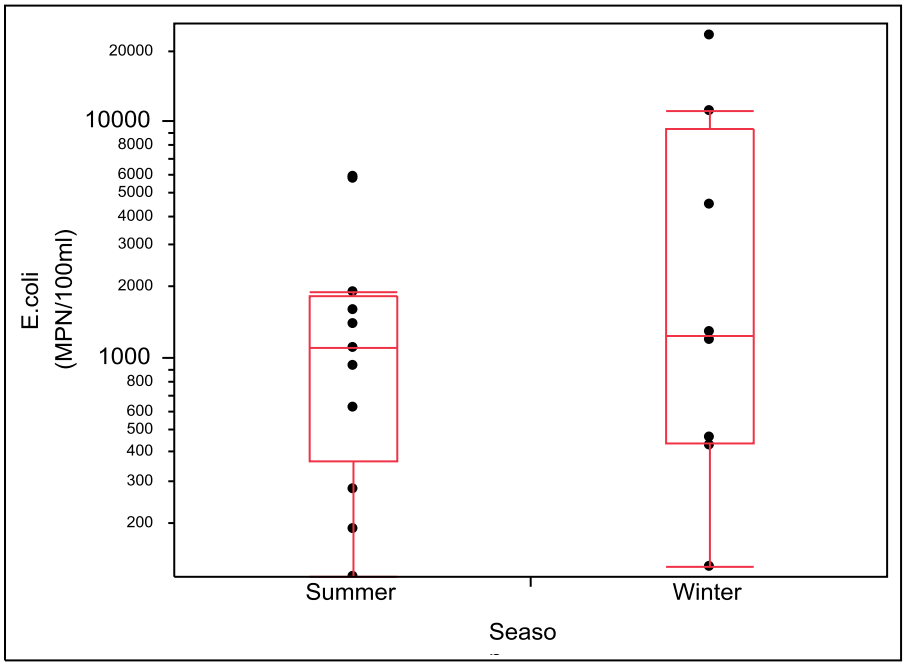
F.4 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 16648 at Buffalo Bayou Tidal on the SJR watershed.



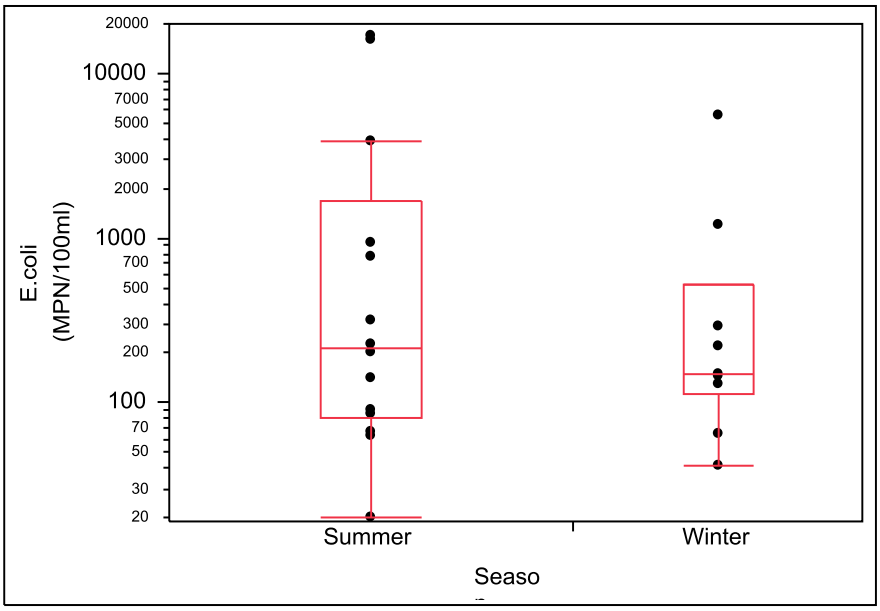
F.5 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11334 at Caney Creek on the SJR watershed.



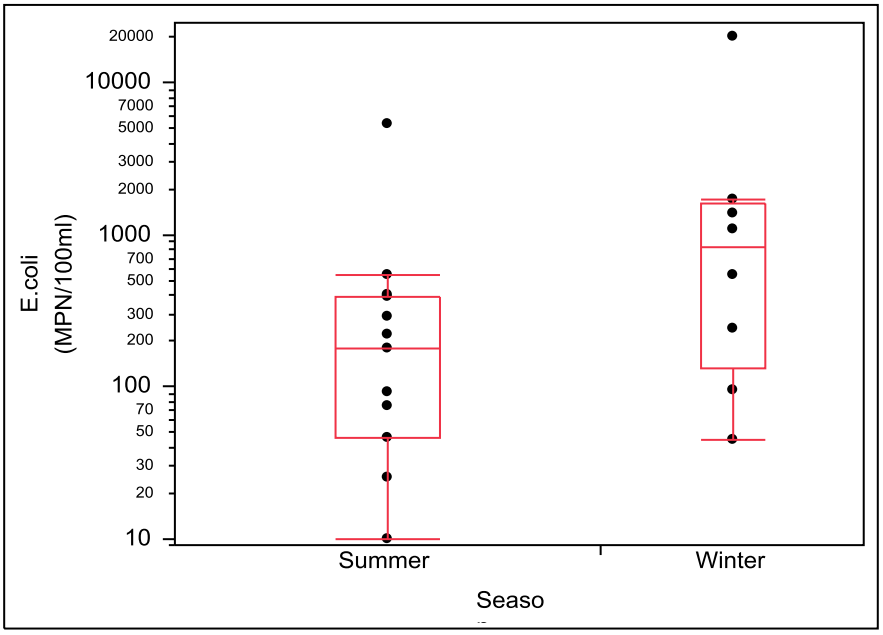
F.6 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11328 at Cypress Creek on the SJR watershed.



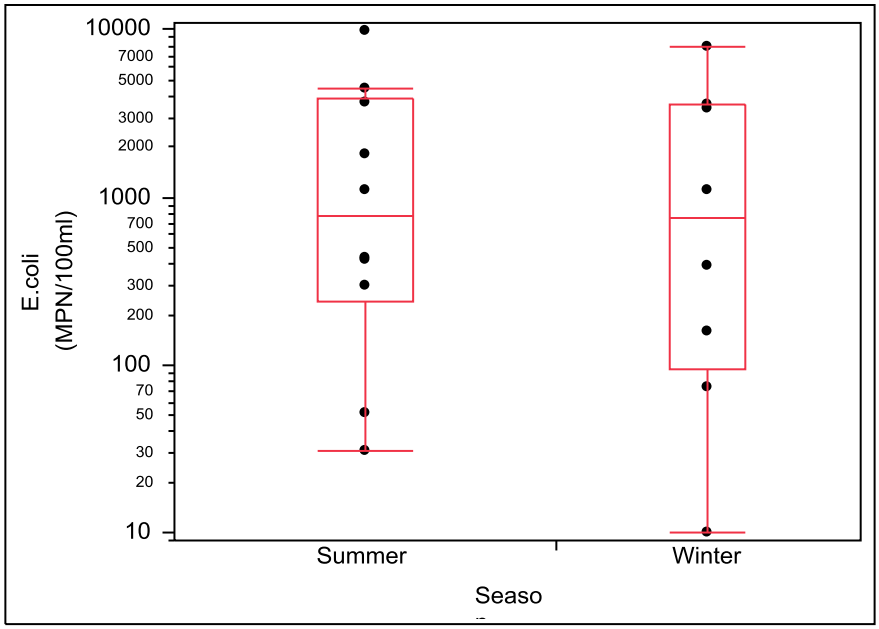
F.7 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11360 at Cypress Creek on the SJR watershed.



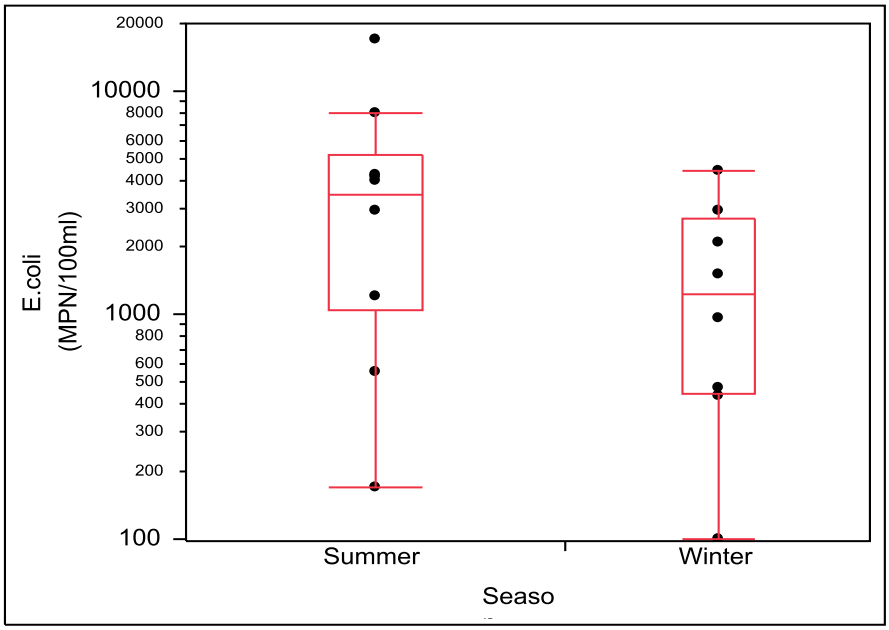
F.8 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11235 at East Fork San Jacinto on the SJR watershed.



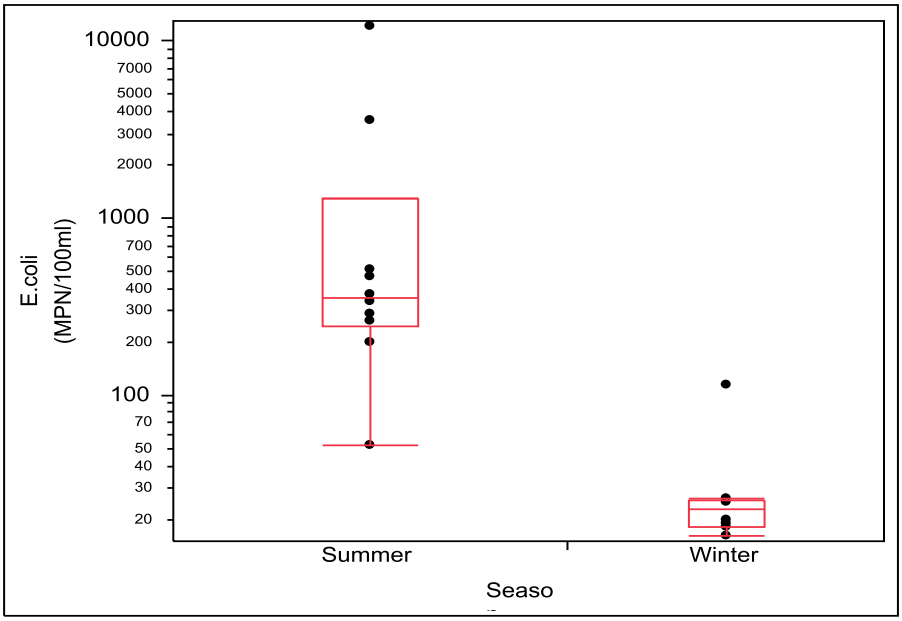
F.9 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11369 at Greens Bayou on the SJR watershed.



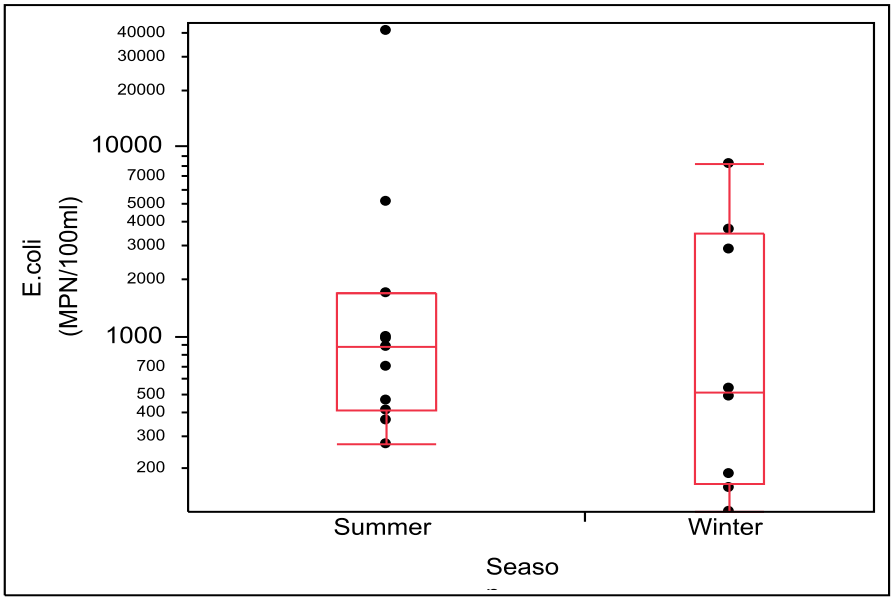
F.10 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11371 at Greens Bayou on the SJR watershed.



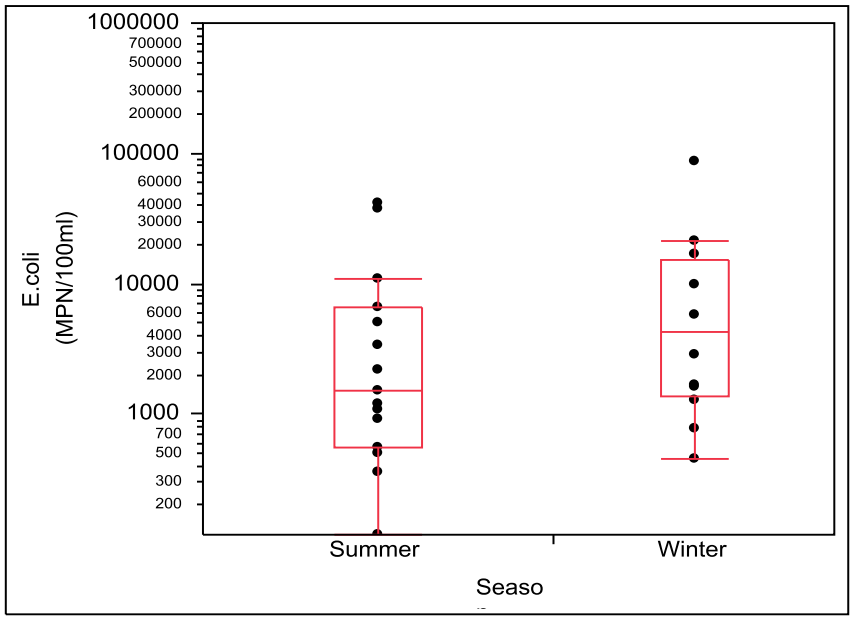
F.11 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11925 at Greens Bayou on the SJR watershed.



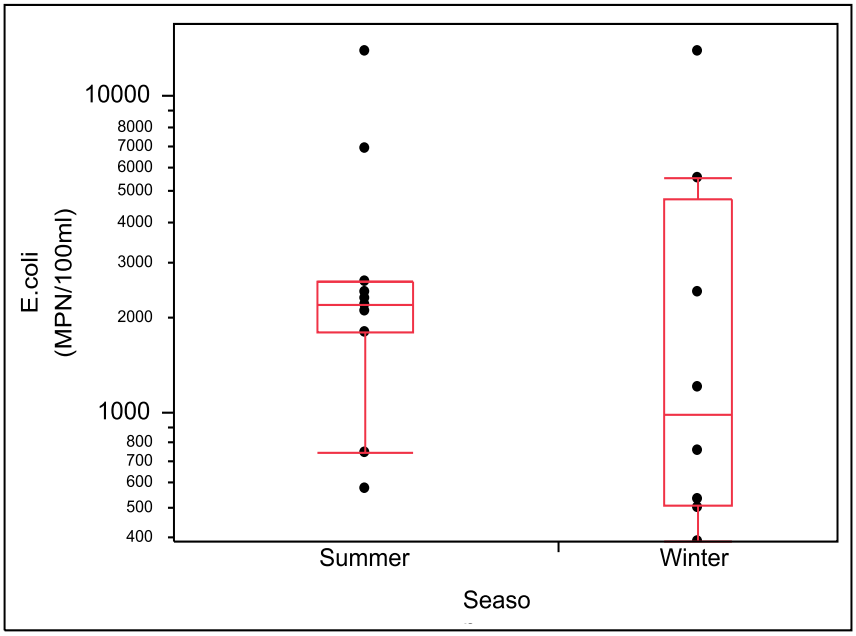
F.12 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11135 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed.



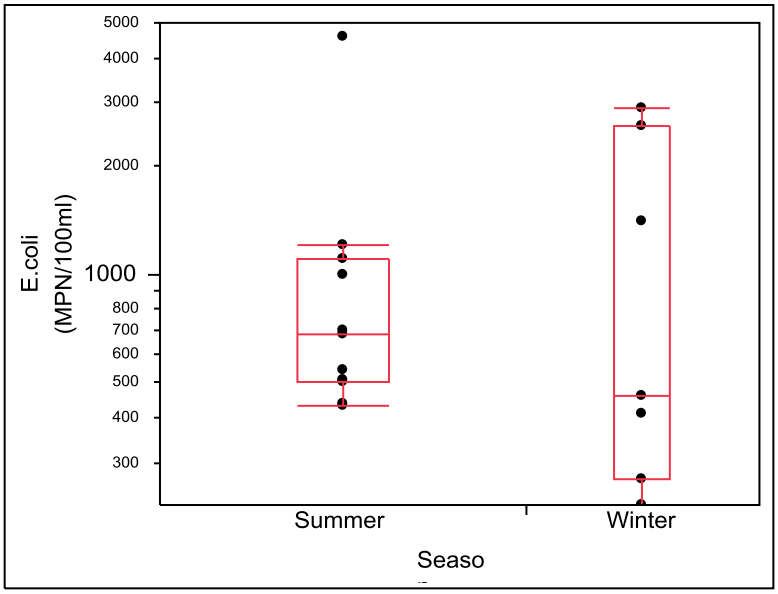
F.13 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11139 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed.



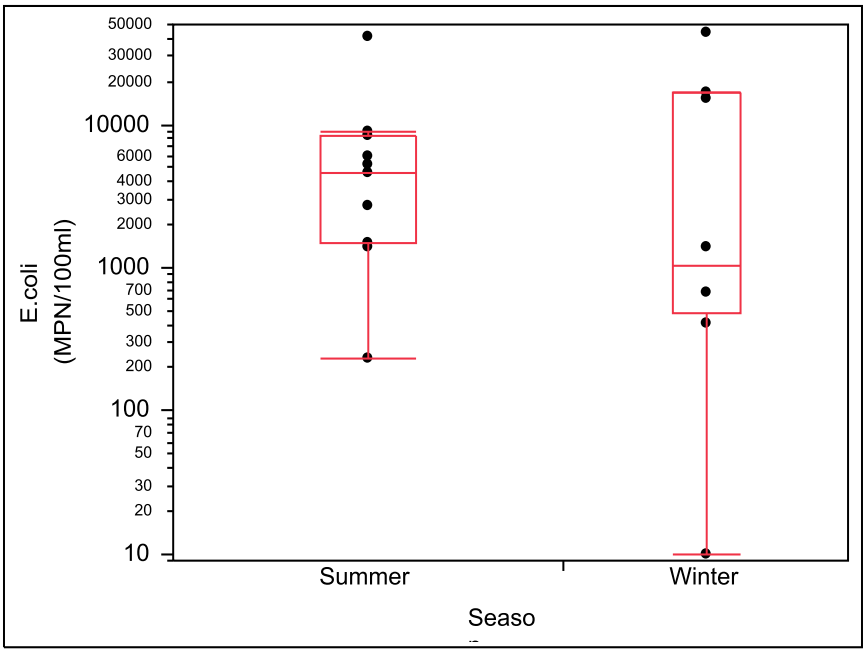
F.14 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11140 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed.



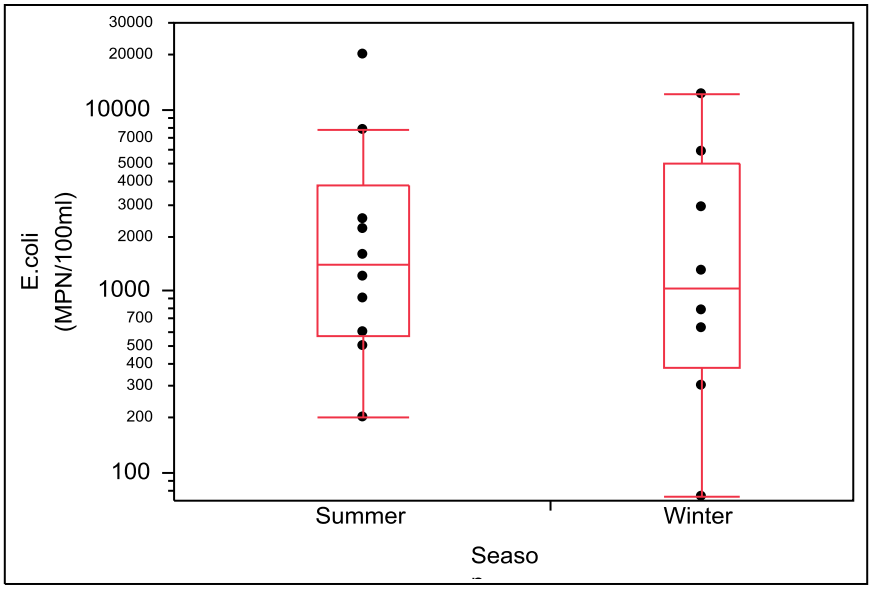
F.15 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 15851 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed.



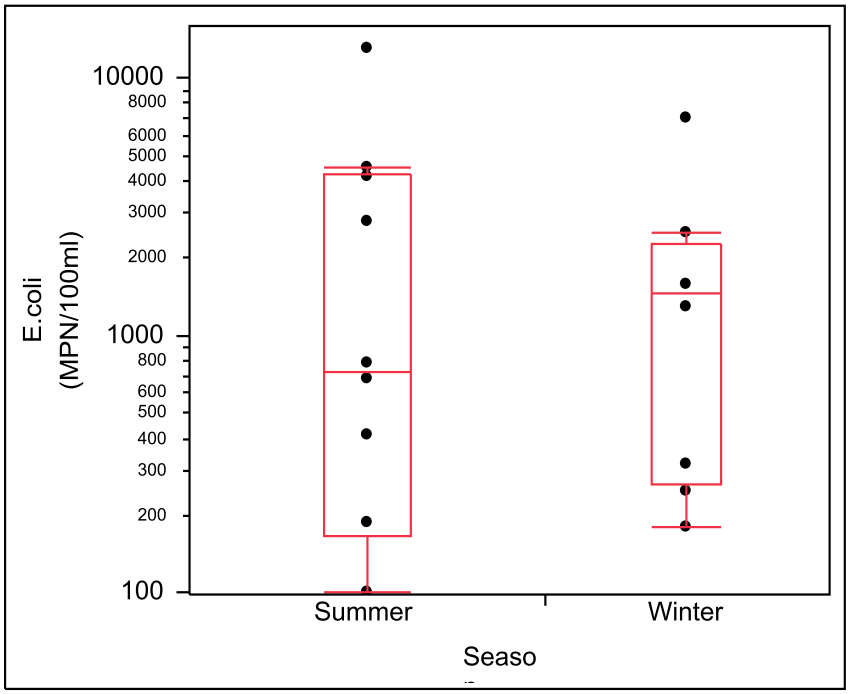
F.16 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 16661 at Houston Ship Channel-Buffalo Bayou Tidal on the SJR watershed.



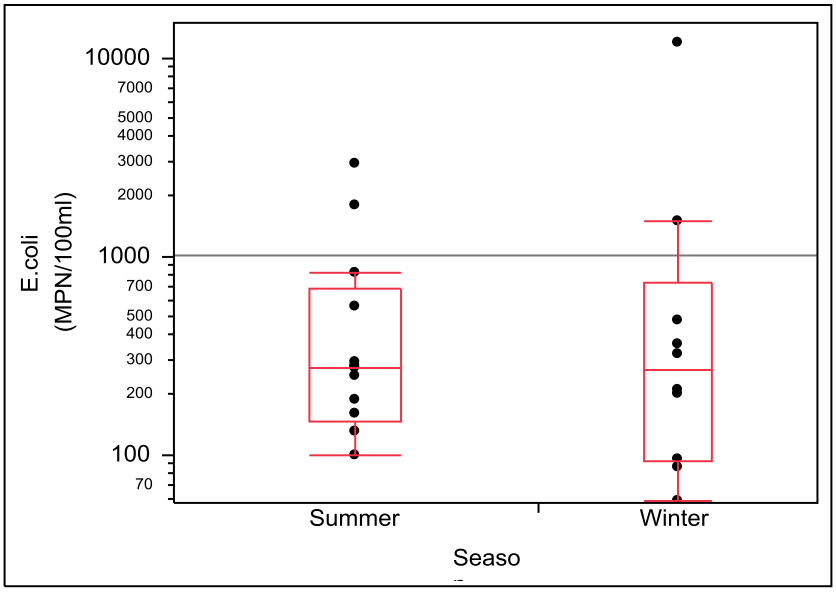
F.17 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11279 at Houston Ship Channel on the SJR watershed.



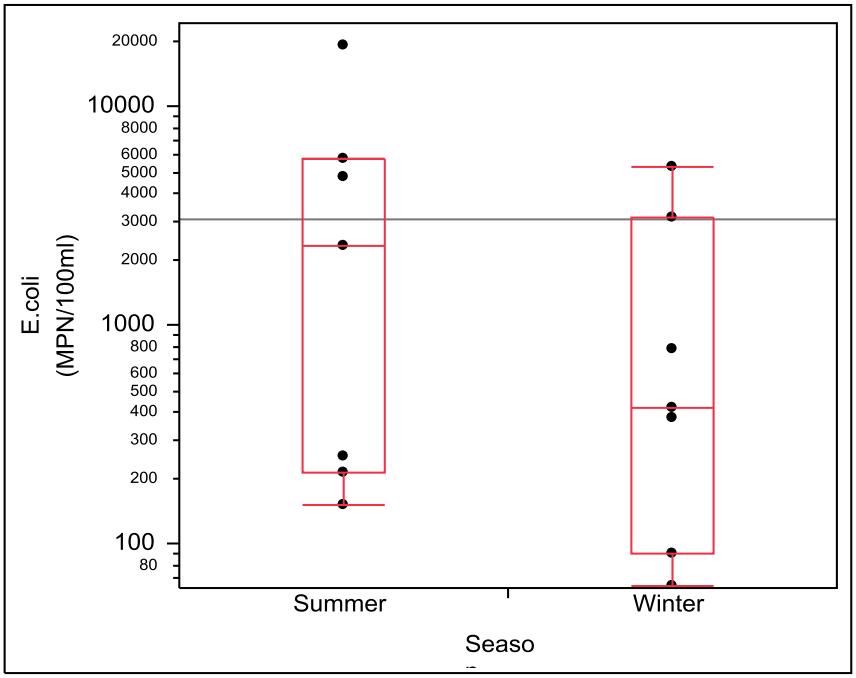
F.18 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 16665 at Houston Ship Channel on the SJR watershed.



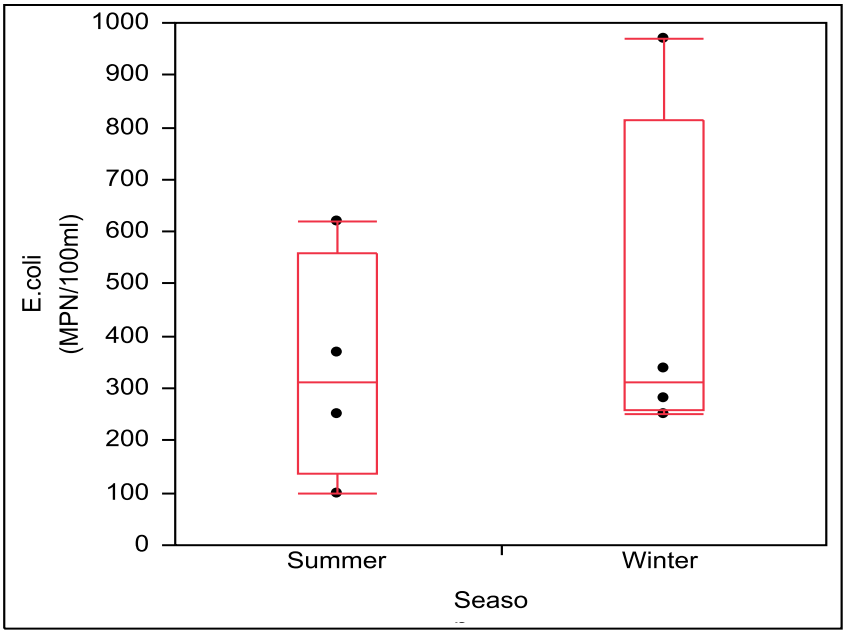
F.19 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11336 at Peach Creek on the SJR watershed.



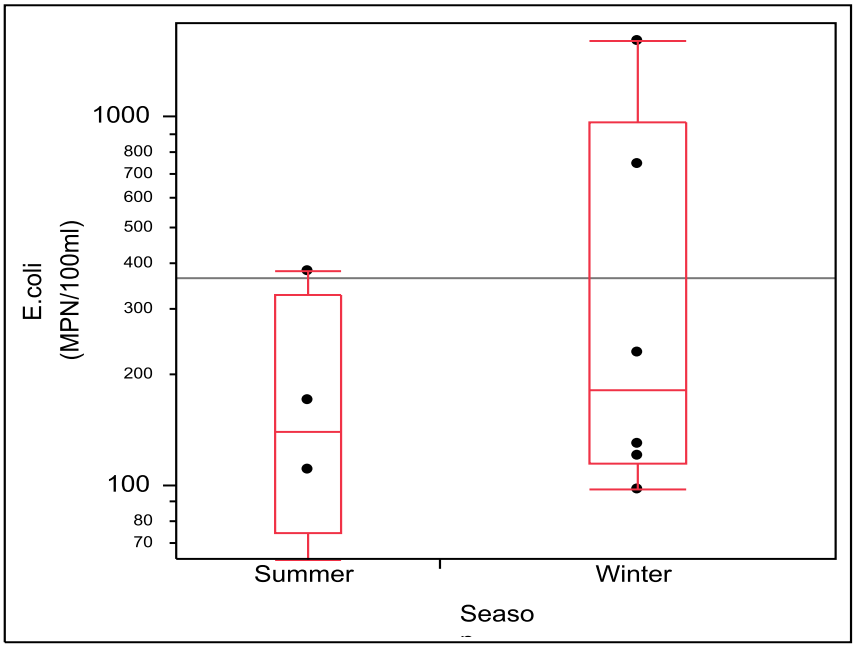
F.20 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11312 at Spring Creek on the SJR watershed.



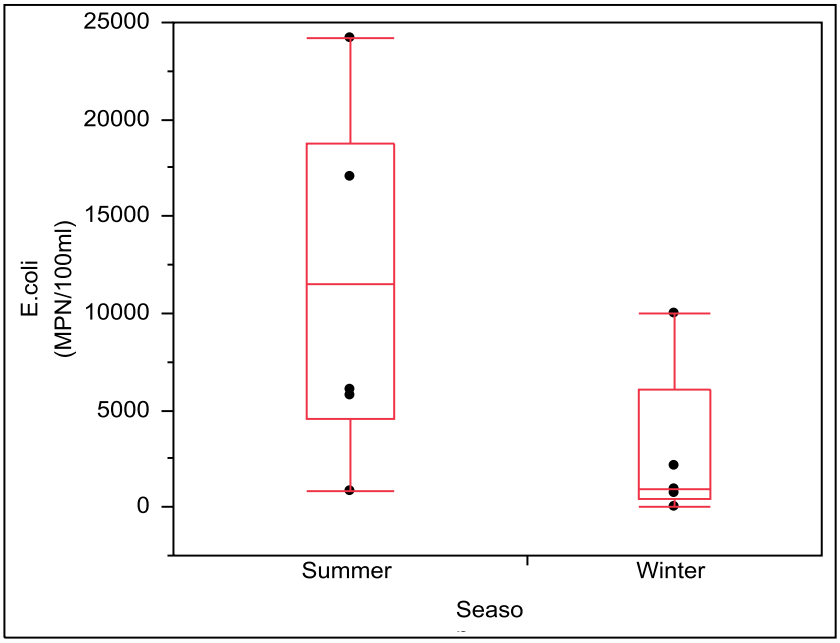
F.21 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11314 at Spring Creek on the SJR watershed.



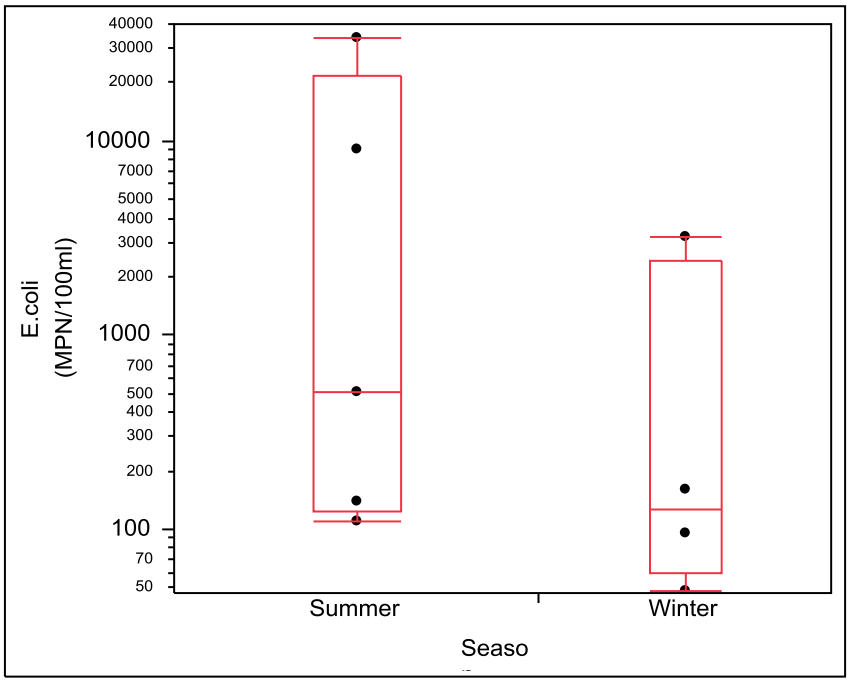
F.20 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11250 at West Fork San Jacinto on the SJR watershed.



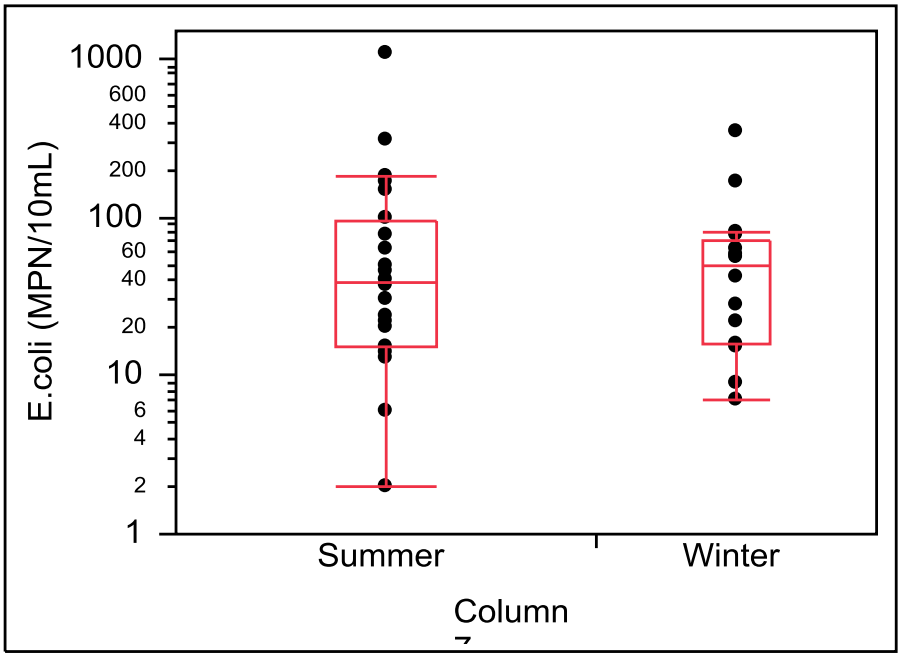
F.23 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11387 at White Oak Bayou on the SJR watershed.



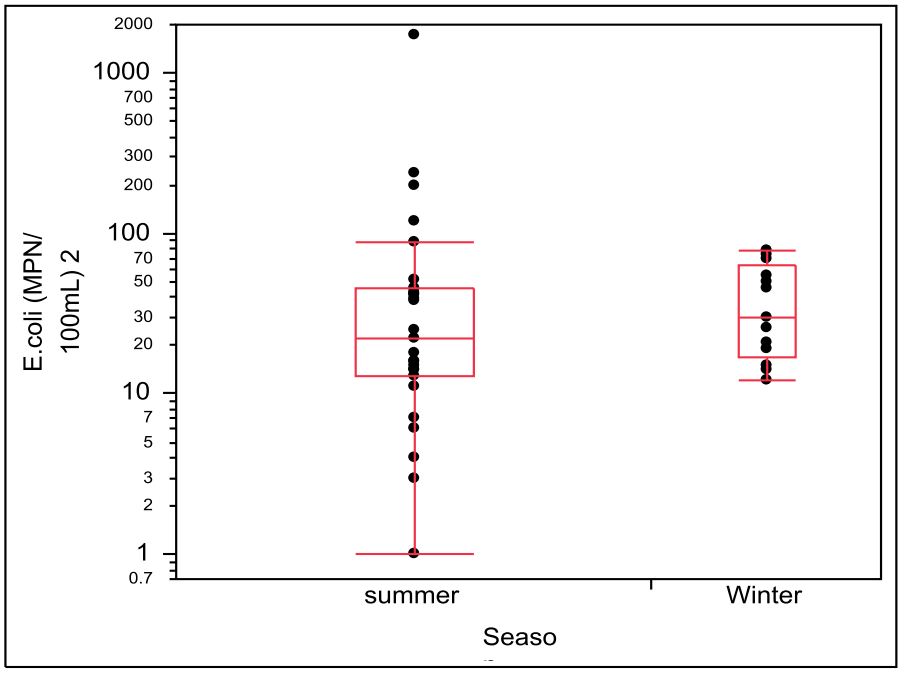
F.24 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11394 at White Oak Bayou on the SJR watershed.



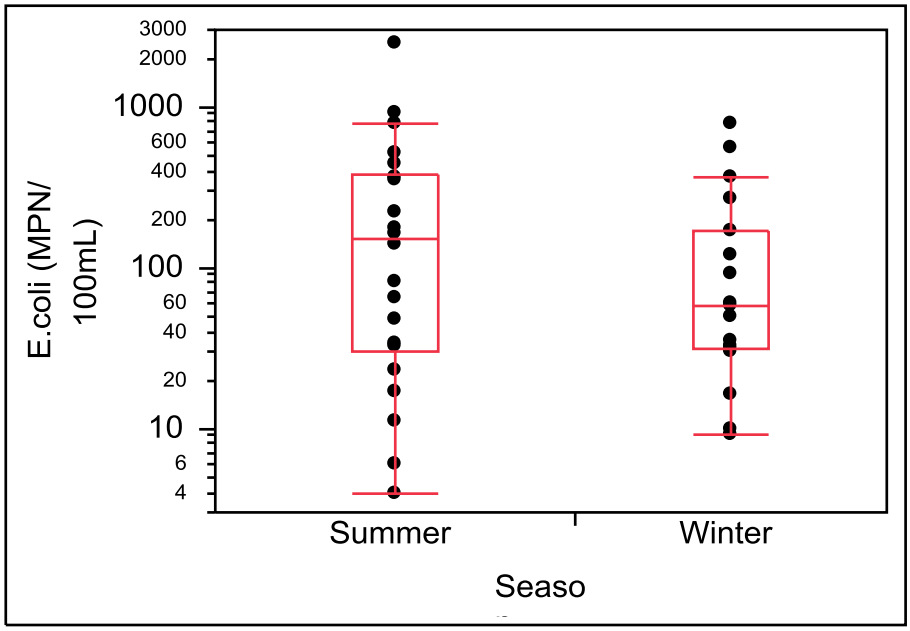
F.25 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11954 at North Bosque River on the Bosque River Watershed.



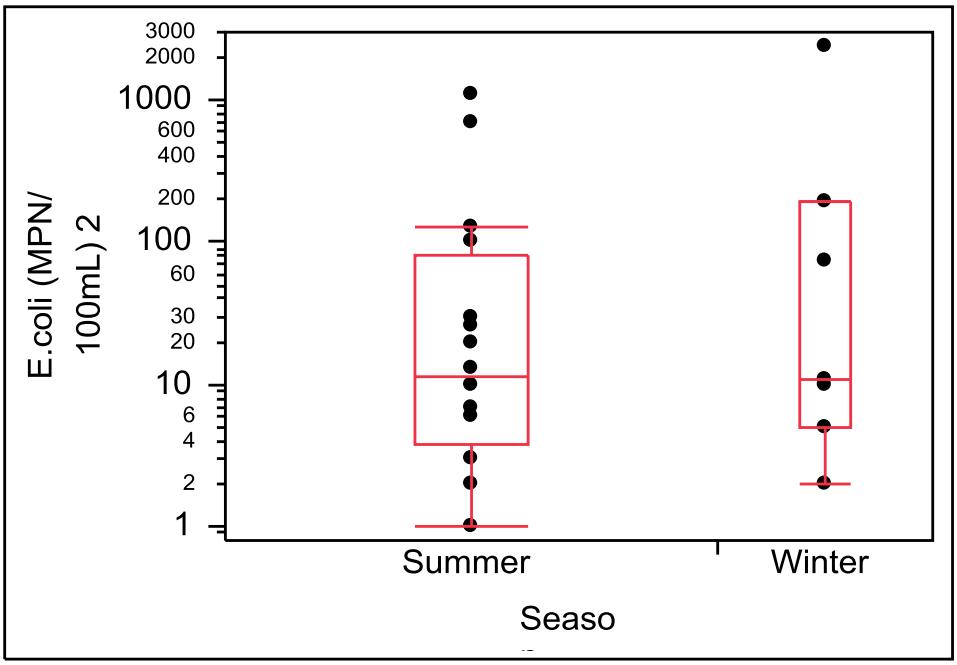
F.26 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11956 at North Bosque River on the Bosque River Watershed.



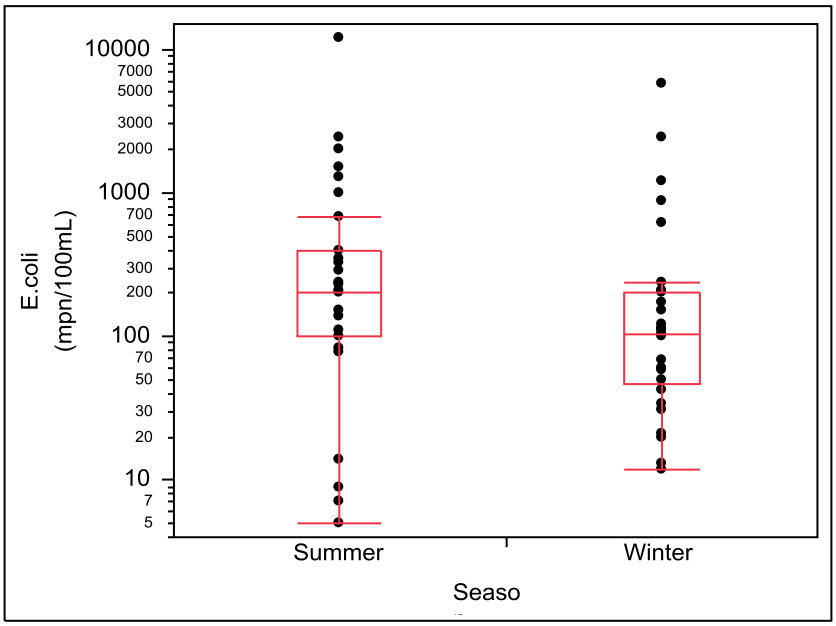
F.27 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11961 at North Bosque River on the Bosque River Watershed.



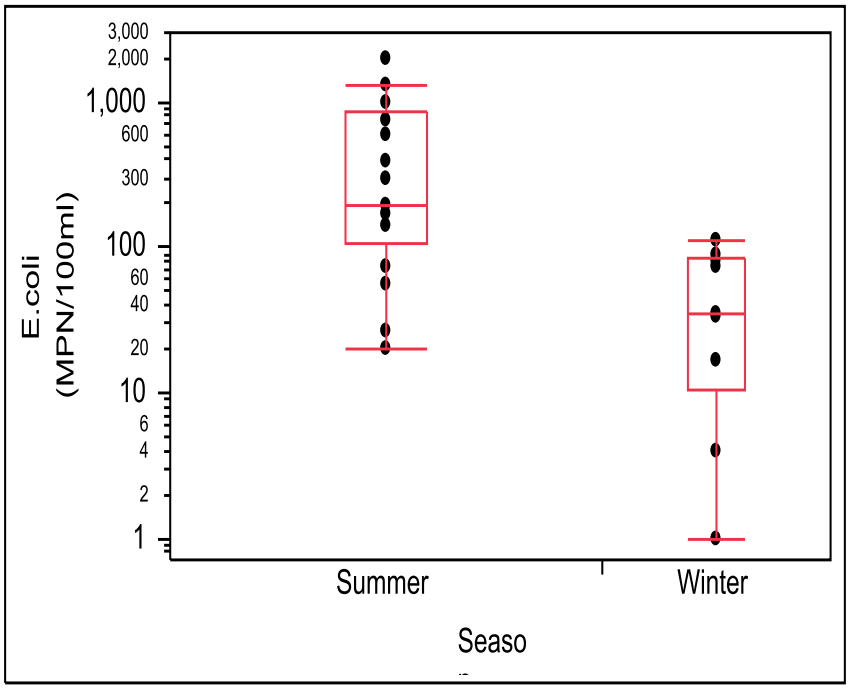
F.28 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17500 at North Bosque River on the Bosque River Watershed.



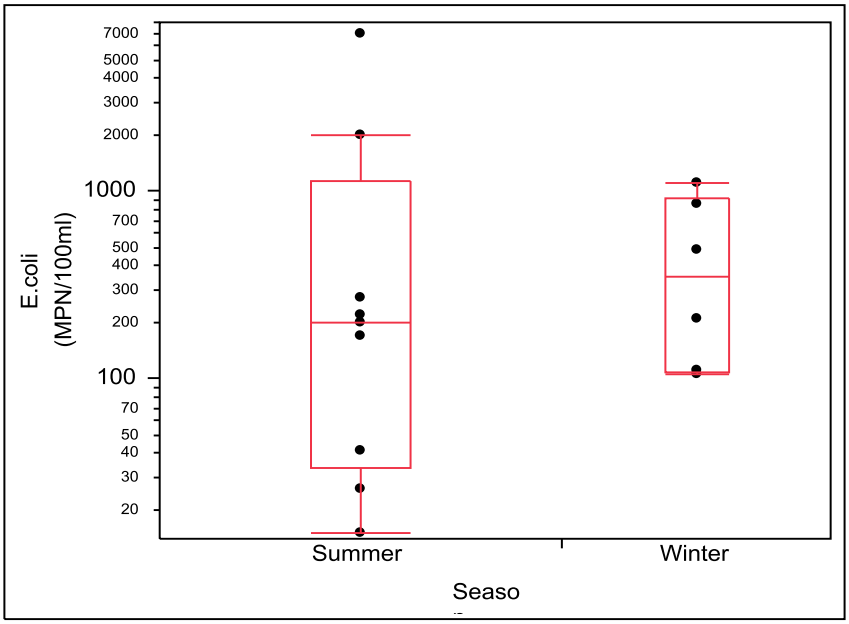
F.29 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17607 at Duffau Creek on the Bosque River Watershed.



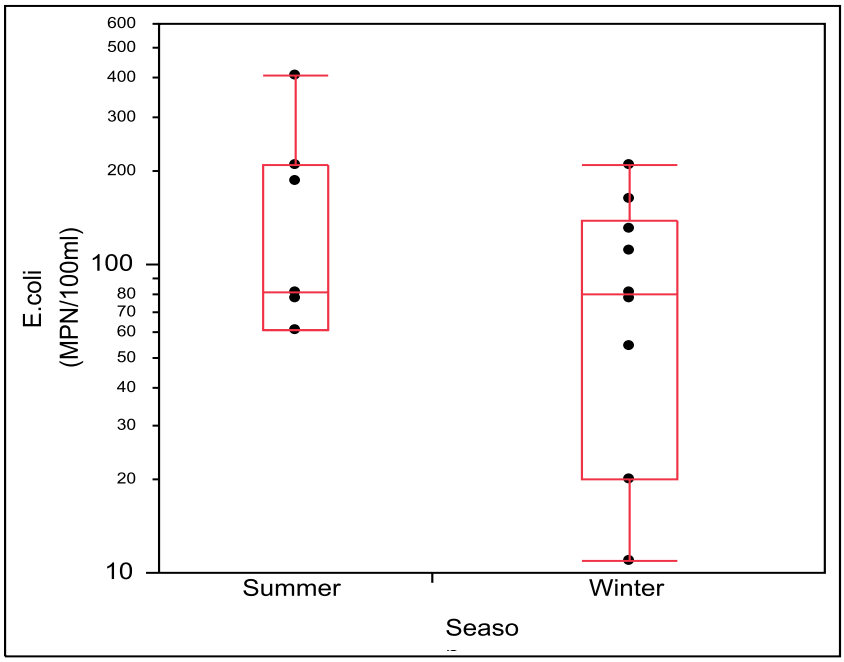
F.30 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 13486 at Green Creek on the Bosque River Watershed.



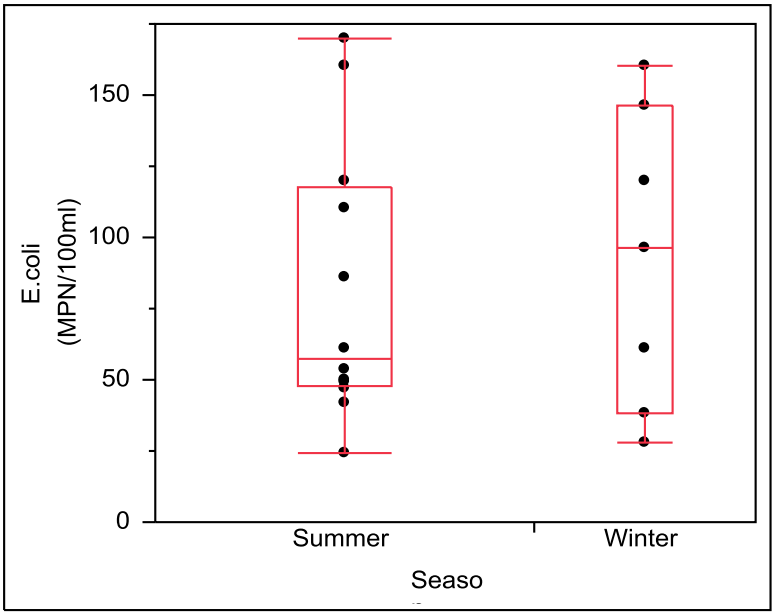
F.31 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17235 at Indian Creek on the Bosque River Watershed.



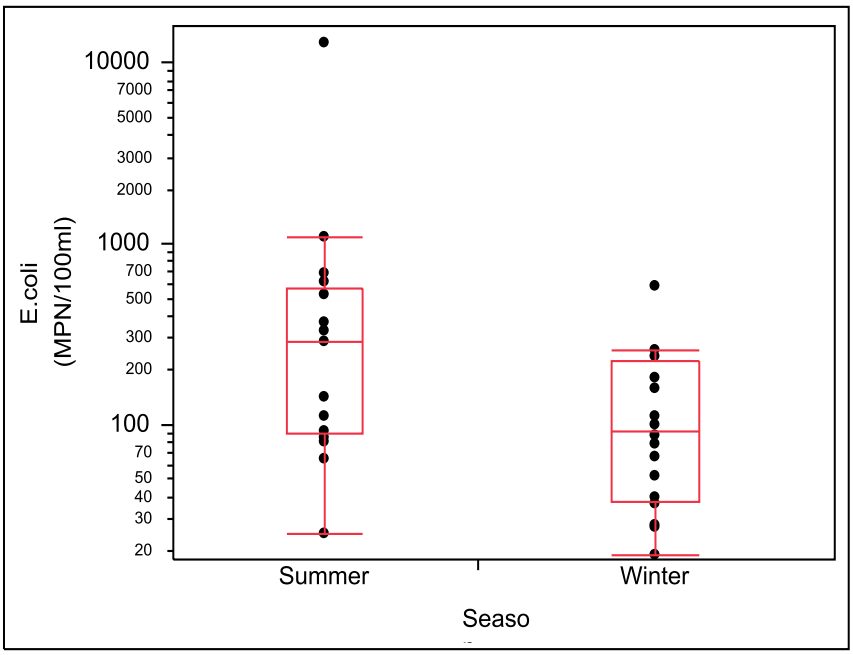
F.32 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 20308 at Middle/South Bosque River on the Bosque River Watershed.



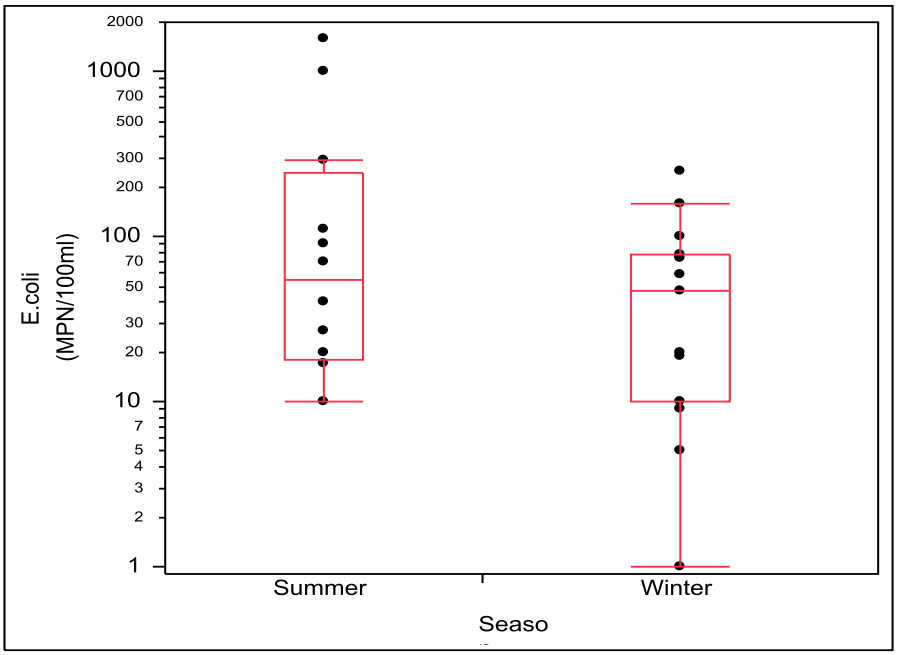
F.33 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11826 at Neils Creek on the Bosque River Watershed.



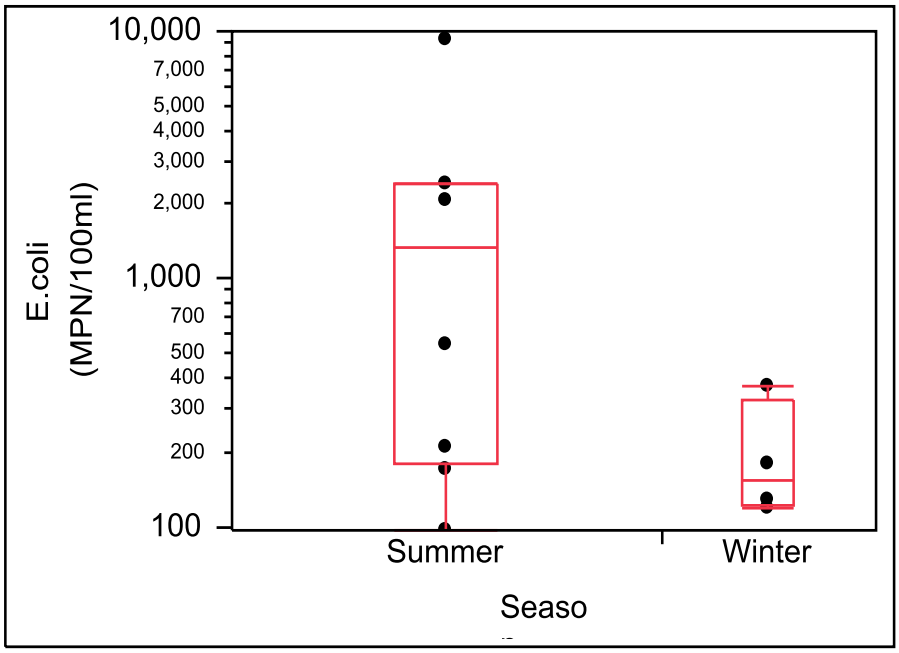
F.34 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17607 at Sims Creek on the Bosque River Watershed.



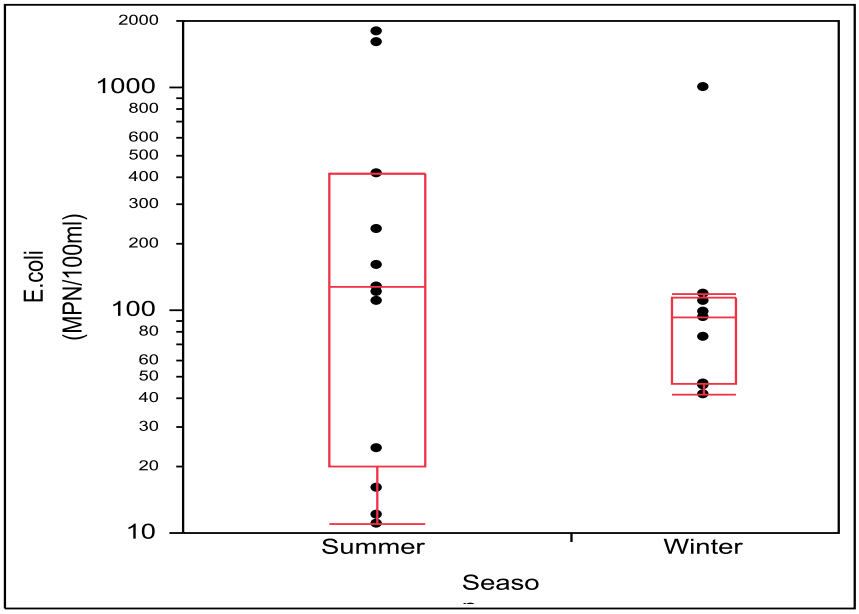
F.35 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17242 at Spring Creek on the Bosque River Watershed.



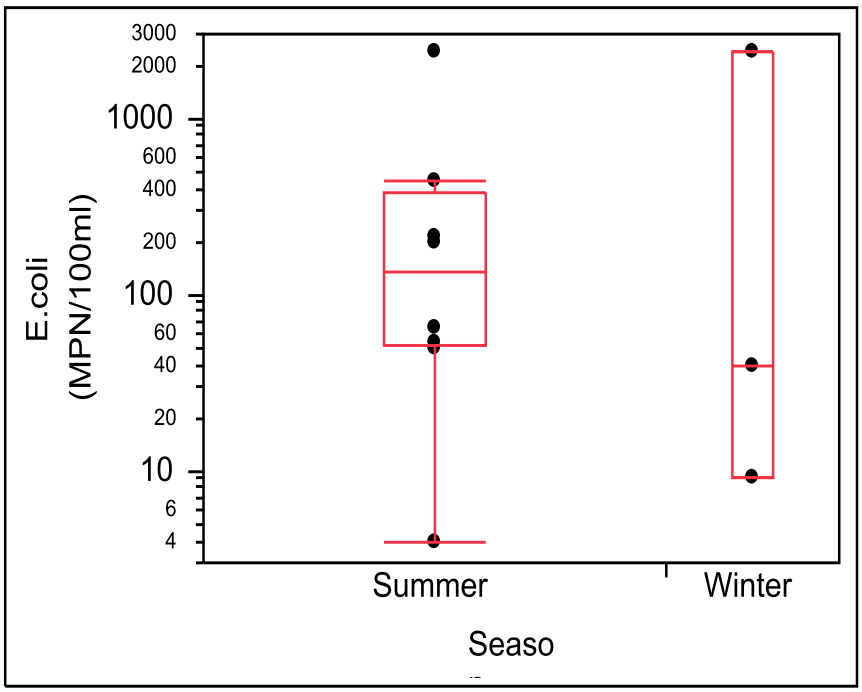
F.36 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17544 at Duncan Creek on the Leon River Watershed.



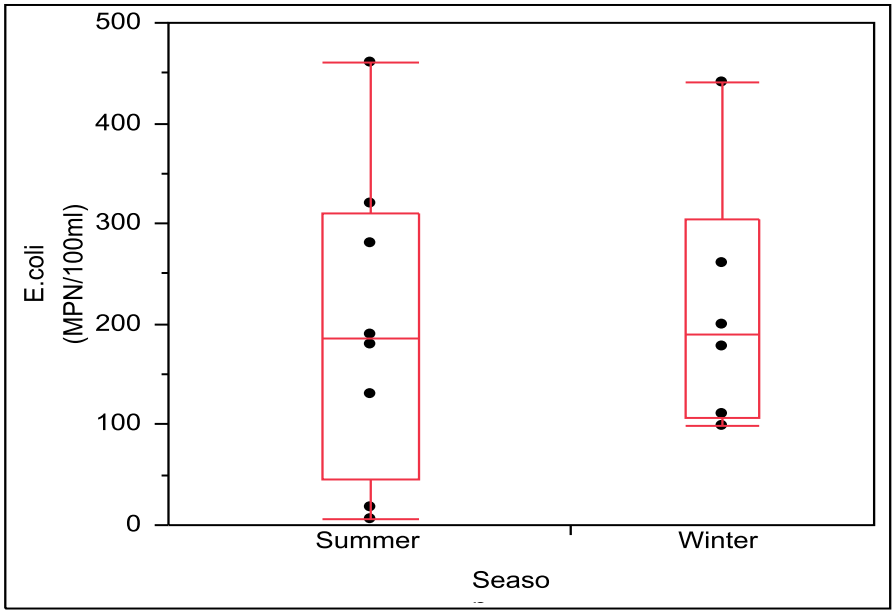
F.37 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11925 at Leon River below Proctor Lake on the Leon River Watershed.



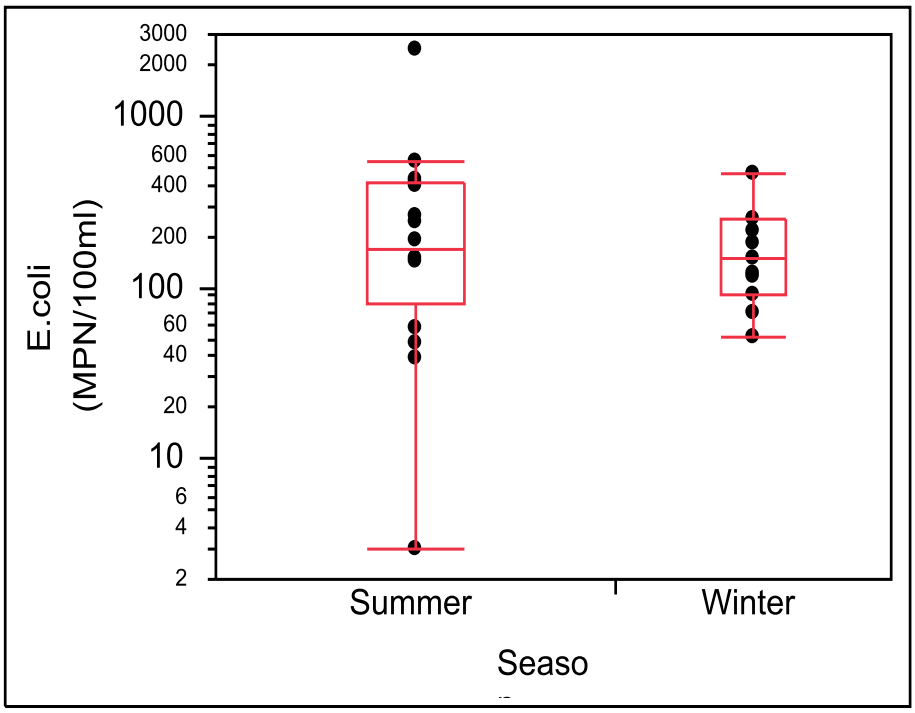
F.38 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11930 at Leon River below Proctor Lake on the Leon River Watershed.



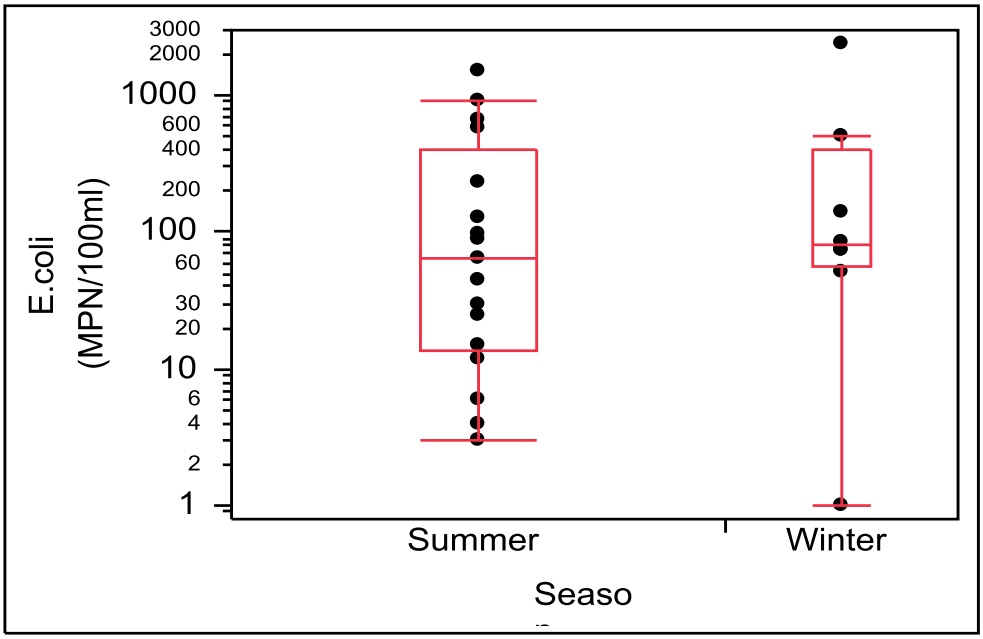
F.39 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11934 at Leon River below Proctor Lake on the Leon River Watershed.



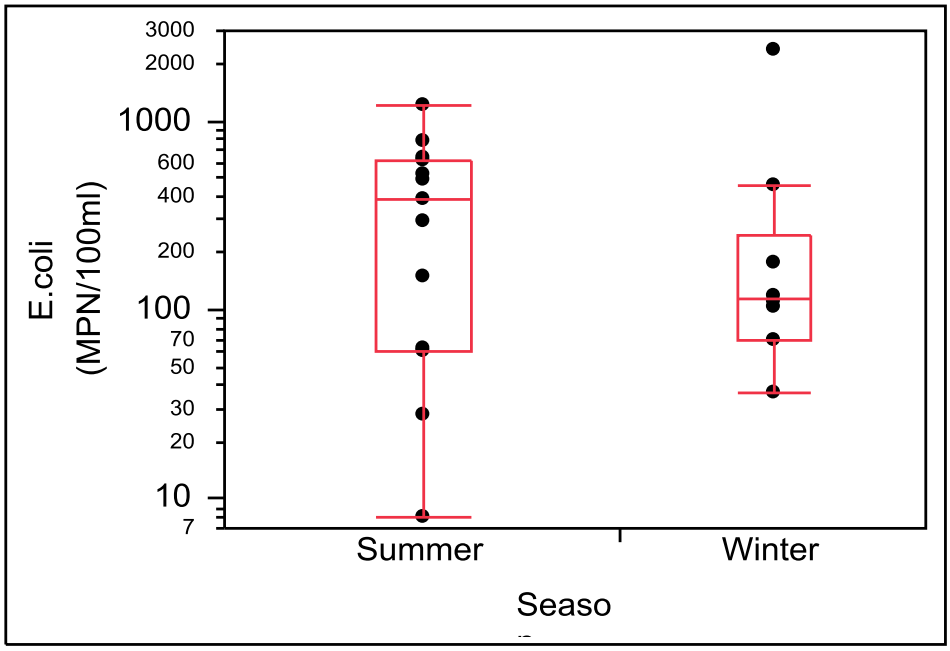
F.40Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 15769 at Leon River below Proctor Lake on the Leon River Watershed.



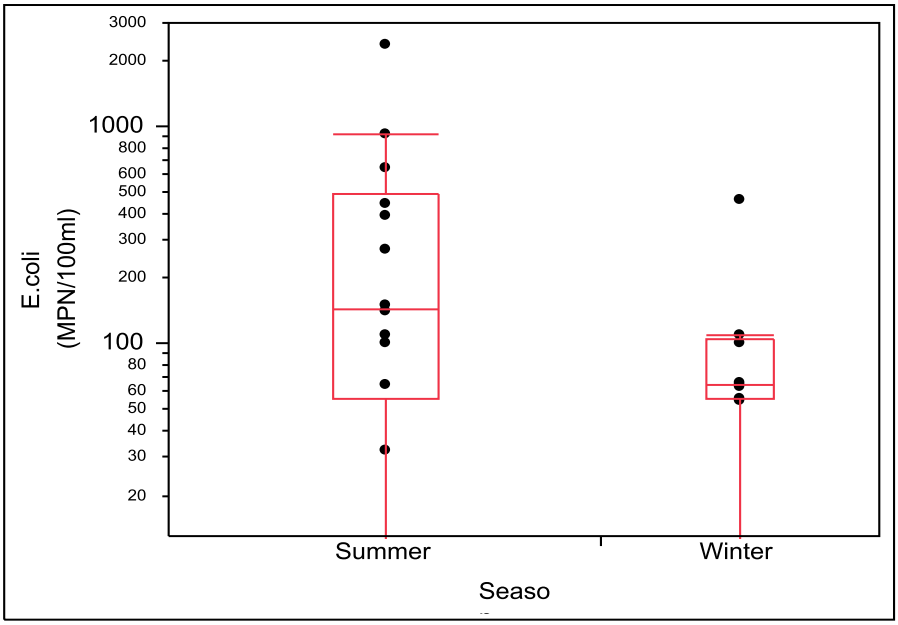
F.41 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17501 at Leon River below Proctor Lake on the Leon River Watershed.



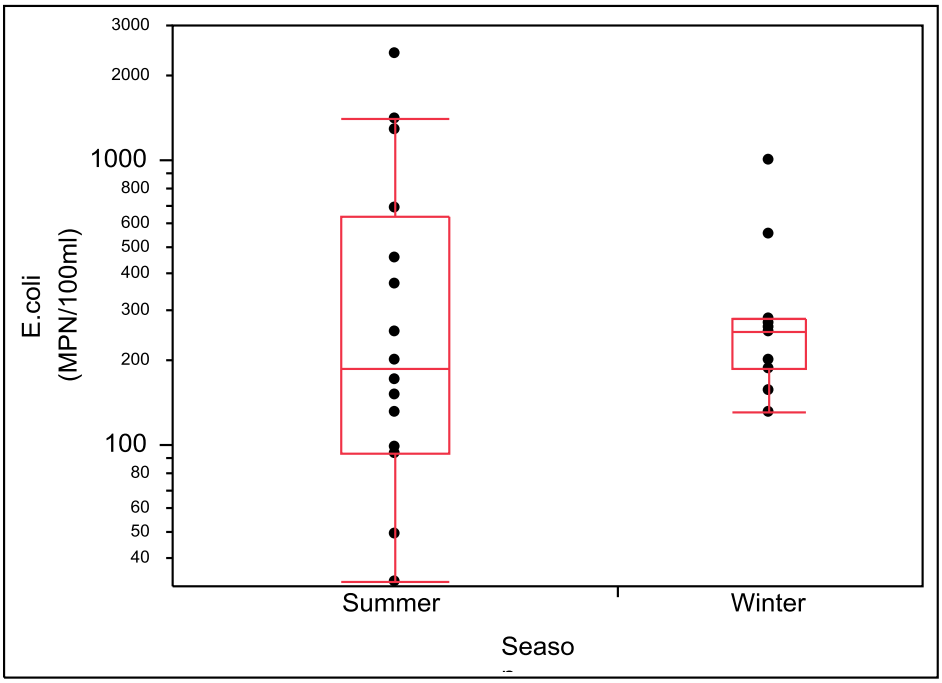
F.42 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17545 at Leon River below Proctor Lake on the Leon River Watershed.



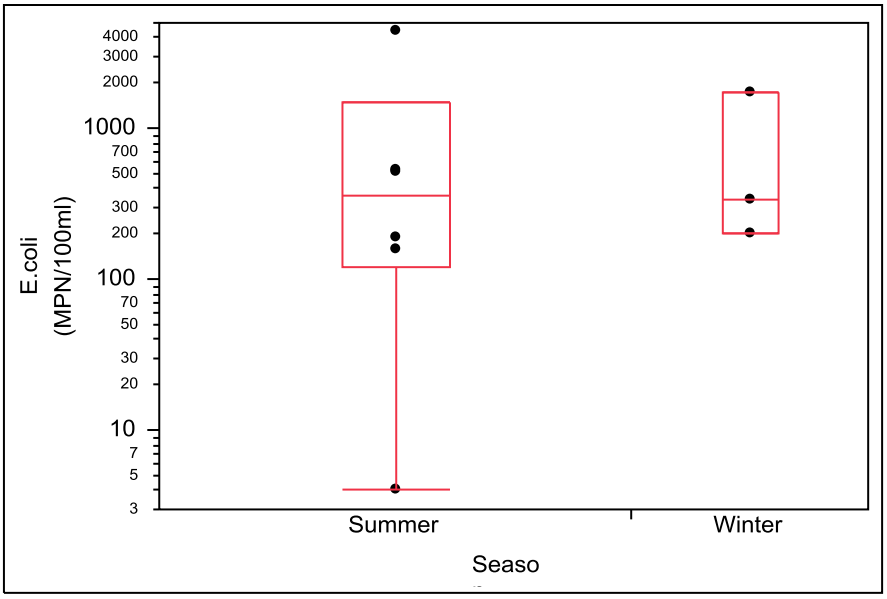
F.43 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 18781 at Leon River below Proctor Lake on the Leon River Watershed.



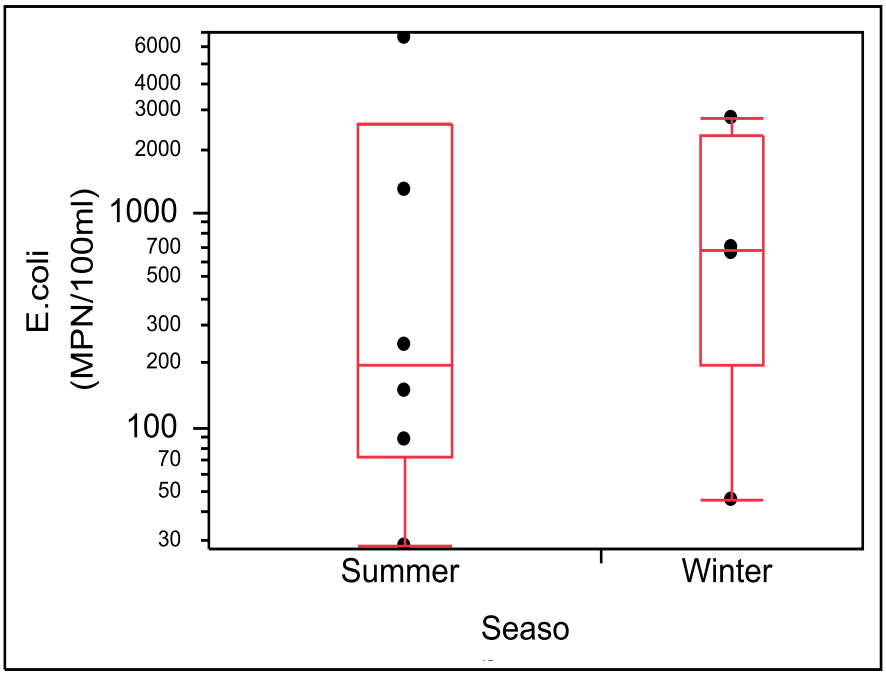
F.44 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17591 at Leon River below Proctor Lake on the Leon River Watershed.



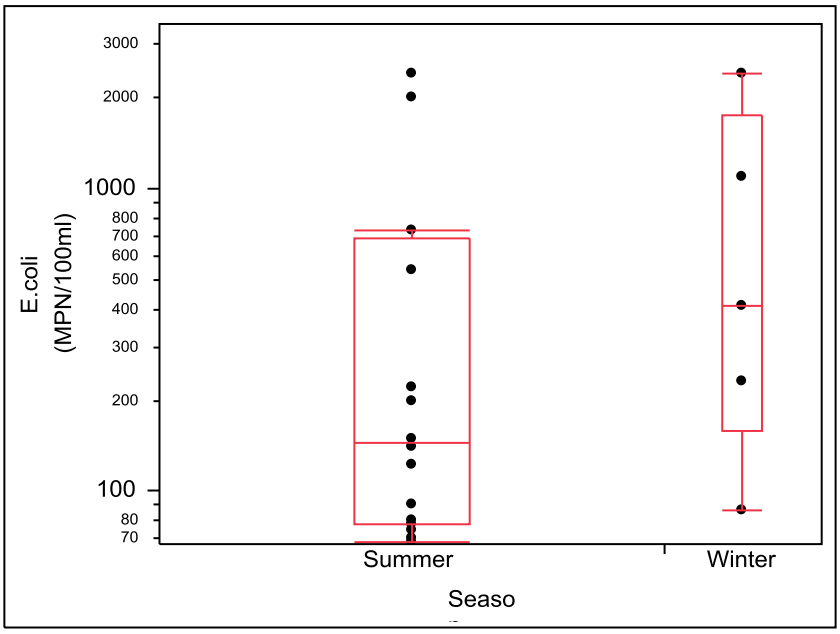
F.45 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 11938 at Leon River below Leon Lake on the Leon River Watershed.



F.46 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17376 at Resley Creek on the Leon River Watershed.



F.47 Box-Plots showing difference in *E.coli* concentrations observed between the summer and winter months for monitoring station 17377 at Resley Creek on the Leon River Watershed.



VITA

Name	Sriambharrish Srinivasan Ravichandran
Address	Department of Civil Engineering 3136 TAMU College Station, Texas 77843-3136
Email	ambarish.ravi@gmail.com

Education	M.S., Civil Engineering, Texas A&M University, 2011
	B.Tech., Civil Engineering, Visvesvaraya National Institute of Technology, Nagpur, India, 2008