LOADING AND ATTENUATION OF FECAL INDICATOR BACTERIA IN EMIGRATION CREEK

by

Garrick Douglas Willden

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of a thesis submitted by

Garrick Douglas Willden

This thesis has been read by each member of the following supervisory committee and by majority vote has been found to be satisfactory.

3/21/06 — Chair: Steven J. Burian

3/21/06 — Donald F. Hayes

3-21-06 — P.K. Andrew Hong

03-21-06 — William P. Johnson

ABSTRACT

A two-part study was performed in Emigration Creek from June to October 2005 to determine the warm season loading and concentration variability of fecal-indicator bacteria and investigate the fate and transport of bacteria within Emigration Creek. Emigration Creek is a small mountain stream draining a 47-km^2 urbanizing drainage basin into the Salt Lake City metropolitan area. The warm season monitoring component of the protocol involved measuring streamflow and collecting weekly grab samples from eight locations in the creek for 16 weeks and analyzing for bacteriological and chemical fecal-indicators including total coliform, *E. coli*, enterococci, nitrate, chloride, and ammonia. Samples were collected and flows were measured twice daily to capture diurnal variation of the concentrations and bacteria flux (the number of bacteria passing each sampling site in time). The bacterial fate and transport component of the study involved introducing a bacteria tracer into an upstream reach of the creek in early October and collecting samples downstream to monitor the bacteria breakthrough curve over a period of 2 days. The results of the warm season monitoring indicated that most of the sampling sites exceeded the Utah numeric water quality criteria for *E. coli* (new bacteriological criterion, 206 No./100mL) from July to mid August. Total coliform, *E. coli*, and enterococci concentrations along with the pH and temperature exhibited a diurnal pattern with the morning sampling event being higher than the afternoon for all except temperature. The bacteria tracer results indicated that the attenuation of bacteria

in Emigration Creek during low flows was much greater that previously published loss rates have indicated. The dominant mechanism of bacteria attenuation was hypothesized to be attachment to materials (e.g., vegetation, channel bottom and sides), filtration, and predation. To synthesize the results of the warm season monitoring and the bacteria tracer a simple model was used. Results from this model indicated that bacterial loadings along Emigration Creek varied spatially and temporally and were likely greater than just the difference in flux from sampling site to sampling site observed throughout the warm season monitoring.

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CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Impairment of water bodies due to fecal contamination is of great concern nationally due to the consequences associated with public health, impacts to waterbody biota, and degradation of the overall usefulness of the water resource. Specifically, fecal pollution in concentrated levels can, if contacted, lead to gastrointestinal illnesses in humans due to the presence of pathogenic bacteria, and in addition, increase nutrient concentrations (such as nitrate and phosphorus) causing excessive growth of algae which decreases the vital dissolved oxygen required by aquatic life. The United States Environmental Protection Agency (USEPA) found that bacteria (an indicator of fecal contamination) were the leading pollutant in rivers and streams nationwide (U.S. EPA 2000).

There have been several studies demonstrating the impact of fecal-contamination (observed using indicator bacteria) of recreational waters on human health. Most telling, are the epidemiological studies that have examined the relationship between swimming-associated illness (namely, acute gastrointestinal illness) and the microbiological quality of the waters used by recreational bathers (U.S. EPA, 1986 and Haile et al., 1996). These studies showed a positive correlation between

reported illnesses and observed indicator bacteria concentrations. Further, the 1986 USEPA study demonstrated that fecal coliforms, the indicator originally recommended in 1968 by the Federal Water Pollution Control Administration of the Department of the Interior, are correlated less strongly with swimming-associated gastroenteritis than other possible indicator organisms. Two indicator organisms, *E. coli* and enterococci, exhibited a strong correlation to swimming-associated gastroenteritis, the former in fresh waters only and the latter in both fresh and marine waters (U.S. EPA, 2004). The realization of this correlation has motivated the EPA to urge States to adopt *E. coli* and enterococci into their regulatory water quality criteria.

Utah is one of the states that have recently transitioned to the use of *E. coli* as the fecal-indicator bacteria for regulatory purposes. An important water body in the Salt Lake metropolitan area coming under scrutiny for bacteriological water quality violations is Emigration Creek. The bacteriological water quality of Emigration Creek has been evaluated by two Salt Lake County studies (Jensen et al., 2003; Glenne and West, 1981). Results from the Salt Lake County studies showed high levels of pathogenic indicator bacteria, specifically fecal and total coliforms. The observed levels of fecal coliform exceeded the Utah 2005 bacteriological numeric criteria (Utah Division of Administrative Rules, 2005) for domestic, recreation and agricultural uses for Class 2B (secondary contact recreation) waters (Jensen et al., 2003). The exceedance resulted in Emigration Creek being placed on the State 303(d) list of impaired waters (Utah Department of Environmental Quality, 2006). After this thesis study was underway the Utah Department of Environmental Quality changed the bacteriological numeric criteria for waters from a combination of total and fecal

coliforms to solely *E. coli* (Utah Division of Administrative Rules, 2006) as suggested by the U.S. Environmental Protection Agency (U.S.EPA, 1986). It was assumed that if the current water quality standards for Emigration Creek were being exceeded, namely the fecal coliform limit of 200 fecal coliforms per 100 mL, then the new criteria for the maximum allowable *E. coli* concentration (206 per 100 mL for class 2B watersheds) would also be exceeded; thus the listing on the current 303(d) list.

In addition to the high concentration of fecal coliforms in Emigration Creek, counterintuitive observations were noted by Jensen et al. (2003). They found bacteria concentrations in the upper reach to be higher than downstream locations even though likely urban sources (e.g., septic system effluent) of fecal contamination are concentrated in the central part of the creek length. Further, a large increase in total coliform flux (number of bacteria passing a point reported in billions per day) was observed by Glenne and West (1981) with dually noted decreasing flows and fluxes in downstream reaches possibly attributed to infiltration to subsurface and recharge to groundwater flow in the vicinity. These observations have not been sufficiently studied to substantially define the quantity and type of bacteriological loadings within Emigration Creek especially with respect to *E. coli*. More generally, the understanding of bacteria loadings in complex mountainous terrain exposed to urbanization in the Salt Lake Valley and elsewhere in the intermountain west and the fate and transport of bacteria in streams is not well defined.

1.2 Research Motivation

The research objectives of this study were designed to encompass the three issues described above, namely to determine the concentration of *E. coli*, to elucidate the counterintuitive bacteria flux results, and to better define the general bacteriological attenuation dynamics in mountain streams traversing a rural to urban gradient. The first part of the study involved warm season monitoring of Emigration Creek to quantify the spatial distribution of concentrations and flux of total coliform, *E. coli*, enterococci, nitrate, ammonia, and chloride for a longitudinal transect covering most of the main channel. The flux was deemed important to identify source areas (i.e., "hot spots") and sinks in addition to being useful for further study regarding in the Total Maximum Daily Loads (TMDL) required by most states for 303(d) listed water bodies. The warm season monitoring results were also useful in validating the status of the water body relative to the new (2006) and historic (2005) State of Utah numeric water quality criteria. The second part of the study was a bacteria tracer experiment conducted to quantify attenuation of bacteria along the main channel length of Emigration Creek to help explain the variability in concentrations and flux observed in the warm season monitoring. Collectively, the results of the warm season monitoring and bacteria tracer experiment were used to identify spatial locations of fecal contamination and advance the understanding of the fate and transport of bacteria in the mountain stream.

The two components of this thesis research project are consistent with the recent call for research activities related to Emigration Creek. Jensen et al. (2003) listed eight recommended future activities based on the results of the Salt Lake County 2003 study. Two of the listed items are to 1) conduct a follow up *E. coli* assessment using the

Colilert® methodology and 2) conduct a follow up coliform assessment with streamflow measurement to determine pollutant sources *and loads*. To support the first recommendation in the late 1970s and early 1980s the USEPA conducted public health studies evaluating the use of several organisms as possible pathogenic indicators, including fecal coliforms, *E. coli*, and enterococci (U.S. EPA, 2004). These studies showed that fecal coliforms were not reliable predictors of human illness. That is, the USEPA did not find a strong statistical relationship between the amount of fecal coliforms in the water and the likelihood of people getting sick. In contrast, the USEPA states that *E. coli* was a very good predictor in fresh waters and enterococci was a very good predictor of illness in both fresh and marine waters. As a result, the USEPA recommended in 1986 the use of *E. coli* for fresh recreational waters and enterococci for fresh and marine recreational waters (U.S. EPA, 1986). The second suggestion, which was to conduct a follow up coliform assessment with stream gages to better assess pollutant sources by calculating the loads, is valuable because loads are not affected by the dilution effect of influent streams. Canceling out the component of streamflow dilution helps clarify increases and decreases in the amount of pollutant in the stream.

1.3 Research Objectives

The goals of this study were to (1) determine the spatial and temporal distribution of concentration and loading of bacteriological and chemical fecal-contamination indicators and (2) document spatial variations in bacteria attenuation

along the main channel of Emigration Creek. These goals were met by achieving the following objectives:

1. Conduct 4-month, warm season monitoring of the total coliform, *E. coli*, enterococci, nitrate, ammonia, and chloride concentrations.
2. Measure streamflow during sample collection to determine the flux differences along the rural to urban stream transect for the constituents monitored.
3. To quantify bacteria attenuation using a bacteria tracer experiment along the rural-to-urban transect to identify bacteria loading sources and magnitudes.

1.4 Project Description

To accomplish the three experimental objectives listed above and meet the goals of the project required a detailed experimental plan. The first step of the research project was to perform a reconnaissance study of the Emigration Creek watershed. The reconnaissance was preformed by a two member research team, which walked the main stream channel, where feasible, to identify points of interest and describe basic stream characteristics. The points of interest for the warm season monitoring study included locations of inflows (both natural and man-made) to the stream, possible source locations of bacteria contamination, reaches of the stream channel conducive to streamflow measurement, points of easy access for sample collection, and areas of possible significant surface water-groundwater interaction were identified.

Based on the data collected during the stream reconnaissance, combined with results from previous studies, eight sampling sites were selected for the warm season monitoring part of the study. An experimental plan was designed to capture not only the temporal warm season concentration and flux trends at the eight sampling sites, but also to spatially investigate the variability of the concentrations and fluxes along the longitudinal transect. A weekly time interval was chosen because it was the smallest interval of time that would allow the desired goals and objectives to be met while remaining within the time and budget allocated to this project. On the weekly sampling day grab samples were collected twice, once in the morning and once around noon, to track diurnal changes in concentration and flux following identified changes in Emigration Creek total and fecal coliform concentrations found by Jensen et al. (2003).

In order to accomplish the first objective at each of the 8 sampling locations total coliform, *E. coli*, enterococci, ammonia, nitrate, and chloride samples were collected, stored, and transported to the laboratory facilities in the Department of Civil and Environmental Engineering at the University of Utah for processing. At the lab the total coliform and *E. coli* concentrations were determined using the Colilert® method by IDEXX. The enterococci concentration was determined using the Enterolert™ method also by IDEXX and the other parameters (nitrate, ammonia, and chloride) were determined using an Orion 5 Star meter with the respective ion sensitive electrode (ISE). In addition, general water quality parameters including temperature, pH, and conductivity were recorded in the field at the time samples were collected. A rigorous quality assurance and quality control plan was implemented to collect field blanks and field duplicates each amounting to approximately 10% of the respective samples

collected. In addition one set of duplicate samples was sent to the Utah State Health Laboratory for analysis and subsequent comparison.

To accomplish the second objective, streamflow was measured at each sampling location when samples were collected. The streamflow rate was measured by taking velocity and stage height readings across a stream cross section perpendicular to the streamflow (Nolan and Shields, 2000). Once the streamflow rate and the constituent concentrations were determined the was found by multiplying the bacteria concentration by the flow in respective units.

To accomplish the third objective a bacteria tracer experiment was planned and executed in coordination with a U.S. Geological Survey (USGS) synoptic hydraulic tracer study at the end of the warm season sampling protocol. The bacteria tracer experiment was designed to holistically quantify losses of bacteria that may be occurring (possibly due to attachment, filtration, mortality, predation, and sunlight exposure) from sampling site to sampling site. Moore et al. (1988) developed die-off coefficients for bacteria in natural streams using a variation of Chick's Law (similar to a simple first-order reaction in chemical kinetics) but it was questioned if these die-off coefficients would be appreciable or applicable in Emigration Creek due to the supposed short hydraulic residence time and the unique nature of Emigration Creek following a rural-to-urban transect in a mountainous environment. The bacteria tracer experiment was performed by releasing a prescribed amount of soil bacteria not indigenous to Emigration Creek in an upper reach of Emigration Creek followed by collecting samples at eight sampling sites starting from near the injection point and ending 6.3 km downstream.

The warm season monitoring data were analyzed by generating logarithmic and normal plots to show the changes in the concentrations and flux of each biological and chemical parameter from site to site (spatially) as well as to compare the bacterial concentration at each site over time. The results were also used to calculate the 30-day geometric mean for total coliform and *E. coli* concentrations. These values were then compared to the new (2006) and historic (2005) State of Utah water quality standards. The results from the bacteria tracer experiment in conjunction with the USGS dissolved tracer aided in defining the changes of bacteria concentration and flux due to bacteria loss and dilution, respectively. These results were then used to better describe the bacteria source and sink locations along Emigration Creek. The data from the bacteria tracer experiment were summarized in a general attenuation equation and integrated with the warm season monitoring results to identify and quantify areas of bacteria loading.

The next chapter presents the literature review of fecal-indicator bacteria studies, bacteria fate and transport studies, and modeling studies. Each is reviewed succinctly with the most relevant studies being highlighted the most. The third chapter of this thesis provides a review of general background information on fecal-indicator bacteria and the Emigration Creek watershed. The fourth chapter presents the experimental methods and procedures. The fifth chapter summarizes the results of the two part study and the sixth chapter summarizes the thesis, presents the final conclusions, and identifies logical extensions to this study.

CHAPTER 2

LITERATURE REVIEW

To clearly define and substantiate the two-part experimental plan to produce viable results relating to the fecal contamination constituent concentrations, loading, and dynamics, a literature review was conducted. The topics of most interest were divided into three categories: warm season fecal indicator bacteria monitoring studies, fecal-indicator bacteria fate and transport studies in water environments, and bacterial tracer experiments, especially those implementing methods similar to those chosen for this study.

2.1 Fecal Indicator Bacteria Studies

Fecal indicator bacteria densities in water bodies are an important parameter that indicates the presence of pathogenic bacteria. This has been proven in epidemiological studies (U.S. EPA, 1986 and Haile et al., 1996). These studies found a positive correlation between the illnesses reported by bathers and fecal-indicator bacteria concentrations. This relationship has resulted in numerous studies of bacteria in all types of water bodies including beaches, lakes, streams, and rivers for both dry and wet weather events. Herein is provided a comprehensive review (but it is by no means

exhaustive) from a cross-section of the literature with particular focus on water bodies that are similar to Emigration Creek, namely streams and rivers.

Skinner et al. (1984) conducted an intense study that utilized 10 bacteriological tests (which included total coliforms, fecal coliforms, and fecal streptococci) to monitor different bacterial populations found in water samples taken from streams draining high mountain rangeland near Laramie, Wyoming. Separate water samples were taken during early July, early August, and late August at 9 sites on 1 stream, 11 sites on another and 4 sites on the last. Sampling sites were distributed from near head water to confluence with each downstream tributary. Livestock grazing and recreation constituted the major uses of the study area. Bacteria counts were determined using auger plate count techniques. They concluded that enteric bacteria and total bacteria counts, often utilized to survey nonpoint and point source pollution, did not vary significantly between sampling sites, and further stated that bacteria serving as indicators of fecal pollution were low and likely caused by native animals and not humans. In a smaller scale effort in the same region, Adams and Skinner (1989) found increased fecal coliforms and fecal streptococci concentrations in a mountain stream near a ski area. The highest concentrations were observed in the afternoons and the day of the week with the highest concentrations varied.

Fisher and Endale (1999) used two experimental watersheds to test for impact of cattle on the concentrations of total coliform, *E. coli*, and enterococci. They used IDEXX methods to determine the concentrations. They observed that grazing cattle elevated the bacteria numbers, and found that positioning animals above a pond in the landscape was an effective means of reducing total coliform, *E. coli*, and enterococci

bacteria in surface water leaving the grazed watershed. The reduction caused by the pond resulted in the bacteria numbers from the pond outflow to be similar to those in surface water from the wooded watershed.

Embrey (2001) examined the density of fecal coliforms, *E. coli*, enterococci, and somatic coliphages for 31 sites in streams draining urban and agricultural regions of the Puget Sound Basin Lowlands located in Washington. The densities of *E. coli* and enterococci in 48% and 71%, respectively, exceeded the U.S. Environmental Protection Agency's suggested freshwater criterion.

Silcox et al. (2001) collected water samples from 58 surface-water sites in the Kankakee and Lower Wabash River Watersheds in Indiana from June through September 1999. Samples were analyzed for concentrations of *E. coli* bacteria. Each site was sampled five times in a 30-day period. Twenty-nine sites were sampled during June and July, and 29 sites were sampled during August and September. A five-sample geometric mean of concentrations was computed for each site. Concentrations of *E. coli* in 126 of the 289 samples exceeded the State of Indiana single-sample standard of 235 colonies per 100 milliliters for waters used for recreation. Concentrations in samples from 38 of the 58 sites exceeded the State of Indiana standard for a five-sample geometric mean of 125 colonies per 100 milliliters for waters used for recreation.

In another study, Knauer (2003) conducted watershed sampling in five drainage basins varying in size, stream order, and relative percentage of development with a primary interest in *E. coli.* The goals of this sampling program were to develop a low-cost strategic testing program that will identify substandard water quality as well as the likely sources of impairment. They found that four of the five watersheds had locations

with high *E. coli* concentrations and that one watershed had very high dry weather *E. coli* concentrations in which they concluded that the source was likely caused by humans. They found that wet weather dramatically affected various sites. Their sampling plan was designed to determine if these watersheds meet the ORSANCO *E. coli* standard by sampling five times within a 30-day period.

Kistemann et al. (2002) quantified the microbial loads of watercourses during rainfall runoff events and compared these loads with loads occurring during regular dry weather conditions. Of the physical and chemical parameters examined they stated that only the turbidity, pH, and nitrate values differed clearly from the values obtained for dry weather samples. Most of the bacteriological parameters that were investigated (colony, *E. coli*, coliform, fecal streptococcal, and *Clostridium perfringens* counts) increased considerably during extreme runoff events. They also noted that if relevant sources of parasitic contamination occurred in catchment areas, the concentrations of *Giardia* and *Cryptosporidium* rose significantly during events. Their concluding results show that substantial shares of the total microbial loads in watercourses and in drinking water reservoirs result from rainfall and extreme runoff events. They thus infer regular samples are considered inadequate for representing the microbial contamination of watercourse systems.

In a similar study, Giddings and Oblinger (2004) evaluated fecal-indicator bacteria (*E. coli* and total fecal coliforms), in a North Carolina watershed, during high and low streamflow conditions. A subset of five sites was sampled for fecal coliform bacteria, *E. coli* bacteria in streambed sediments (low flow only), and coliphage virus for serotyping. The study concluded that during the sampled high-flow condition all

tributaries contained densities of roughly two orders of magnitude greater than the low-flow concentration for *E. coli*. And samples of fecal coliform bacteria collected concurrently with *E. coli* samples had similar densities. The sampling of bacteria in sediments during low flow indicated that sediments do not appear to be a substantial source relative to the water column, with the exception of one area. The coliphage virus serotyping results were inconclusive because most samples did not contain the male-specific RNA coliphage needed for serotyping. If Emigration Creek is similar to this creek then the high-flow (wet-weather) bacteria results will be much higher than in low-flow (dry-weather) conditions.

The majority of recent studies are using the USEPA approved Colilert® methodology to enumerate *E. coli*. The method is being used mostly because of its relative analytical ease and rigor. The combination of easy application and relative accuracy makes it the method of recent choice for community and watershed groups monitoring water quality. One of the studies that led up to Colilert® being accepted by Standard Methods was Edberg et al. (1989). The study evaluated the presence or absence of total coliform based on the Colilert® method and the Standard Methods (membrane filtration, multiple fermentation, P-A broth) in 702 split samples from seven water utilities representing a wide geographic and hydrological spectrum. The overall agreement was 94%. From the Edberg et al. (1989) study Colilert® was shown to be adequate for enumerating *E. coli*, but this methodology doesn't have the ability to identify the specific source of the *E. coli*. In order to determine the *E. coli* source other methods are needed. Stoeckel et. al. (2004) compared seven protocols used to identify *E. coli* sources and they determined that ribotyping with EcoRI and PvuII approached

100% correct classification. This methodology will likely be needed in order to identify the sources of *E. coli* within Emigration Creek.

2.2 Fate and Transport of Bacteria

The in-situ fate of bacteria is an important part of understanding bacteria dynamics in streams. Several factors contribute to the die-off of pathogens once they reach streamwater. The major factors include pH, temperature, nutrients enrichment, pesticides, organic matter content, and solar radiation (Moore et al., 1988).

Rosen (2000) states that the normal pH range for most water bodies is close to 7 (neutral) and would not affect bacterial survival. Only at extreme pH (<4.5 and >8.2) can cell die-off be anticipated to be a major factor. In addition low temperatures, which slow metabolism, generally prolong the survival of pathogens. Lim and Flint (1989) showed that nutrients (namely nitrogen) were important in extending the survival time of *E. coli* in filtered, autoclaved lake water. Micro-organisms in a water body often become adsorbed to organic matter and soil particles. These settle out and accumulate at the bottom of rivers and lakes, and may become a source of organism if resuspended (Rosen, 2000). Recent evidence shows visible light as another inhibitor of cell survival (Barcina et al., 1990). *E. coli* and *Enterococcus faecalis* were significantly reduced when exposed to visible light in both freshwater and marine systems.

Some studies have evaluated bacteria loss using field studies and in some cases attributed losses to specific factors. McFeters and Stuart (1972) conducted field and laboratory studies on two creeks and artificial water using chambers with membrane-filtered side walls. These chambers would be placed in situ in the field and allow the

passage of water while retaining the measured *E. coli* bacteria. This study showed that for both creeks the *E. coli* concentrations slightly increased the first day and then sharply declined three orders of magnitude over the next 4 to 5 days for both creeks. Moore et al. (1988) calculated the die-off rate based on this study to be 3.140 and 1.970 day^{-1} but these values do not seem to account for the negligible losses observed in the first day of the experiment. Francy et al. (1996) investigated the effect of treatment of wastewater or combined sewer overflow effluents on bacterial injury, survival and regrowth by use of replicate flow through incubation chambers placed in the Cuyahoga River or Lake Erie. Results indicated that treatment was important while the site location was not. Easton et al. (2005) studied the in-situ fate of pathogenic bacteria (*E. coli* O157:H7 and *Giardia lamblia*) and indicator bacteria (total coliform, *E. coli*, and enterococci). This study showed that the die-off rate was much greater for the first 7 days (maximum: 0.331 $days^{-1}$) of the experiment when compared to 7 to 20 days (maximum: 0.064 $days^{-1}$) after the experiment began. Based on these studies a water body in which the hydraulic retention time is on the order of a day the loss of bacteria due to die-off would not be substantial. The focus of the research reported later in this thesis is Emigration Creek, which was shown to have a hydraulic retention time of less than 2 days so the die-off of the bacteria within the stream is an unlikely major source of bacteria depletion.

2.3 Bacteria Tracer Experiments

Jamieson et al. (2004) used a tracer-bacteria to study the persistence of enteric bacteria in three alluvial streams located in Southern Ontario, Canada. Within each

stream, a 1.1 m^2 section of the bed was seeded with a strain of *E. coli*. The survival of the tracer-bacteria within the stream bed and the release of the tracer-bacteria to the water column were monitored for approximately 3 weeks. Their results showed that where the water temperatures were typically lower than 16°C, the inactivation of the tracer-bacteria did not follow a first-order decay and where the temperature of the creeks were generally 10°C warmer the inactivation of the tracer-bacteria followed a typical first-order decay, preceded by a 24-h lag phase. They further showed that downstream water quality monitoring indicated the tracer-bacteria were being released from the seeded bed sediments during both baseflow and stormflow in two creeks. However, in one particular creek where bed sediments possessed an organic matter content of 9.5%, they found that the tracer-bacteria were rarely recovered in downstream water samples. They concluded that this experimental approach could be used to further investigate the survival and transport characteristics of sediment-associated bacteria.

Johnson et al. (2001) describe an innovative bacteria tracking technique called ferrography that was used to track bacterial transport in groundwater. Data obtained from this study showed that the timing of bacterial breakthrough was controlled by physical heterogeneity in the vertical dimension as opposes to variation in sediment surface or aqueous chemical properties. This study also used other tracking techniques and found that ferrographic tracking yielded results similar to the other tracking methods but was unique in that it provided a low detection limit of ~20 cells/mL. Zhang et al. (1999) describe the techniques used in ferrography stating that ferrography uses an immunomagnetic method to confer magnetic susceptibility specifically to the bacteria

of interest and uses a Bio-ferrograph to concentrate the deposition of magnetically tagged bacteria onto an exceedingly small area on a glass cover slip. This technique appears to have potential to aid in describing the currently understudied transport of bacteria in surface waters.

CHAPTER 3

BACKGROUND

For many years nonpathogenic bacteria have been used to determine the bacteriological health hazards caused by fecal contamination in water bodies. Enteric nonpathogenic bacteria are called indicator bacteria as their presence indicates the potential presence of pathogenic bacteria and fecal contamination. The USEPA has stated that *E. coli* is a good indicator bacteria for freshwaters (U.S. EPA, 2004). Emigration Creek has been observed to have high levels of indicator bacteria (e.g., total and fecal coliforms) in past studies (Jensen et al., 2003). To help understand the natural and anthropogenic characteristics of the Emigration Creek watershed and to aid the planning of the experimental design of the research reported in this thesis, a comprehensive review of two water quality studies of Emigration Creek that focused on bacteria was performed. This chapter begins with a general overview of the concept of fecal-indicator bacteria, which is followed by a description of the Emigration Creek watershed, and to end the chapter a review of two important studies of the bacteria levels in the Emigration Creek watershed.

3.1 Fecal Indicator Bacteria

High levels of fecal-indicator bacteria in water bodies can indicate the possible presence of pathogenic microorganisms. Cholera, typhoid fever, bacterial dysentery, infectious hepatitis, and cryptosporidiosis are some of the well-known waterborne diseases that spread through water contaminated with fecal matter. Eye, ear, nose, and throat infections also can result from contact with contaminated water. In general, methods are not routinely used to directly detect pathogens in water. Instead, bacteria such as total coliforms, fecal coliforms, fecal streptococci, *E. coli*, and enterococci are used as indicators of sanitary water quality, because they are present in high numbers in fecal material and they have been shown to be associated with some waterborne disease-causing organisms. Indicator bacteria usually are harmless, more plentiful, and easier to detect than pathogens.

The most commonly tested fecal bacteria indicators are total coliforms, fecal coliforms, *E. coli*, fecal streptococci, and enterococci. All but *E. coli* are composed of a number of species of bacteria that share common characteristics such as shape, habitat, or behavior (U.S. EPA, 1997).

Total coliforms are a group of bacteria that are widespread in nature. All members of the total coliform group can occur in human feces, but some can also be present in animal manure, soil, and submerged wood and in other places outside the human body. Thus, the usefulness of total coliforms as an indicator of fecal contamination depends on the extent to which the bacteria species found are fecal and human in origin. For recreational waters, total coliforms are no longer recommended as

an indicator. For drinking water, total coliforms are still the standard test because their presence indicates contamination of a water supply by an outside source.

Fecal coliforms, a subset of total coliform bacteria, are more fecal-specific in origin. However, even this group contains a species that are not necessarily fecal in origin. For recreational waters, this group was the primary bacteria indicator until relatively recently, when USEPA began recommending *E. coli* and enterococci as better indicators of health risk from water contact. Fecal coliforms are still being used in many states as the indicator bacteria.

E. coli is a species of fecal coliform bacteria that is specific to fecal material from humans and other warm-blooded animals. USEPA recommends *E. coli* as the best indicator of health risk from water contact in recreational waters; some states have changed their water quality standards and are monitoring accordingly. In 1986 the USEPA published a document (U.S. EPA, 1986) suggesting that *E. coli* is the best indicator of health risk from water contact in recreational fresh waters. Leclerc et al. (2001) examined the positive and negative attributes of various coliforms including *E. coli* which serve as indicators of pathogenic bacteria in food and aquatic environments. They concluded that many types of indicators are not appropriate and that *E. coli* is the most appropriate but still has some problems. They indicated that *E. coli* serves as a good indicator, in that, its presence is usually in higher concentration than the actual pathogen, *E. coli* is almost completely exclusive to the intestinal tract of humans and other animals, and its detection is relatively quick and simple. They then stated that the disadvantage of *E. coli* is that it does not show a high resistance to disinfection like

some pathogens. These reports help validate the use of *E. coli* to indicate the presence of pathogenic bacteria and fecal contamination.

Fecal streptococci generally occur in the digestive systems of humans and other warm-blooded animals. In the past, fecal streptococci were monitored together with fecal coliforms and a ratio of fecal coliforms to streptococci was calculated. This ratio was used to determine whether the contamination was of human or nonhuman origin. However, this is no longer recommended as a reliable test (U. S. EPA, 1997).

Enterococci are a subgroup within the fecal streptococcus group. Enterococci are distinguished by their ability to survive in salt water, and in this respect they more closely mimic many pathogens than do the other indicators. Enterococci are typically more human-specific than the larger fecal streptococcus group. USEPA recommends enterococci as the best indicator of health risk in salt water used for recreation and as a useful indicator in fresh water as well.

3.2 Emigration Creek Watershed

Figure 3.1 shows the location of the Emigration Creek watershed in relationship to the University of Utah and the Great Salt Lake. The watershed's close proximity to Salt Lake City has greatly influenced the history of human activity within the canyon and continues to affect its future. Emigration Canyon was the main route established by pioneers in the mid 1800s. Homes began being built in Emigration Canyon as early as 1852 (Salt Lake County Public Works, 1999). Timber and rock quarries became established within the canyon to aid in the early establishment of Salt Lake City and were discontinued in the early 1900s. Recreation within the canyon was at first seasonal

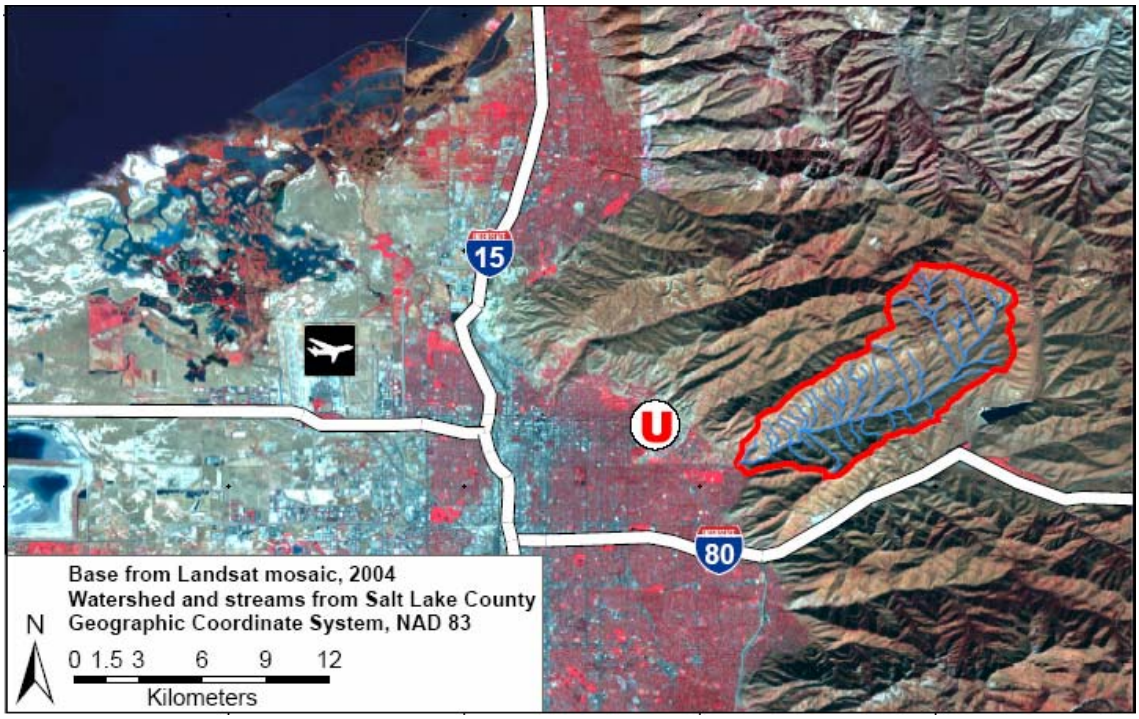

Figure 3.1— Location of the Emigration Creek watershed.

recreation, but with the increased availability of automobiles the canyon became more accommodating to year-round living (Salt Lake County Public Works, 1999).

Emigration Canyon's attractiveness caused many people to purchase land within the canyon which has resulted in 40% of the land within the canyon being privately owned (Salt Lake County Public Works, 1999), although the watershed is predominantly open space (see Figures 3.2 and 3.3). The developed land use within the canyon is almost entirely single family residential, with 440 of the 780 developable lots developed. The number of undeveloped lots suggests the canyon can experience growth nearly doubling its current population. The 1998 population within the Emigration Watershed was 1,238. The residents within the canyon receive their culinary water by individual wells or springs or are incorporated in small localized culinary water

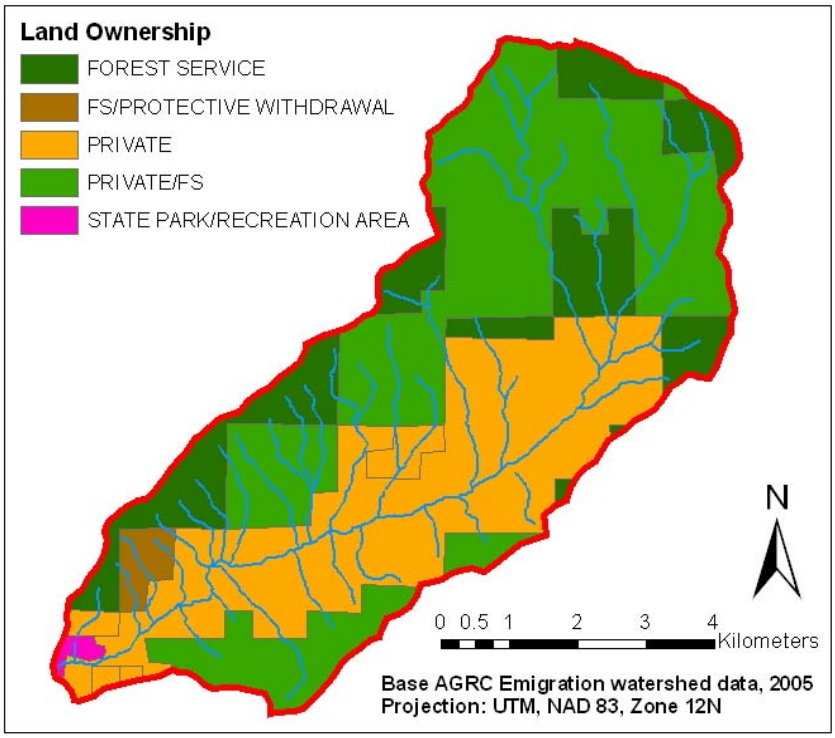

Figure 3.2— Land ownership in the Emigration Creek watershed.

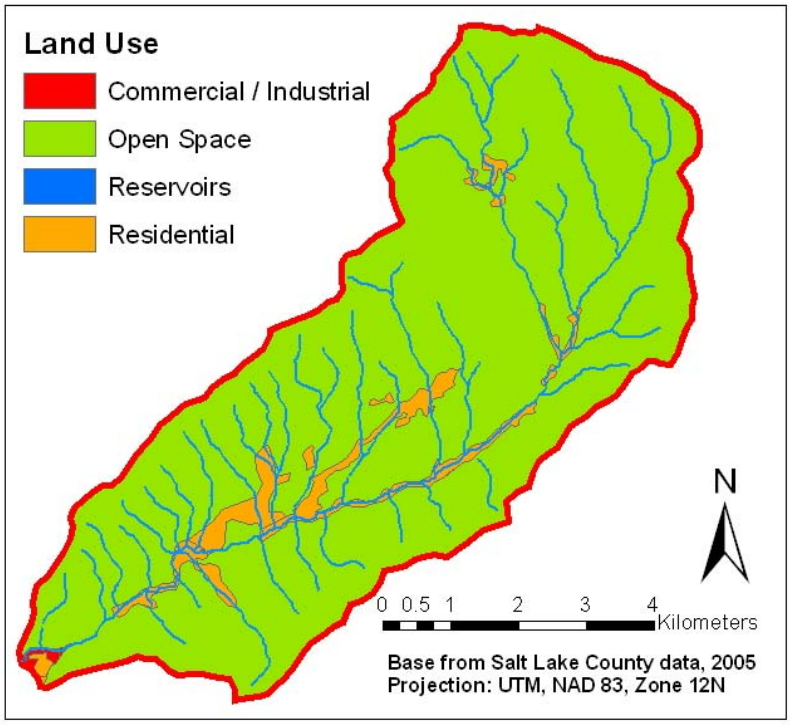

Figure 3.3— Land use in the Emigration Creek watershed.

systems. The residents utilize septic tank systems or holding vaults to dispose of wastewater.

The Emigration Creek watershed is 46.6 km^2 (18 mi^2) with an estimated length of 16 km (10 miles) and elevations ranging from 1,494 to 2,728 m (4,900 to 8,950 ft). The soils within the canyon consist of consolidated crystalline rocks, shales, sandstones, limestone, and volcanic rock and streamside soils consisting of sand and silty alluvial soils (Glenne and West, 1981). The vegetation in the canyon consists mainly of willows and cottonwoods near the creek with mainly scrub oak and grasses along the sides of the canyon, and a few aspen and pine groves in the upper reaches of the canyon. The average annual precipitation is 74 cm (29 in) ranging from 51 cm at lower elevations and 102 cm at the higher elevations (Glenne and West, 1981).

Emigration Creek has ~30 tributaries (see Figure 3.4), although most of them only flow during early spring due to snowmelt runoff. The main channel of Emigration Creek from its headwaters in Kilyon Canyon to the mouth of the canyon is approximately 14.5 km (9 miles) with an average slope of 0.048 ft/ft. Figure 3.5 displays the profile plot of the Emigration Creek main channel from its headwaters to the mouth of the canyon. The average annual discharge at the mouth of the canyon ranges from per year $5.4x10^6$ to $7.5x10^6$ m^3 per year (4,400 to 6,110 acre-feet). In addition to its antidegradation status Emigration Creek is currently protected under the 2B (for noncontact recreational use) and 3A (fishery uses) class uses.

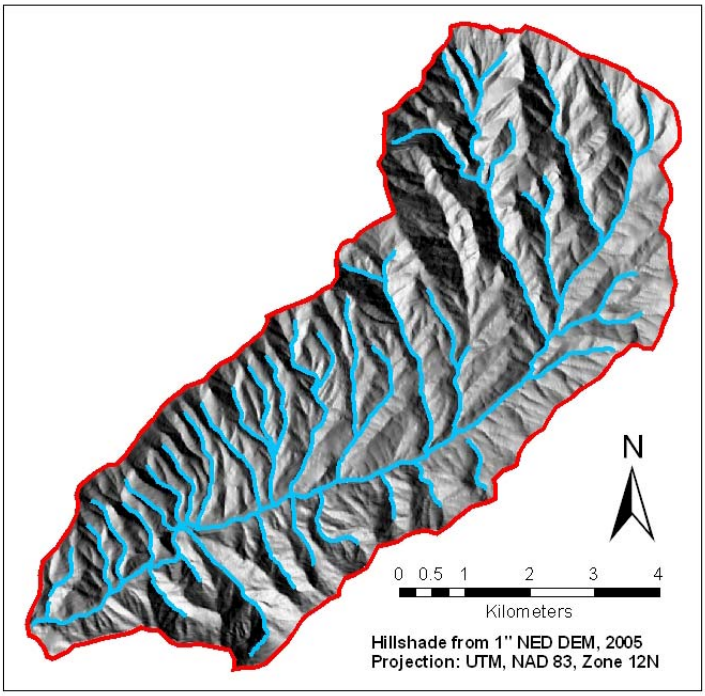

Figure 3.4— Emigration Creek tributaries.

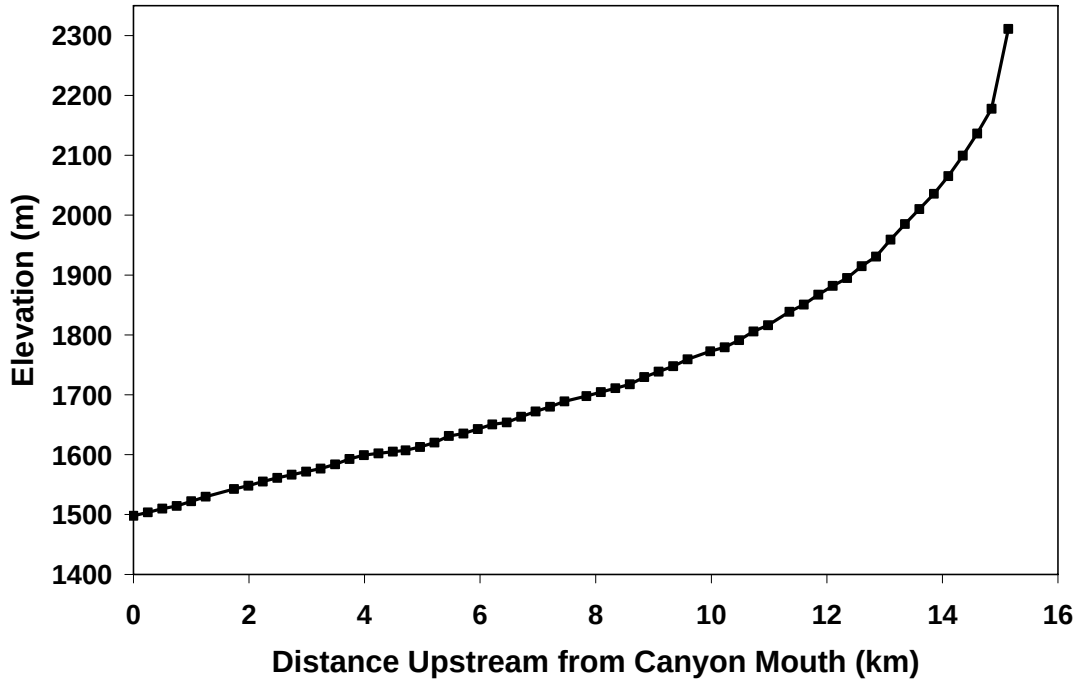

Figure 3.5— Emigration Creek elevation profile from mouth to headwaters.

3.3 Previous Bacteriological Studies of Emigration Creek

Glenne and West (1981) determined the total coliform concentrations and flux at 16 sites along Emigration Creek (Figures 3.6. and 3.7). Figure 3.6 shows the total coliform concentration at each site. Site 15 and 16 were sites located in Burr Fork and Kilyon Canyon, respectively, and represent the most upstream sampling locations (These two sources combine before reaching site 14). Site 1 is the most downstream site located downstream of the Hogle Zoo. Figure 3.7 shows the flux at each sampling site. The flux indicates the number of bacteria passing the sampling location irrespective of streamflow thus emphasizing sources of total coliform contamination. From these figures a drastic change from site 10 to 9 is observed. Other notable changes are a decrease in flux between sites 7 and 6. This information was helpful in determining sampling locations where changes in bacteria and streamflow were likely to occur.

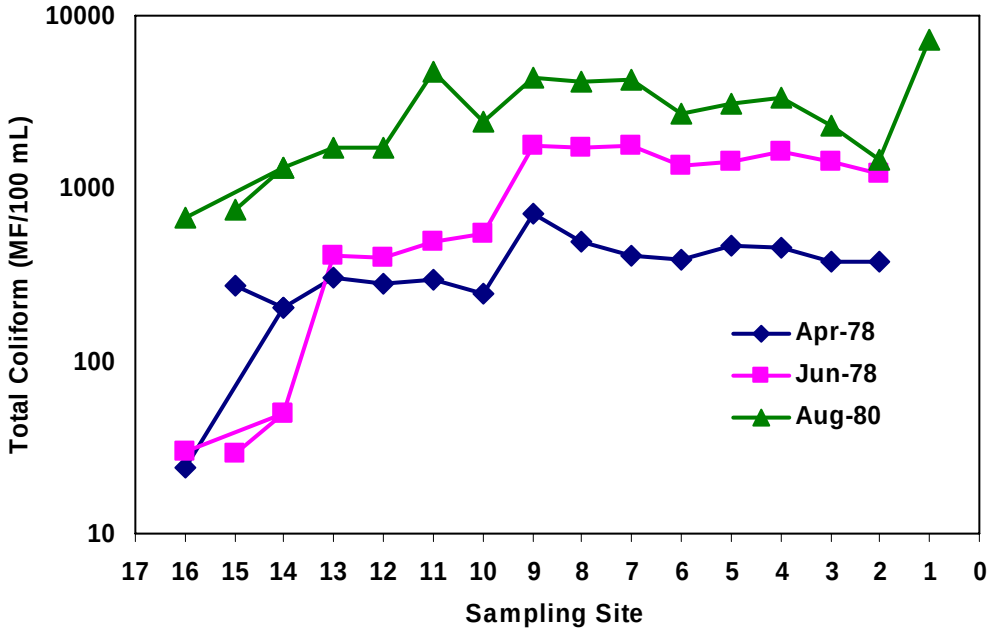

Figure 3.6—Total coliform concentration at each sampling site for April and June of 1978 and August of 1980 (figure produced using data from Glenne and West (1981)).

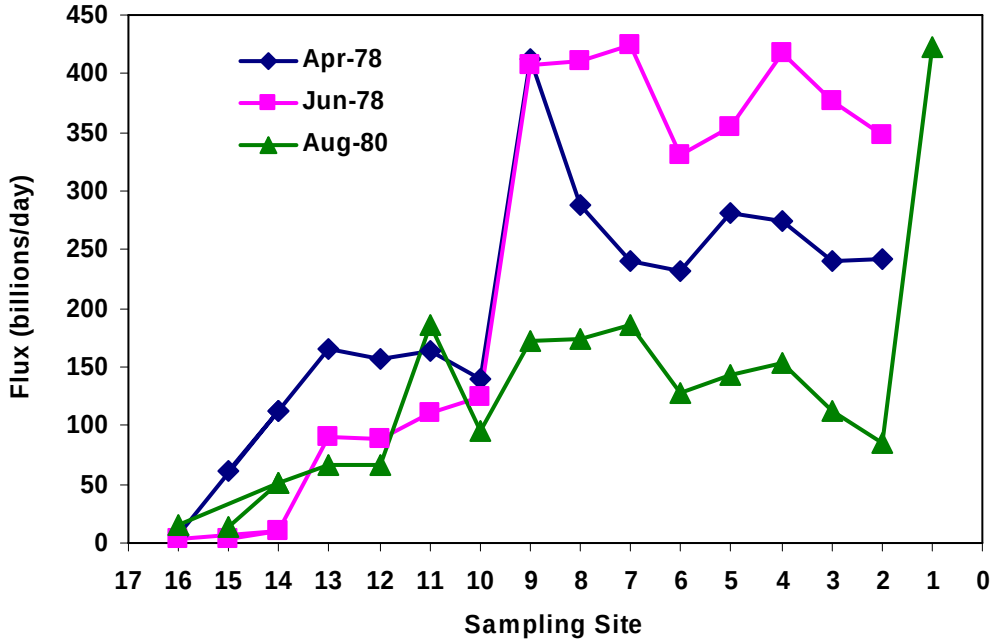

Figure 3.7—Total coliform flux at each sampling site for April and June of 1978 and August of 1980 (figure produced using data from Glenne and West (1981)).

In addition to coliform concentrations and flux, Glenne and West (1981) presented a mathematical model to relate pollution generation, pollution transport, and pollution survival to stream conditions in hopes of better understanding the causes of pollution and possible mitigation measures. The modeling indicated that 87% of the stream coliform pollution load was generated by people and animals with about 5% coming from underground disposal systems. They felt the most effective mitigation measures would be domestic animal control and the provision of a buffer zone along the stream.

In 2003, Jensen et al. performed an intensive bacteriological study of Emigration Creek in which they collected grab samples once a week at five sampling sites three times a day (6 am, 12 pm, and 6 pm) for a period of about 6 months (May to November of 2001). They analyzed the samples for total and fecal coliform concentrations. The

dry weather data they collected were analyzed to see if there was a significant difference in the fecal concentration observed during the morning, noon, and evening samples, suggesting a diurnal variation. The dry weather fecal coliform concentrations observed at the morning and noon sampling times were found to have statistically significant differences when tested with the pooled variance one tailed *t*-test at a significance level of 95% ($\alpha = 0.05$). Table 3.1 shows the basic statistics and results of the *t*-test. At a 0.05 level of significance the *t* value obtained is less than critical *t* and the *p* value is less than the level of significance therefore the average fecal coliform concentration is lower for the noon sampling time than the morning sampling time. This difference can also be observed by plotting all the data against there respective cumulative probabilities as in Figure 3.8. Included in Figure 3.8 is a line for each sampling time constructed based on the mean and standard deviation of the logarithmic data. The difference in the morning (AM) and noon distributions is graphically shown, with the morning sampling time concentrations being higher than the noon concentrations, while the evening (PM) distribution is in-between the other two distributions.

Table 3.1—t-Test of log transformed fecal coliform data at the morning and noon sampling times assuming equal variances.

	Morning	**Noon**
Mean	1.96	1.79
Variance	0.29	0.34
Pooled Variance		0.31
t		-1.92
p Value		0.028
t Critical one-tail		-1.65

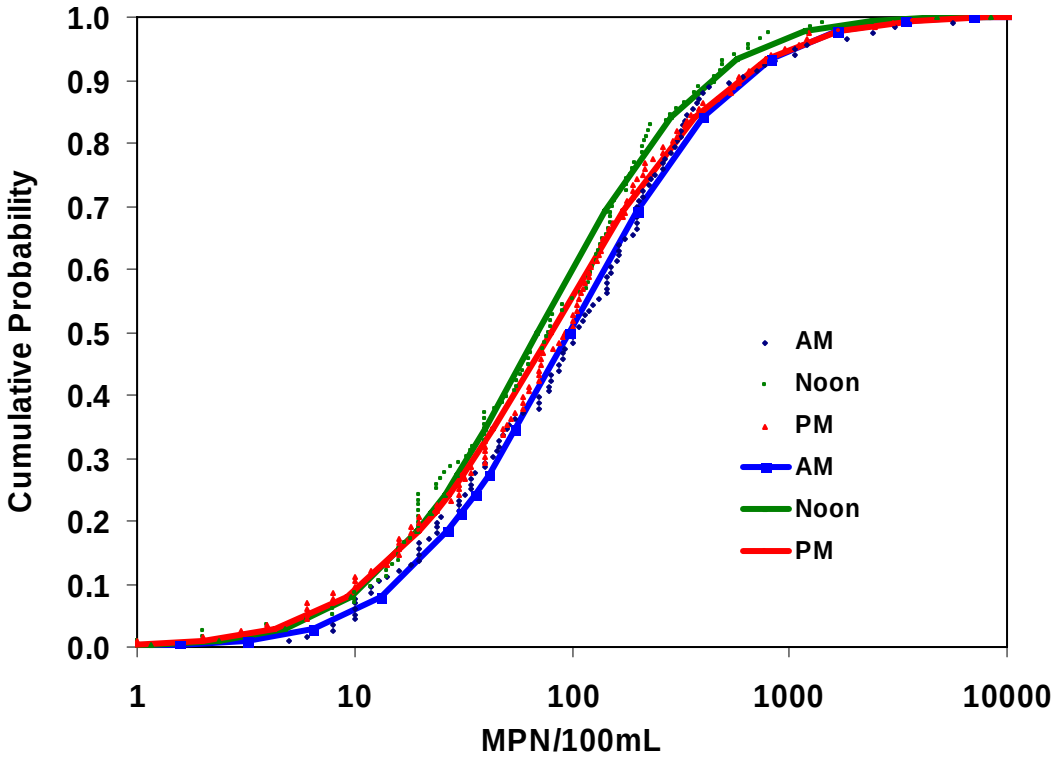

Figure 3.8—Difference in cumulative probabilities for the morning, noon, and evening fecal coliform concentrations from Jensen et al. (2003) data.

Their results also indicated that the fecal coliform concentrations exceeded the 2005 State of Utah water quality regulation for fecal coliform, which was 200 organisms per 100 mL, but the total coliform concentrations did not exceed the 2005 State of Utah water quality regulation of 5,000 organisms/100mL. The high level of fecal coliforms placed Emigration Creek on the state 303(d) list of impaired waters.

Figure 3.9 illustrates a counterintuitive phenomenon with the average fecal coliform *concentrations* decreasing from the upper most sampling locations to the most downstream location (this was also observed in the total coliform concentrations). They suggest that further study is needed to better explain this observed concentration decrease by determining the loading distribution along the creek main channel.

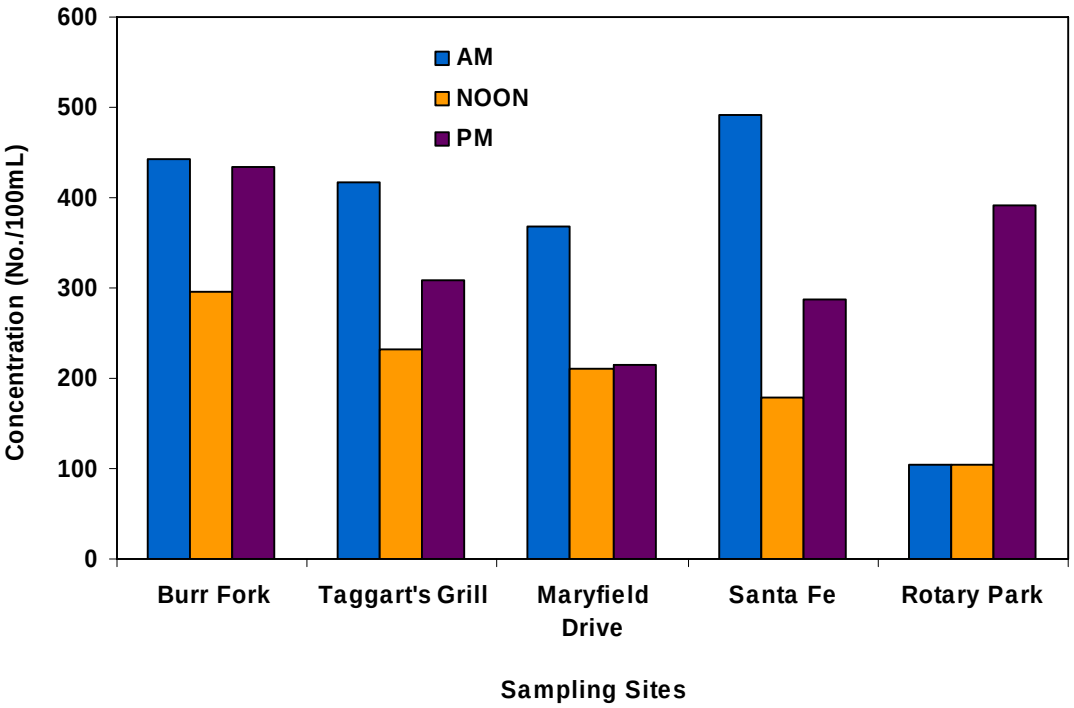

Figure 3.9—Average fecal coliform concentration based on weekly samples for each sampling time (AM, noon, and PM) from June to September of 2001 (figure produced using data from Jensen et al. (2003)).

CHAPTER 4

EXPERIMENTAL METHODS AND PROCEDURES

4.1 Introduction

The goals of this study were to (1) determine the spatial and temporal distribution of concentration and loading of bacteriological and chemical fecal-contamination indicators and (2) document spatial variations in bacteria attenuation along the main channel of Emigration Creek. The monitoring program to achieve these goals was developed by first analyzing and synthesizing the findings of the previous Emigration Creek bacteriological studies (Glenne and West 1981 and Jensen et al. 2003). The results from these studies pointed to several possible locations of potential sources as well as external influences on the creek that could be affecting bacteria fate and transport (e.g., surface-groundwater interaction). The second step was to review the literature and learn what other researchers had done to study bacteriological contamination and bacteria dynamics in water bodies. The results of this review were presented in Chapter 2. Finally, two general bacteriological monitoring descriptions were used to help guide the development of the monitoring protocol. First, Francy et al. (2000) commented on the difficulty performing nationally consistent methods and procedures to study microbial quality of the Nation's water resources because objectives and data collection practices varied. This summary of observations from the

U.S. Geological Survey's (USGS) National Water-Quality Assessment (NAWQA) Program indicated that a review of other studies would be helpful, but ultimately the monitoring protocol would be specific to Emigration Creek. The second general source used extensively was the *Stormwater Effects Handbook* by Burton and Pitt (2001). The general information on experimental design and water quality sampling, and documented case studies of urban water quality was combined with the information from Francy et al. (2000) and the previous Emigration Creek studies to craft the monitoring protocol described in this chapter.

The first goal required selecting constituents that would indicate fecal contamination. The most widely used constituents which indicate fecal contamination are bacteria. For this study, *E. coli*, enterococci, and total coliforms were the bacteria selected. In conjunction with the bacteriological samples, the dissolved chemical constituents ammonia and nitrate were selected as suggested by Burton and Pitt (2001) to indicate fecal contamination from sanitary sewage sources such as septic tanks. The chloride concentration was also included in the study because Giddings (2000) found high chloride concentrations (~100mg/L) in Emigration Creek persisting throughout the summer months. According to *Standard Methods* (1998) this high chloride concentration would interfere with the determination of nitrate (weight ratio of chloride to nitrate exceeds 10); therefore, it was included in the study to permit the correct analytical procedures to be used.

In addition to the fecal contamination indicators and chloride, the pH, temperature, and conductivity were included to describe the basic water quality characteristics of Emigration Creek and because any appreciable change in these

parameters will aid in describing changes in the fecal indicator concentrations and possibly aid in identifying inflows to and losses from the stream. Table 4.1 lists the water quality constituents that were monitored in this study.

The second goal of the thesis required developing a bacteria tracer study. A bacteria tracer was prescribed to better understand the bacteriological die-off and attenuation dynamics of bacteria in the creek. The methods, procedures, and planning of the bacteria tracer were developed by reviewing previous studies and obtaining in-depth guidance from Dr. William Johnson (University of Utah), an expert in using ferrography to track tracer bacteria and Dr. Briant Kimball (USGS) an expert in dissolved tracer studies. The bacteria tracer procedures were then carried out and accomplished with the help of Dr. Steven Burian, Dr. William Johnson, Dr. Briant Kimball, and post-graduate and graduate students at the University of Utah.

Table 4.1—Constituents to be measured in the field and in the lab.

Field	Laboratory
pH	Ammonia
Temperature	Chloride
Conductance	Nitrate
	Total Coliform
	E. coli
	Enterococci

4.2 Warm Season Monitoring

In order to accomplish the goals listed above, several research objectives were defined. The first objective was to monitor for a 4-month, warm season period the total coliform, *E. coli*, enterococci, nitrate, ammonia, and chloride concentrations during dry weather conditions. The warm season monitoring protocol involved collecting weekly samples from eight locations in the creek beginning June 13, 2005 and ending September 20, 2005. Samples were collected twice daily to capture diurnal variation of the concentrations. The warm season protocol also involved the measurement of the streamflow rate at each sampling site on the day samples were collected. This was required in order to accomplish the second objective, which was to determine the flux of each constituent at all eight sampling sites.

4.2.1 Methods

The methods used for this study were selected based on their effectiveness in meeting the objectives, method standardization or acceptance, ease of use, timely results, and cost effectiveness. The field methods used to collect the grab samples followed the guidelines presented in *Standard Methods* (1998). The analytical methods used to determine the concentration of each constituent are listed in Table 4.2. The methods chosen to determine the bacteriological concentrations were developed by IDEXX (Colilert® (total coliforms and E. coli) and Enterolert™ (Enterocooci)), and are accepted by *Standard Methods* (1998). The dissolved constitutes (ammonia, chloride, and nitrate) were determined using an ISE connected to an Orion 5 Star Meter by Thermo Electron Corporation which displayed the determined concentrations. For the

Table 4.2—Methods used in the determination of each constituent.

Constituents	Method
Total Coliform	9223 B [1]
E. coli	9223 B [1]
Enterococci	9223 B [1]
Ammonia	4500-NH_3 D [1]
Chloride	Thermo ISE [2]
Nitrate	4500-NO_3^- D [1]
pH	Oakton PC 10 Meter [2]
Temperature	Oakton PC 10 Meter [2]
Conductivity	Oakton PC 10 Meter [2]

[1] Standard Methods 1998
[2] Manufacture's Method

determination of the dissolved constituents the manufacture's methods were followed in conjunction with the information available in *Standard Methods* (1998). The pH, temperature, and conductivity were measured in the stream using an Oakton PC 10 Meter by following the manufacture's instructions.

The streamflow rate measurements were determined by wading using a Gurley 625D pygmy meter, tape measure, and wading rod. This method was chosen due to the variability in the channel cross section for each sampling location in addition to the cost of the equipment being within the allocated budget constraints for this project. The wading procedures used for this method were based on the USGS instructional CD, "Measurement of Stream Discharge" (Nolan and Shields, 2000).

4.2.2 Procedures

With the methods selected, the procedures were developed to help accomplish the objectives of the thesis. The first step of the procedures was to perform a

reconnaissance of Emigration Creek. Following the reconnaissance and review of past studies, sampling sites were selected. A sampling plan was developed based on research of different sampling schemes, previous studies, and the total number of samples that could feasibly be collected and analyzed. This sampling plan included when, where, and how samples were to be collected and how field measurements were to be made. Collected samples were then processed using the methods described above. Quality control measures were also prescribed and monitored throughout the study to ensure the results were viable. The remainder of this section describes the detailed procedures used in the warm season monitoring phase of the research. The next section describes the methods and procedures used in the bacteria tracer.

4.2.2.1 Reconnaissance

To gain a practical understanding of Emigration Creek and to begin to plan the study, a reconnaissance of the creek was performed. The reconnaissance consisted of walking along the creek starting from Kilyon Canyon (above the residential area in the upper reach of Emigration Canyon) downstream to Rotary Park (located at the mouth of Emigration Canyon), a distance of 13.3 km. A field notebook and GPS unit were used to document (1) locations of influent streams, (2) possible pollution source locations, (3) supposed areas of groundwater interaction, and (4) acceptable stream flow rate measuring locations (meaning stream reaches that have smooth laminar flow with a relatively defined channel that is devoid of large cobble such that flow rates can be determined accurately using a velocity-area approach). Accessibility to Emigration Creek from adjacent roadways was factored into the selection of sampling locations.

The way points collected by GPS were exported into a text file and then imported in a geographic information system to overlay the points with other spatial data for the watershed.

4.2.2.2 Sampling Site Selection

Based on the information from the reconnaissance and past studies (Jensen et al., 2003 and Glenne and West, 1981) eight sampling sites were selected as shown in Figure 4.1.

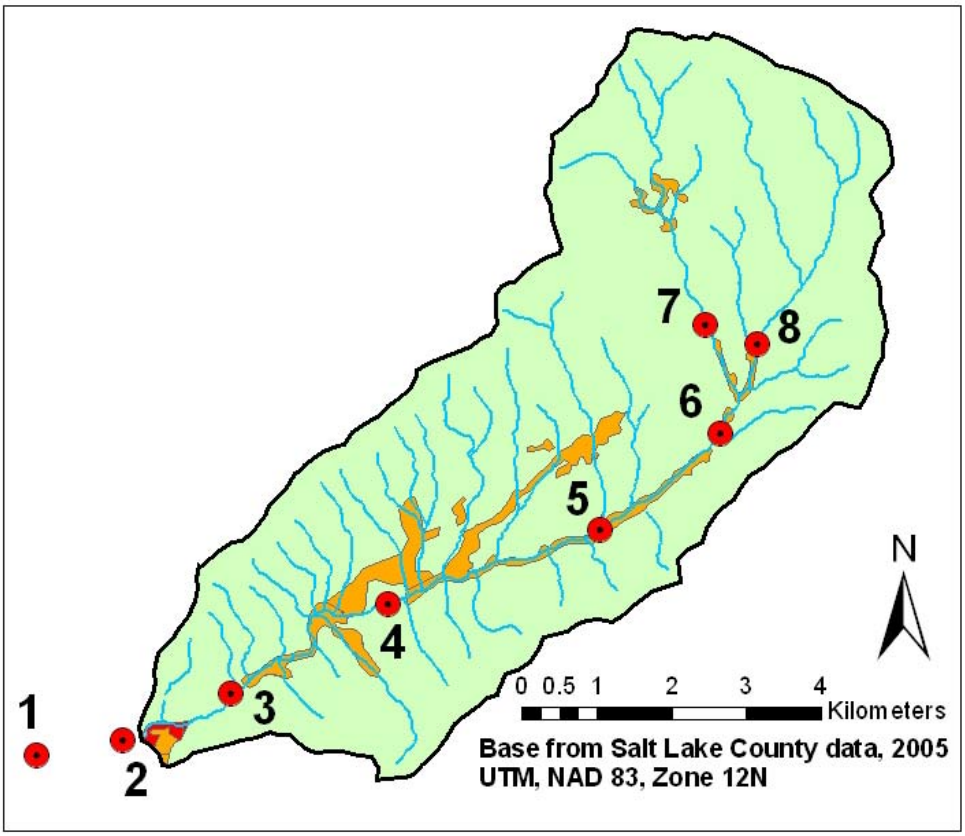

Figure 4.1—Location of sampling sites

The furthest upstream sampling site, located in Kilyon Canyon, was numbered site 8. Site 8 was selected to be upstream of urban development to provide a representative background location and was preliminarily thought to be the most pristine sampling site. The water quality was measured and grab samples collected about 100 m upstream from the location where the streamflow was measured. This was necessary because the stream profile at the sampling location was very erratic. No inflows were observed between the streamflow location and the sampling location during multiple checks so this modification seemed acceptable. Streamflow and samples were collected at the same location for all other sites. Although site 8 is the furthest upstream site, it does have a trail adjacent to the creek channel, with approximately 2 to 5 m buffer with some open creek crossings. The trail is frequented by mountain bikers, hikers, domestic dogs, and wildlife.

Sampling site 7 is also located at the upstream end of the Emigration Creek watershed, except it is located on the Burr Fork Creek tributary to Emigration Creek. The sampling site was located approximately 1 km upstream from the confluence of Burr Fork Creek and Emigration Creek. The sampling site is downstream of approximately 30 residential homes. Sampling site 7 was selected to quantify the inputs from Burr Fork Creek entering into Emigration Creek.

Sampling site 6 was located approximately 600 m downstream of the Burr Fork Creek confluence. At site 6 is a flume owned by the Salt Lake City Public Utilities. This site was convenient because the flume was used to determine the flow rate (using a stage measurement and an equation provided by Salt Lake City Public Utilities), though often wading measurements were take to verify the flume measurements. This site was

also used in previous studies (Jensen et al., 2003 and Glenne and West, 1981) providing a consistent measuring point for potential comparison and assessment of trends.

Sampling site 5 was located just downstream of the inflow of Brigham Creek and Freeze Creek. Figure 4.1 above shows Brigham Creek and Freeze Creek entering Emigration Creek from the north, one a few meters and the other a few hundred meters upstream of the sampling site. Sampling site 5 was selected because it was downstream of two influent creeks, thereby positioned to quantify the input from these two sources. Between sampling site 6 and 5 are residential homes adjacent (~5 – 10 m) to Emigration Creek, another potential source of bacteria contamination.

Sampling site 4 was located near the upstream end of Perkin's Flat. Perkin's Flat is an open area with no residential areas adjacent to Emigration Creek. Between sampling sites 5 and 4 is predominantly residential housing. Sampling site 4 was selected because it was near the boundary between an upstream residential area and a downstream wetland area.

Sampling site 3 was located downstream of nearly all residential area within Emigration Canyon. From sampling site 4 to 3 there is currently (from upstream to downstream) a wetland area, a recreation area (Camp Kostopulos) (which often diverts water from Emigration Creek into a small pond and then discharges the overflow from the pond back into Emigration Creek), and two restaurants (Santa Fe and Ruth's Diner) followed by a small residential area (~40 houses).

Sampling site 2 was located just upstream of the Salt Lake County's automated stream gage below Rotary Park. Sampling site 2 was selected because it was just upstream of the Hogle Zoo and major residential area at the mouth of the canyon.

Between sampling sites 3 and 2 there were suspected surface water-groundwater interaction zones, a dog park, a small debri basin and no residential areas that noticeably drained into Emigration Creek. The stream gage at site 2 was often used to determine the streamflow rate, though as the study progressed through the summer water was dammed from extending across the entire weir due to silt build up likely making the streamflow measurements high. Because of this most of the streamflow rate measurements were determined by wading.

Sampling site 1 was located downstream of the Hogle Zoo, adjacent to a golf course, and just upstream of a culvert. Between sampling sites 2 and 1 was a small portion of the dog park, Hogle Zoo, a golf course, and residential homes. Intuitively, a high flux of bacteria was expected at this final downstream site, especially from the dog walk park and the zoo.

4.2.2.3 Sampling Plan

A general systematic sampling scheme described by Burton and Pitt (2001) was used in this study. A systematic sampling protocol is used to describe general trends based on evenly spaced samples (by time) collected for an extended period of time. For this study samples were taken weekly at the eight sites described above and shown in Figure 4.1. Samples were collected twice a day for 16 weeks beginning June 13, 2005 and ending September 20, 2005. Weekly sampling was performed because a previous study by Jensen et al. (2003) showed bacteriological changes from week to week were relatively small, during dry weather, yet the sampling interval was able to capture the warm season trend. Further, weekly sampling was able to observe variations such as

large increases in bacteria due to storm events or other factors. Additional motivation to collect weekly samples was to obtain five samples in 30 days to compute a regulatory compliant geometric mean. For example, the state of Michigan requires that, "[c]ompliance shall be based on the geometric mean of all individual samples taken during 5 or more sampling events representatively spread over a 30-day period" (Michigan Department of Environmental Quality, 2003). The sampling plan for Emigration Creek resulted in at least 10 samples per site every 30 days (2 samples per sampling day). All samples were collected on Monday or Tuesday. Samples were collected twice a day because as mentioned in Chapter 3 the report by Jensen et al. (2003) revealed that the mean fecal-coliform bacteria concentration observed in the morning was statistically different from the mean concentration in the afternoon.

4.2.2.4 Sampling and Data Collection Preparation

Prior to sample collection, sample bottles and storage coolers, field measurement probe, streamflow measuring device, and ancillary equipment were prepared and organized. The sampling bottles used to collect the bacteria were disposable sealed IDEXX bottles containing a small amount of sodium thiosulfate (to extinguish any chlorine residual). The bottles used to collect the ammonia, nitrate, and chloride samples were reusable polypropylene bottles that were washed and rinsed with distilled water prior to each sampling run. On the morning of the sampling day the sampling bottles were labeled and placed in a large cooler along with at least four ice packs to keep the temperature of the samples after collection at 4°C +/- 2°C (*Standard Methods*, 1998). Also on the morning of sample collection, the pH and conductivity

meter was calibrated using known standards of pH 10 and 7 and a certified solution with a specific conductivity near that of the stream. A sterile bottle filled with at least 1000mL of distilled water was taken to collect field blanks. The velocity meter, measuring tape, and staff gage were gathered in order to measure the streamflow rate at each sampling site. The velocity meter used was a 625D Pygmy Velocity Meter manufactured by Gurley Instruments. Prior to use the velocity meter was cleaned, oiled, and tested using a spin test (Nolan and Shields 2000). Rubber boots or waders were used to reach the sampling location and take field measurements. The equipment needed to accomplish the sampling and streamflow rate measurements are listed in Table 4.3.

Table 4.3—Sampling and streamflow rate measuring equipment.

Distilled Water
Small Cooler
Large Cooler
Boots or Waders
Gurely Instruments 625D Pygmy (Velocity) Meter
Velocity Profile Data Sheet
Wading Rod
Measuring Tape
Watch
Pen

4.2.2.5 Field Data and Grab Sample Collection

After the required materials listed above were prepared the sampling team traveled to sampling site 1 at 05:45 +/- 10 minutes and again that afternoon around 13:00. The water samples and streamflow rate measurements were taken from the most downstream location to the most upstream location so that disturbances due to walking in the stream were not included in subsequent samples. It is worth noting that due to the travel time of Emigration Creek it was later determined that the afternoon sampling run may include water that was disturbed upstream during the morning sampling run. This disturbance did not seem to have any effect on the afternoon results.

Upon arriving at the sampling site the two member sampling team was divided into a sample/data collector and a data recorder. The sample/data collector placed the needed number of sampling bottles in a bag. If this site was used to collect the field blanks and duplicates the sample/data collector included the additional bottles and distilled water in the bag with the other bottles. Then the sample/data collector connected the velocity (pygmy) meter to the wading rod, remove the shipping pivot, and replaced it with the sharper pivot used for measurements. The bucketwheel on the pygmy meter was then spun to ensure that the pygmy meter was operating properly. The data recorder then retrieved the measuring tape and data collection sheet. After this was done the team would proceed to the sampling site. Upon arriving at the creek the sample/data collector stretched the tape across the stream perpendicular to the streamflow. The data recorder looked over the site and recorded any interesting features in the field notes section. The team then decided based on visual stream velocity, the visual cross section, and past data the increment(s) to be used between velocity

measurements across the stream. The USGS suggests that one measurement location should not make up more than 10% of the flow. This was often exceeded by a small margin (~ 5%) in our measurements because of the nonuniform profile that caused a high variability in stream velocities over the cross section. Most often large increments were used near the edge of the creek where the water depth and velocity were small compared to mid-stream where smaller increments were used because it was transmitting the majority of the flow. After the increment(s) was determined the velocity and depth of the stream were measured by the sample/data collector at each specific location (based on the determined increment) from one side of the creek to the other. This usually resulted in 20 to 25 measurements for each site. The data recorder recorded the velocity, stream depth, and distance from the edge of the creek for each measurement location. After the streamflow rate data were collected the tape was removed from across the stream.

Once the streamflow rate data were collected the sample/data collector moved upstream a few meters and used the Oakton PC 10 Meter to determine the pH, conductivity, and temperature. This was done by placing the probe in a well-mixed area near the middle of the creek. Also because the creek was quite shallow it was important that the probe was placed in an area with enough depth to cover the sensors and did not disturb the streambed sediment. After the probe was placed in the stream and the reading stabilized the data recorder recorded the values on the data collection sheet.

Next the sample/data collector collected the needed samples. At each sampling site a specific sampling location in the creek was selected. This location allowed for sample collection without disturbing the bed sediment. The sampling location was also

located in a mid-stream, well-mixed area of the creek to obtain a sample that was representative of the majority of the stream.

To collect the samples the sampler held the bottle near its base in the hand and plunged it, neck downward, below the surface. The sampler then turned the bottle until the neck pointed slightly upward and the mouth was directed toward the current taking care to avoid contact with the bank or streambed.

Standard Methods (1998) suggests to "fill sample containers without prerinsing with sample." They indicate that "prerinsing can bias results high when certain components adhere to the sides of the container." *Standard Methods* (1998) also suggests leaving about 1% of the volume as air space for thermal expansion in the grab sample collected to determine ammonia, chloride, and nitrate. For the bacteria samples *Standard Methods* (1998) suggests leaving ample air space in the bottle to facilitate mixing by shaking. The 120mL IDEXX bottles used to collect the bacteria samples required 100mL of sample for laboratory analysis and so each sample was filled to the line indicating 100mL. This allowed for 20mL of air space in each sample collected. For the bacteria samples if the bottle was filled past the indicated volume the excess was slowly poured out until the correct volume (100mL) was obtained. The bottle was then capped making sure that the inside of the bottle or rim of the container was not touched. Each sample container was then labeled with date, time, and location. If a field blank was to be taken the sampling bottle was filled with distilled water from the lab, labeled blank, and then placed with the other field samples. Each sample container was then placed in an ice cooled container at 4°C +/- 2°C (*Standard Methods*, 1998) to be transported to the lab.

After all the field data and samples were collected and stored properly for that particular sampling site the team would proceed to the next upstream sampling site. This procedure was followed for all eight sampling sites. After collecting samples at sampling site 8 the team would proceed to the lab to prepare and store the samples. This sample collection protocol was repeated at 13:00 for the afternoon sampling run.

4.2.2.6 Changes in the Field Data and Grab Sample Collection

At all the sampling sites except sampling site 5 the sampling location did not change throughout the study. On June 27, 2005 sampling site 5 was moved downstream roughly 50 m to a stream location with more stream depth. This was done in order to properly use the wading rod and Gurley 625D Pygmy Meter to measure the streamflow rate because the stream depth should be greater than 0.2 feet. As the study progressed the streamflow within Emigration Creek decreased to a depth below 0.2 feet at the initial location of sampling site 5.

4.2.2.7 Laboratory Analysis

Upon arriving at the lab the sampling bottles containing the ammonia, nitrate, and chloride samples were placed in a refrigerator at a temperature of 4°C +/- 2°C (*Standard Methods*, 1998) and the bacteria samples where immediately processed.

The total coliform and *E. coli* concentrations were determined simultaneously using the Colilert® Method by IDEXX. This method consists of mixing one Colilert® reagent packet per 100mL total coliform/*E. coli* sample in the sampling vessel. Once the reagent was completely dissolved the solutions was poured into a Quanti-Tray®/2000

and then sealed using a Quanti-Tray® sealer. The processed tray was then placed in an incubator and incubated at a temperature of 35°C +/- 0.5°C for at least 24 but no more than 28 hours. After incubation the trays were removed and the number of positive (yellow) large and small wells was counted for each tray. Based on the ratio of large positive wells and small positive wells a MPN (most probable number) was determined using an MPN table produced by IDEXX. This MPN number is a concentration representing the statistically most probable number of bacteria per 100mL of sample. The Quanti-Tray®/2000 contains 49 large wells and 24 small wells. Early on in the study some samples resulted in all the wells being positive. Because of this, most of the total coliform/*E. coli* samples had to be diluted 10X in order to obtain an accurate number of total coliform bacteria. This dilution was preformed prior to adding the Colilert® reagent and accomplished by using 120mL Hardy Diagnostic bottles filled with 100mL of sterile water for most of the total coliform/*E. coli* samples that were diluted. From the Hardy Diagnostics bottle 10mL of sterile water was removed and replaced with 10mL of sample, resulting in a 10X diluted sample. After this dilution the Colilert® reagent was added and then processed as indicated above. The MPN of the diluted samples was then multiplied by the dilution factor (10) to determine the MPN of the original sample.

After determining the total coliform concentrations the *E. coli* concentrations were determined using the same Quanti-Tray®/2000 used in determining the total coliform for each site. Each Quanti-Tray 2000 was placed under a 6 watt, 365 nm, UV light in a dark environment. The number of large and small wells exhibiting fluorescence (meaning the well was positive for *E. coli*) were enumerated, and then

based on the MPN table these two numbers were used in determining the *E. coli* concentration for each sample, as described above.

The enterococci samples were processed and analyzed similar to the total coliform/*E. coli* samples with the exceptions of mixing the enterococci sample with Enterolert™ Reagent instead of Colilert®, incubating the enterococci samples at a temperature of 41°C +/- 0.5°C, and none of the enterococci samples had to be diluted due to the lower concentrations (as was required for total coliform).

The ammonia, nitrate, and chloride concentrations were determined in the lab using an Orion 5 Star Meter with the respective ion selective electrodes (ISE). The sample collected at each sampling site was thoroughly mixed and then split into three separate bottles (one for each analysis). Each ISE was connected to the Orion 5 Star Meter, calibrated using known standards and then placed in each sample. The resulting concentrations for that particular constituent were then recorded for each sample. This procedure was repeated for each constituent. After analyzing samples on July 18 it was determined that the ammonia concentrations at all the sampling sites were near the detection limit of the probe (0.01mg/L). A set of samples was tested again the week of August 22 and again the concentrations were near the detection limits. In addition the nitrate concentrations were very low, less than 0.6 mg/L which is well below the State of Utah water quality guideline of 4 mg/L (Utah Division of Administrative Rules, 2006). The nitrate concentrations were 10 times lower than the chloride concentrations in most of the samples so silver sulfate ($AgSO_4$) was required to reduce the interference of chloride, by precipitation, before the nitrate concentrations could be determined per *Standard Methods* (1998).

4.2.3 Quality Control and Assurance

Burton and Pitt (2001) summarize *Standard Methods* (1995) in suggesting seven elements of a good quality control program: certification of operators, calibration with standards, recovery of known additions, analysis of external standards, analysis of reagent blanks, analysis of duplicates, and the use of control charts. All of these elements were included in the quality control plan for this study with the exception of using known additions. Also the quality control plan used for the bacteriological constituents relied upon the specific elements: certification of operators, analysis of reagent blanks, analysis of duplicates, and the use of control charts because the bacteriological methods used currently do not have quantifiable standards available.

In order to check the certification of each operator *Standard Methods* (1998) suggests that the analysts perform pre and periodic tests. The operators that preformed the analysis for this study were trained using the manuals supplied by the manufacture and performed each analytical procedure prior to analyzing any of the samples used in this study.

The second element, calibration with standards, was accomplished by establishing a plan that included calibrating the pH meter, conductivity meter, and each ISE prior to analyzing any samples.

The analysis of external standards was conducted at least once a day while operating the equipment. These standards were necessary to ensure the accuracy of the results. The standard concentrations used were within the range of values expected in the samples.

Standard Methods (1998) also suggests that at least 5% of the total sampling effort be reagent blanks or a blank should be used for each batch of samples, whichever is more frequent. The sampling plan included the analysis of a blank sample for each constituent analyzed for each batch of samples collected during a sampling run. This resulted in blanks accounting for more than 10% of the sampling effort.

Standard Methods (1998) suggests that at least 10% of the total sampling effort be duplicates or a duplicate should be taken for each batch of samples which ever is more frequent. The sampling plan included a duplicate for each constituent taken for each batch of samples collected during a sampling run. This resulted in duplicates accounting for more than 10% of the sampling effort. These duplicates were randomly placed between samples for analysis.

Standard Methods (1998) suggests a way to know if the variability between a duplicate and the respective sample is excessive. The necessary calculations were preformed and the only duplicate that showed excessive variability was the enterococci duplicate and respective sample collected during the morning sampling run on September 6. The data from this batch of enterococci samples were still used because of the large amount of data collected (reducing the dependence of each individual value) and also the error did not appear to be extremely excessive with respect to the trends observed for the preceding and following batch of samples. The pH and chemical constituent concentrations were tracked and showed very little variation from week to week. This in conjunction with the measurement of known standards explained above ensured the precision and accuracy of the results for the chemical constituents.

4.3 Bacteria Tracer

A bacteria tracer was prescribed to better understand the bacteriological die-off and attenuation dynamics in Emigration Creek. The results and conclusions formulated from the bacteria tracer study were then applied to the warm season total coliform, *E. coli* and enterococci results to shed light on the magnitude of additional bacteriological sources and identify the most likely bacteria removal mechanisms. One study by Moore (1988) described the die-off of enteric bacteria in natural stream water using a variation of Chick's Law (a simple first order reaction in chemical kinetics). It was suspected that the bacteria loss coefficients from previous studies may not be applicable or appreciable to Emigration Creek due to the effects of the high anthropogenic activity within the canyon on physical and chemical components of Emigration Creek and the relatively short travel time (~36 hours in October).

4.3.1 Methods

The methods used to perform the bacteria tracer were very similar to typical dissolved tracer methods. Basically, a unique soil bacteria (DA001), at a specific concentration and rate, was released in an upper reach of Emigration Creek Samples were then collected at specific predetermined locations downstream of the injection point beginning with site A roughly 20 m downstream of the injection site (see Figure 4.2). These samples were then analyzed using ferrography (an innovative technique for determining bacteria at low concentrations) (Johnson et al., 2001 and Zhang et al. 1999) to develop curves showing the plume of bacteria passing each sampling point. It was necessary to try and identify where the tracer bacteria were in the stream so a slug of

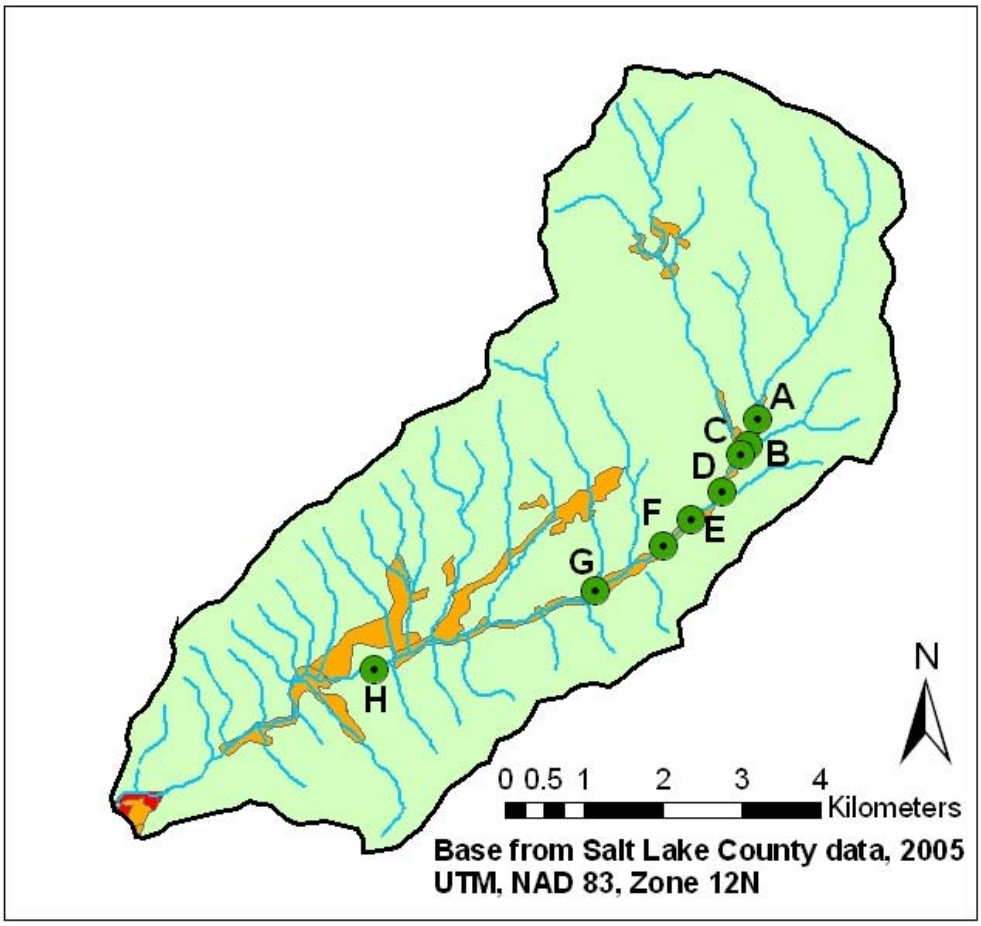

Figure 4.2—Location of bacteria tracer sampling sites.

bromide was injected into the stream 30 minutes prior to the bacteria injection. Because the bromide concentration could be measured quickly with a field probe its presence provided a way for each sampling site to know when to begin sampling, the adjustment in the frequency of samples, and when to terminate the sampling.

4.3.2 Field Procedures

The bacteria tracer was conducted on October 13, 2005. Before the bacteria or bromide tracers could be injected the equipment and tracers used for the injection and

sampling had to be prepared. The injection equipment and bromide solution was supplied and prepared by the USGS. The bacteria strain used was DA001 (1.1μm long by 0.3μm wide) supplied by Envirogen Inc. at a concentration of 8×10^{13} cells per mL and a total volume of 14 L. This cell solution was shipped in an ice packed cooler and was received the morning of the injection date.

To begin the tracer experiment a bromide solution was injected midstream at the injection site beginning at 11:50 and ended 30 minutes later at 12:20. Shortly after at 12:30 the bacteria solution injection was initiated at a rate of 490 mL per minute using the positive displacement pumps supplied by the USGS. The bacteria injection continued for 30 minutes and ended at 13:00.

To mark the time to begin sampling at each of the sampling sites a bromide probe was used to identify when the plume of bromide had reached the site. Collection of the bacteria tracer samples began roughly 15 minutes after the bromide plume had reached the site. The samples were collected in 15mL polypropylene vessels from predetermined locations within the stream that were most likely to be representative of the instream concentrations, meaning samples were taken midstream in well-mixed areas similar to the warm season sampling protocol. The sample frequency was first based on approximations of how long it would take the plume to pass each sampling site, but were adjusted based on the longevity and intensity of the bromide plume. This most often resulted in decreasing the sample frequency. After the samples were collected they were preserved with 1% formaldehyde and stored in an ice packed cooler and transported to a lab whereupon they were stored in a refrigerator at ~4°C prior to analysis.

4.3.3 Laboratory Procedures

The concentration of tracer bacteria for each sample was determined using ferrography (Johnson et al., 2001 and Zhang et al. 1999). This method requires the concentration of tracer bacteria to be ~1000 to 20 cells per mL; thus a rough estimate of the concentration was determined so the sample could be diluted to be within this acceptable range. This rough estimate of the concentration was determined using a filter counting technique. This technique was preformed by mixing 1.0mL of sample with 5.0mL of pure water (Milli-Q) and 50 μL of antibody solution. This solution was mixed for 5 minutes, during this time the antibody solution attaches to the tracer bacteria. Once mixed this solution was strained through a 0.2 micron filter, leaving the tracer bacteria with attached antibody deposited on the filter. This filter was placed on a glass slide and viewed under an epifluorescence microscope. The epifluorescence microscope caused the antibody attached to the tracer bacteria to fluoresce to allow for visually enumeration over a specific area. For each filtered sample tracer bacteria were enumerated over ten areas on the filter. An average of these countings multiplied by a factor to account for the entire filtered area of the filter was used to represent the number of tracer bacteria per mL of sample. By repeating this protocol for a few samples at each site a rough estimate of the concentrations of bacteria in time was determined for each sample at each respective site. After determining a rough estimate of the concentration for each sample, if the concentration was predicted to exceed the 1000 cell per mL limit the sample was diluted by means of serial dilutions using pure water (Milli-Q) to be slightly less than 1000 cells per mL. Once diluted the sample was ready for ferrographic analysis.

To begin the ferrograph procedure a solution containing 0.5mL pure water (Mill-Q) was added to 40µL of microbeads and 160µL of antibody. This solution was mixed for 15 minutes to allow the antibody to attach to the microbeads. The solution was then run through a separation column that was placed in a magnet; this allows the microbeads with antibody attached to be separated from the remaining solution. The separation column was then removed from the magnet and 1.0mL of Milli-Q water was flushed through the column collecting the microbeads with attached antibody. Next 0.1mL of this microbead-antibody solution was added to 0.5mL of sample (diluted if necessary) and 0.2mL 2M NaCl solution. This solution was mixed for 15 minutes to allow the microbead-antibodies to attach to the tracer bacteria. The mixed solution was then placed in one of five small reservoirs (meaning five samples could be run at one time) attached to the ferrograph. The ferrograph was then turned on and the solution was drawn slowly through a small flat chamber. A small sample reservoir (0.5 mL) fed the sample into the chamber which was composed on one side of a flat plastic wall and the other side was a glass slide. The two surfaces were separated by a thin (<1mm) gasket. The glass slide part of the chamber was placed against a surface with a strong magnetic field. As the solution flowed through the chamber the microbeads attached to the bacteria were attracted to the magnetic field and stuck to the surface of the slide. After all the solution was drawn through the chamber the mounting reservoirs were detached from the ferrograph and the slide was removed from the gasket. A drop of Prolong anti-fade glue was placed on each of the five samples areas. The anti-fade glue slows the degradation of the fluorescent antibody attached to the bacteria so the tracer bacteria deposited on the slide can be counted conveniently a few days later rather than

a few hours. Next a glass slide was carefully placed on top of the slide so the glue would spread out evenly across the slide. The slide was placed in a dark area and the glue permitted to dry for 24 hours. Sometime after 24 hours the slide was placed under an epifluorescence microscope (same microscope used in filter counting) where each of the five areas containing the bacteria was viewed. The light from the microscope and antibody connected to the tracer bacteria would cause a fluorescent halo to surround the tracer bacteria allowing visual enumeration. The entire area where the tracer bacteria were deposited was viewed and all the tracer bacteria were counted. This number was then multiplied by 2 (only 0.5 mL of sample was analyzed) to obtain the concentration of the diluted solution. This concentration was then multiplied by the respective dilution factor in order to obtain the actual concentration of bacteria in the sample.

4.3.4 Quality Control and Assurance

Blanks and standards were used to ensure the quality of the bacteria tracer data. Blanks and standards each accounted for 10% of the analyzed samples. All blanks and standards were treated as samples and analyzed using the above procedures.

The blanks consisted of samples taken prior to any of the bacteria plume reaching the sampling site and pure water (Milli-Q) used in the procedures above. Positive results would indicate either contamination or that the natural bacteria in Emigration Creek was a receptor for the antibody solution and would have resulted in a review of the procedures. All blanks tested negative for tracer bacteria, although some of the blanks contained a few (~5) much smaller and dimmer bacteria shaped matter.

Standards consisting of three different concentrations of the bacteria DA001 were produced and preserved in the lab the day prior to the bacteria tracer. Changes in bacteria counts for these artificial standards would indicate loss of activity of the antibodies or degradation of the magnetic microbeads used in this method.

CHAPTER 5

RESULTS AND DISCUSSION

The goals of this study were to (1) determine the spatial and temporal distribution of concentration and loading of bacteriological and chemical fecal-contamination indicators and (2) document spatial variations in bacteria attenuation along the main channel of Emigration Creek. These goals were met by achieving the following objectives:

1. Conduct 4-month, warm season, monitoring of the total coliform, *E. coli*, enterococci, nitrate, ammonia, and chloride concentrations.
2. Measure streamflow during sample collection to determine the flux differences along the rural to urban stream transect for the constituents monitored.
3. To quantify bacteria attenuation using a bacteria tracer experiment along the rural-to-urban transect to identify bacteria loading sources and magnitudes.

In this chapter the results from this study are summarized and analyzed to determine changes in constituent concentration and loading both spatially and temporally. The results will be compared to previous studies and the historic (2005) and new (2006) State of Utah water quality criteria. The bacteria tracer results were used to determine general bacteria attenuation dynamics and include consideration of the major

form of bacteria loss. A simple model that indicates input loadings into Emigration Creek along each of the warm season study reaches was used to synthesize the results of the warm season monitoring and the bacteria tracer. Included within the results is contemplation on the reasons for the results obtained. Further more specific studies will likely be necessary to better validate the reasoning described herein.

5.1 Spatial Variation

Spatial trends from sampling site to sampling site over the course of the warm season monitoring were observed in constituent concentrations, conductivity, and streamflow in addition to the flux of each constituent passing the sampling sites. This section will describe the trends of each constituent and discuss their relationship.

5.1.1 Variation in Concentration

Figures 5.1 through 5.5 present the geometric mean (for bacteriological constituents) or mean (for chemical constituents) concentrations for the water quality and quantity constituents (with the exception of ammonia; because ammonia concentrations observed were near the detection limit of the probe (0.01mg/L) and thus insignificant) analyzed by this study for all eight sampling sites. In order to understand these results recall that site 7 is not downstream of site 8. Site 8 is on the Emigration Creek main channel in Kilyon Canyon, while site 7 is on the Burr Fork channel that enters into Emigration Creek ~0.7 km downstream of site 8 (see Figure 4.1).

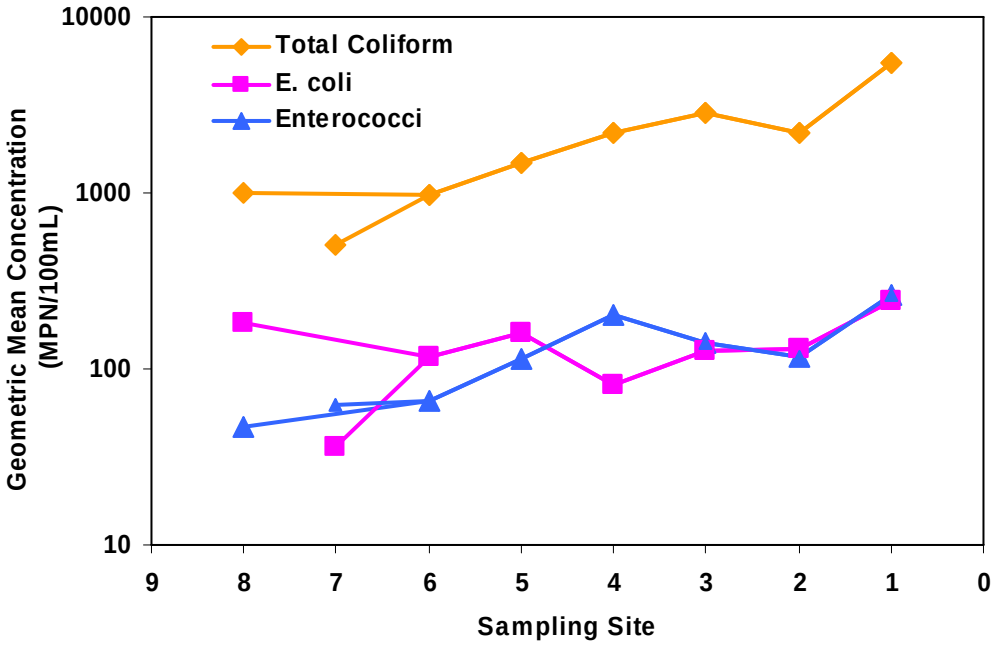

Figure 5.1—Calculated geometric means for each bacteriological constituent based on all (both AM and PM) samples collected at that site.

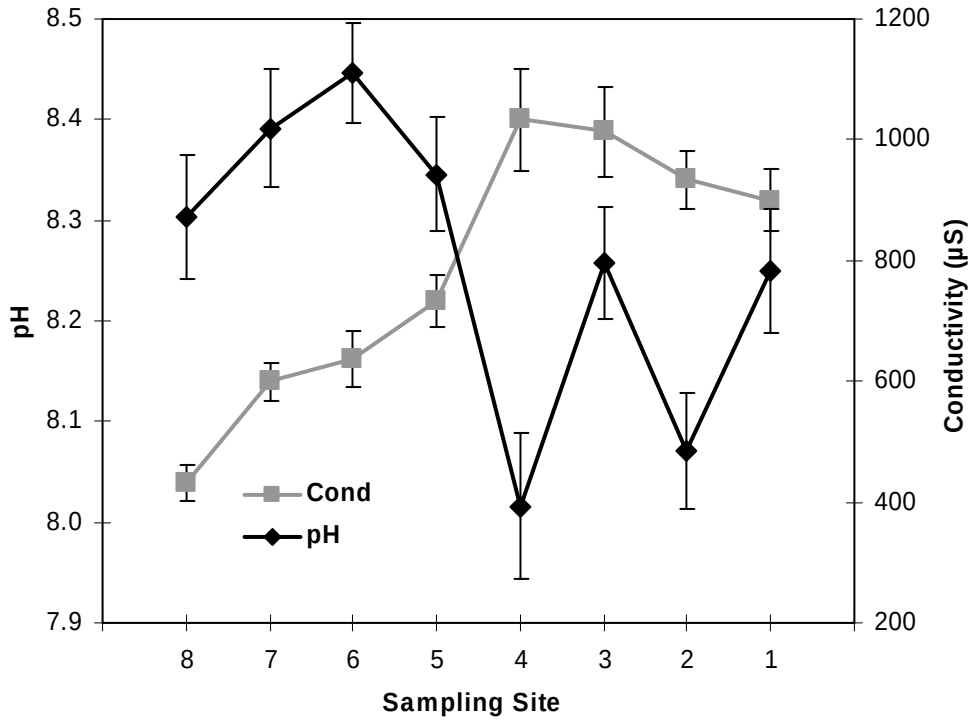

Figure 5.2—Average of all (both AM and PM) pH and conductivity measurements conducted in the field at each sampling site.

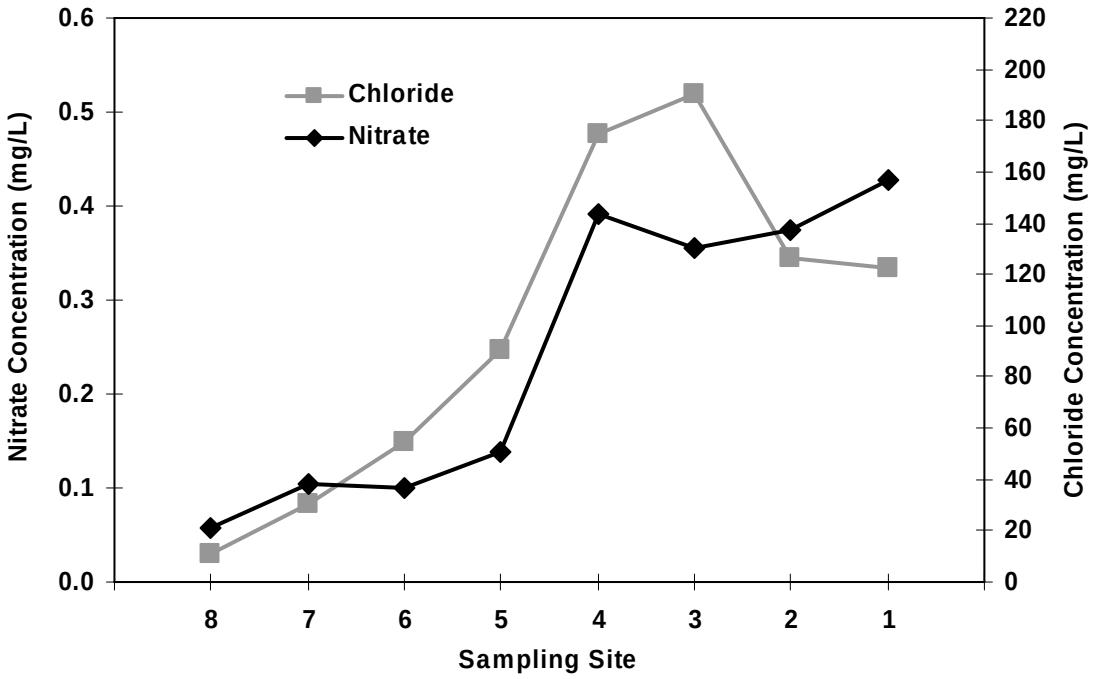

Figure 5.3—Average of all (both AM and PM) nitrate and chloride samples analyzed for each sampling site.

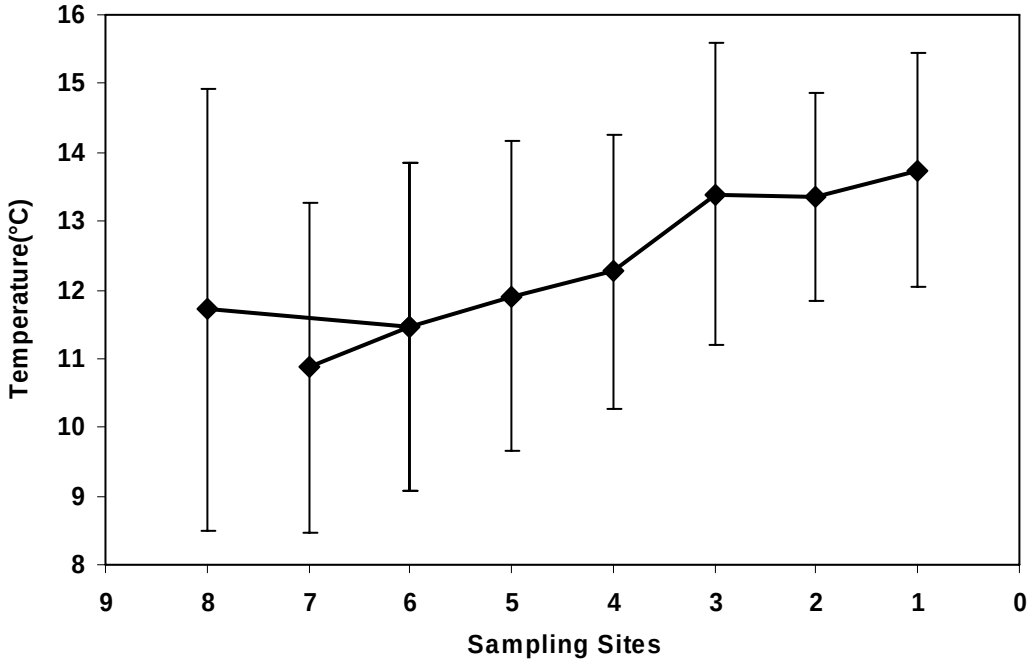

Figure 5.4—Average of all (both AM and PM) temperature measurements recorded in the field at each sampling site.

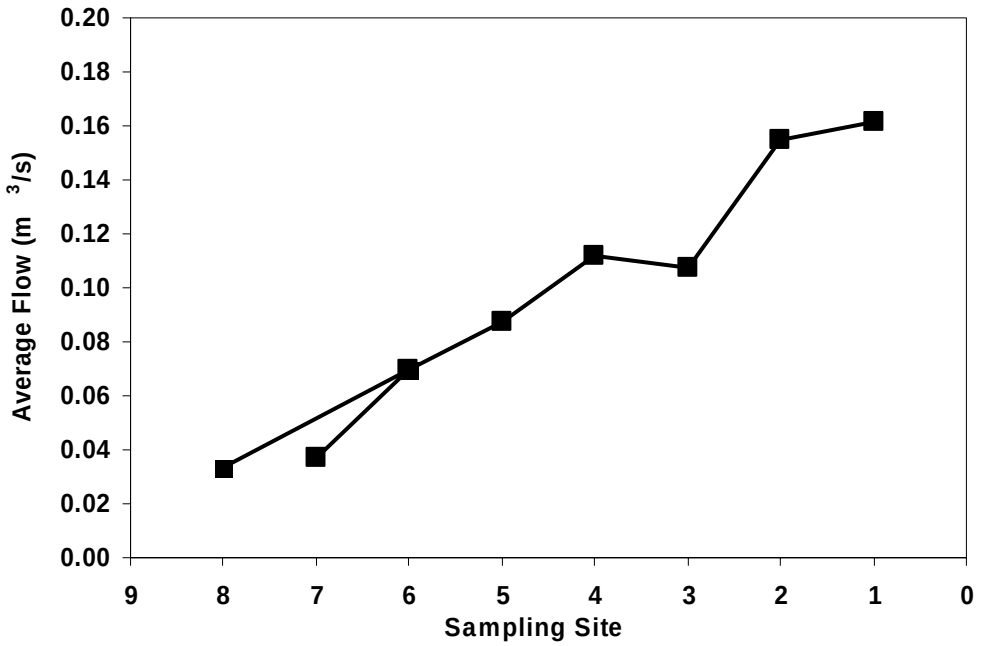

Figure 5.5—Average of all (both AM and PM) stream flow rate measurements calculated at each sampling site.

Three commonalities in Figures 5.1 though 5.5 are: (1) a decrease in most parameters from sampling site 3 to 2 with the exception of nitrate (Figure 5.3) and streamflow (Figure 5.5) which both show increases; (2) significant changes between sampling sites 5 and 4; (3) and a general increasing trend from upstream to downstream with the exception of pH, which varies. These commonalities will continue to be discussed due to there repetitiveness in the results obtained.

The first commonality shows symptoms of groundwater inflow between sampling sites 3 and 2. The strongest indicators being increased streamflow with no observable surface inflows and slightly decreased water temperature (groundwater is usually cooler that surface water). In contrast groundwater usually has greater conductance and dissolved constituents (such as chloride) both of which show a

counterintuitive decrease. Additional study will be necessary in order to determine the chemical composition of the groundwater and its effects.

The second commonality also shows symptoms of groundwater inflow, but with drastically different effects on the bacteriological and chemical constituents. As in the reach from 3 to 2 a substantial increase in flow was observed with little observed surface inflow, but instead of a diluting effect a large increase was observed with respect to total coliform and enterococci. In addition a large increase in the dissolved constituent concentrations; nitrate, chloride, and $[H^+]$ (shown as a decrease in pH) was observed. A fault was suspected of transecting Emigration Creek just upstream of sampling site 4. Groundwater flow along this fault entering into Emigration Creek is probable. Natural groundwater contributing to Emigration Creek along this reach would explain increases in the chloride concentrations and conductivity and possibly the nitrate concentrations, but the only way the influent groundwater could solely explain the large increase in the flux of total coliform and enterococci would be if a hydraulically active bacterial subsurface source (or sources) was leaching into the groundwater upstream of the fault. This bacteria source would plausibly be laden with coliforms (including *E. coli*), enterococci, nitrate, and have a lower pH than normal groundwater. It seems probable that if the hydraulic retention time from the bacteria source to the fault was on the order of a few days and the chloride concentration of the groundwater was high that the *E. coli* concentration may decay more rapidly and more significantly than the more robust (in saline environments) enterococci and more abundant total coliform. Another reason may be that the total coliform, enterococci, nitrate, and hydrogen ion concentrations (pH) are coming from the surface adjacent to

the creek. This is supported by the observation of an area that appeared to contain livestock (horses in particular) within and along the reach from 5 to 4.

In the past the ratio of fecal coliform (which includes *E. coli*) to fecal streptococci (which includes enterococci) was used to describe the source as human related (higher fecal coliform) or animal related (higher fecal streptococci), but is currently not widely accepted. In the case of sampling site 4 the enterococci concentrations are much higher than the *E. coli* which if the above relationship is valid would indicate an animal related source or sources. Additional study of this reach will likely be necessary in order to better explain the unique bacteriological and chemical changes.

The third commonality, a general increase in bacteriological concentrations over the entire reach, likely indicates many contributing sources along the study reach. This will be further discussed in light of the flux of the bacteriological constituents.

Other noteworthy points illustrated in Figure 5.1 include a relatively high concentration of *E. coli* observed at sampling site 8 and higher concentrations of enterococci, than *E. coli,* observed at sampling site 7. These differences in the upper reaches (sampling sites 7 and 8) are likely due to different source types or differences in the mode and timing of the surface or subsurface bacteriological transport mechanisms.

Figure 5.2 shows the average pH and conductivity measurements for each sampling site with error bars representing one standard deviation. As mentioned and discussed previously the most notable changes for these averaged measurements takes place from sampling site 5 to 4, possibly due to reasons discussed above. Also of interest was the decrease in pH from sampling site 3 to 2, possibly due to dilution from

groundwater. Overall there was not much change in the pH and conductivity measurements at each site as noted by the error bars. These consistent measurements indicated that pH and conductivity were not strongly associated with the quantity of flow which changed from around 0.4 m^3/s in June to around 0.05 m^3/s in September at Rotarty Park (sampling site 2).

The chloride and nitrate concentrations (Figure 5.3) also illustrated substantial increases along the reach from sampling site 5 to 4 with an interesting decrease in chloride from sampling site 3 to 2. This decrease may be related to changes in water chemistry or dilution.

The water temperature (Figure 5.4) seemed to follow a general increasing trend with water temperatures being the coldest at sampling site 7 and warmest at sampling site 1. Usually the temperature from upstream to downstream varied by only a few degrees throughout the study period, this was likely due to shading of the stream by dense vegetation and influent cooler groundwater. As noted by the error bars (representing one standard deviation) the water temperature at the upper sampling sites varied more than those downstream.

The streamflow (Figure 5.5) shows a steep increasing trend with major increases from sampling site 5 to 4 and 3 to 2. These increases are likely due to groundwater because there were only three major influent streams observed: Burr Fork (confluence between sampling site 8 and 6); Brigham Creek and Freeze Creek (both confluences between 6 and 5). The observed loss (on average of 4 % of the flow) from sampling site 4 to 3 is likely a function of groundwater recharge or it may be due to losses associated with a diversion at Camp Kostopulos that diverts a portion of water from the creek into

a small fish pond and then discharges the overflow back into the stream roughly 200 m downstream.

5.1.2 Variation in Flux

Based on the streamflow rate and bacteriological and chemical concentrations a flux for each constituent was determined. The units of flux are in the form of a number (bacteria) or a mass (chemical) passing a point (sampling location) per day. The flux eliminates the confusion created by dilution of the constituents by influent flow. The flux obtained for each bacteriological constituent, considering every sample taken, is shown in Figure 5.6 and the fluxes for the nitrate and chloride samples are shown in Figure 5.7. In comparing Figures 5.1 and 5.6 we see that the increases in flux of total coliform and enterococci from sampling site 5 to 4 are much more pronounced than the concentration plot shown in Figure 5.1. This supports the evidence stated above that there is a source of total coliform and enterococci in this region. Also evident in comparing Figures 5.1 and 5.6 is the decrease in *E. coli* concentration, which is most likely due to dilution from influent groundwater flow or removal by processes within the stream (this removal will be discussed later) as the flux remained nearly constant from sampling site 5 to 4. In addition, the losses observed from site 3 to 2 in Figure 5.1 and 5.3 are not observed in the flux (Figure 5.6 and 5.7), indicating that the decrease observed earlier is due to dilution.

From Figure 5.6 a decrease in the flux of total coliform and enterococci is observed from sampling site 4 to 3. In connection with this, a loss in streamflow and nitrate and chloride fluxes were also observed from 4 to 3 (Figure 5.5 and 5.7).

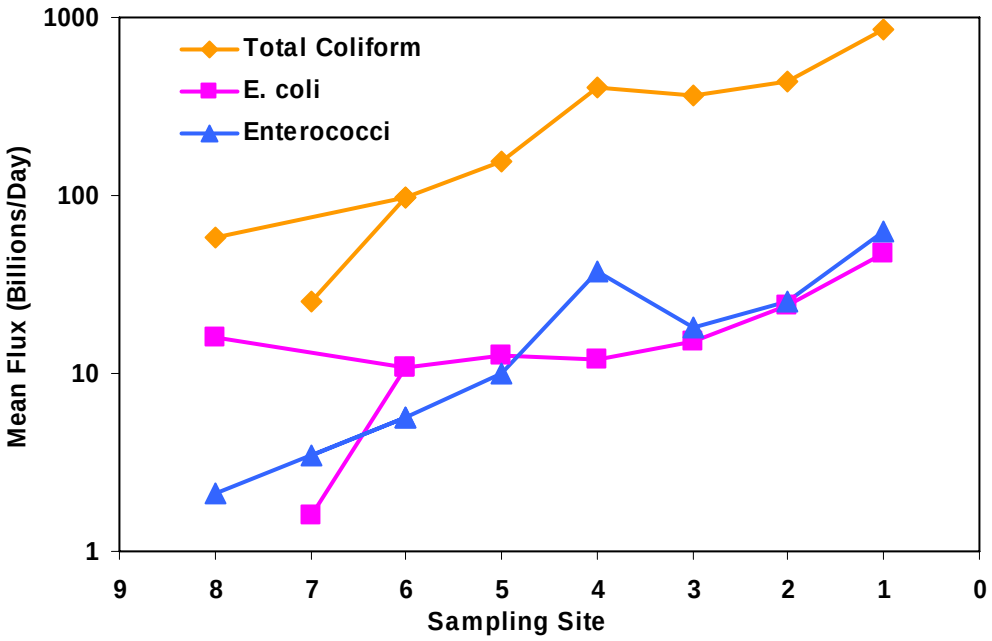

Figure 5.6—Calculated mean fluxes for each bacteriological constituent based on all (both AM and PM) samples collected at each sampling site.

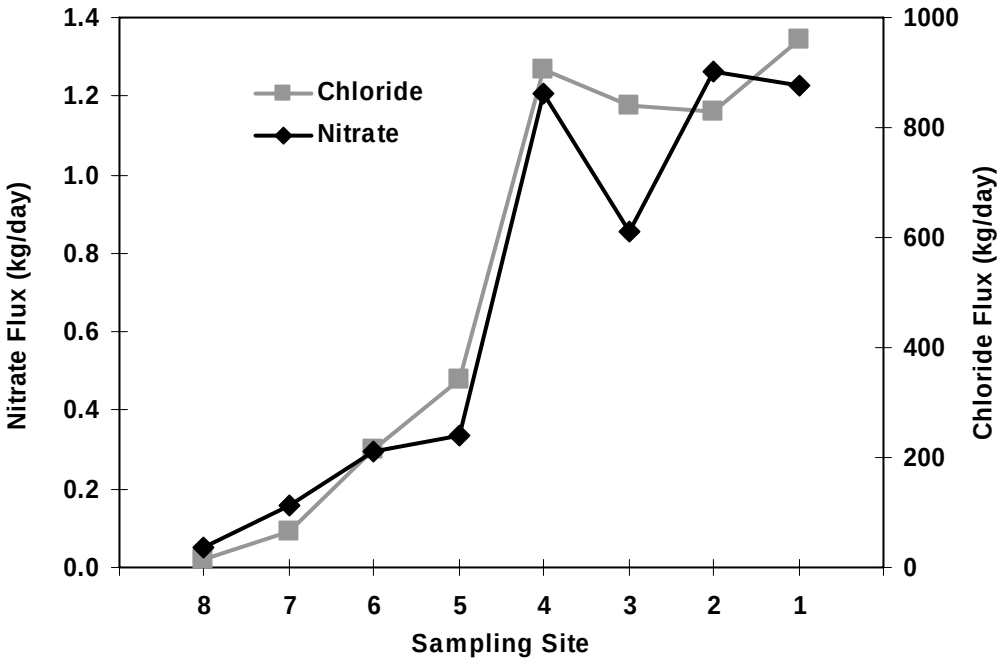

Figure 5.7—Average flux of all (both AM and PM) nitrate and chloride samples analyzed for each sampling site.

The loss of flux along this reach may possibly be explained by groundwater recharge, changes in water chemistry that favors the removal of the constituents, the increased hydraulic retention time of the water diverted into the small pond at Camp Kostopulos, or a combination of these.

5.2 Temporal Variation

Temporal trends were observed in the constituent concentrations and fluxes, conductivity, and streamflow. This section will describe the temporal trends of each constituent and discuss the similarities and differences observed. It is worth noting that because the sampling began June 13 and ended September 20, the monthly geometric means and averages for these 2 months are based on only 3 weeks of data.

5.2.1 Variation in Concentration

Figure 5.8 shows the decrease in streamflow from the beginning (June) to the end (September) of the sampling period. This decrease is the expected effect of seasonal high flows in the spring, from snowmelt runoff and shallow groundwater sources, to the low flows in the fall after the relatively dry warm season. Figure 5.8 also illustrates the increasing flow from upstream to downstream during June and July with a relatively constant flow spatially in August and September. This trend was likely due to the increasing amount of drainage area downstream. Of particular interest was the consistent decrease (on average of - 4%) for every month in streamflow from site 4 to site 3, possibly due to factors explained above.

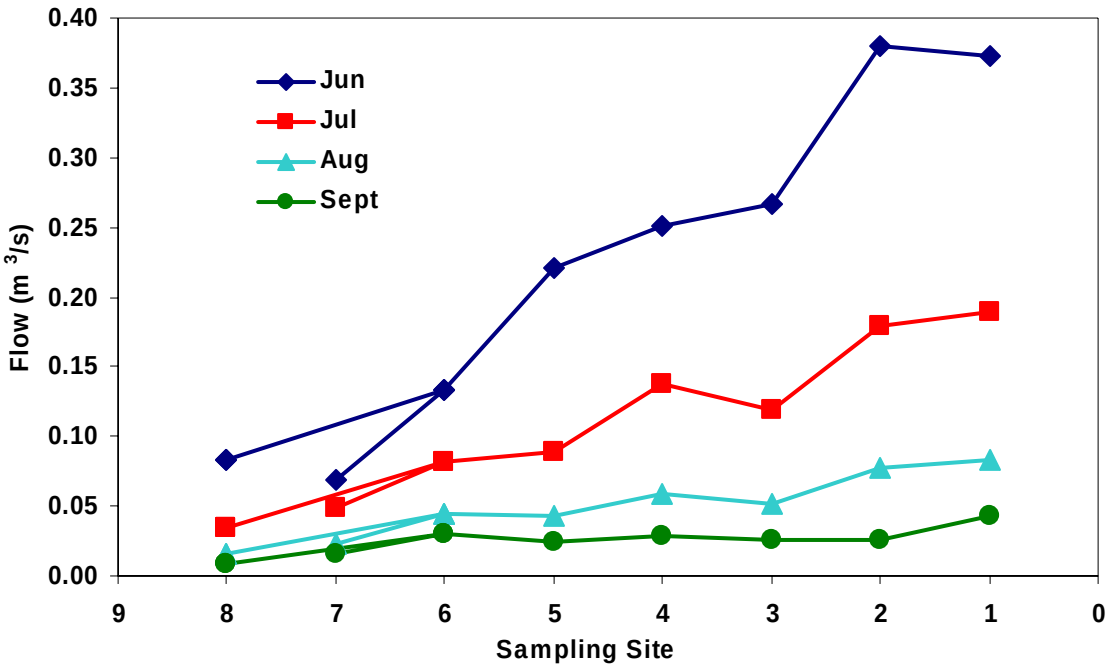

Figure 5.8— Average of all (both AM and PM) monthly stream flow rate measurements calculated at each sampling site.

The reach (from site 3 to site 2) following the upstream loss showed a substantial increase in streamflow, with no visible influent streams after July. This likely means that groundwater was replenishing the streamflow along this reach during all months observed.

Figures 5.9, 5.10, and 5.11, respectively, show the geometric mean of *E. coli*, enterococci, and total coliform for all the concentrations observed at each sampling site for each month. For each of the bacteriological constituents the trend and magnitudes observed in July and August appeared to be elevated and quite similar. These increases are likely due to increased activity within the canyon, which will be discussed later. Trends in June showed decreased concentrations, likely due to the dilution effect of more streamflow. Trends in September showed more irregularity likely due to the

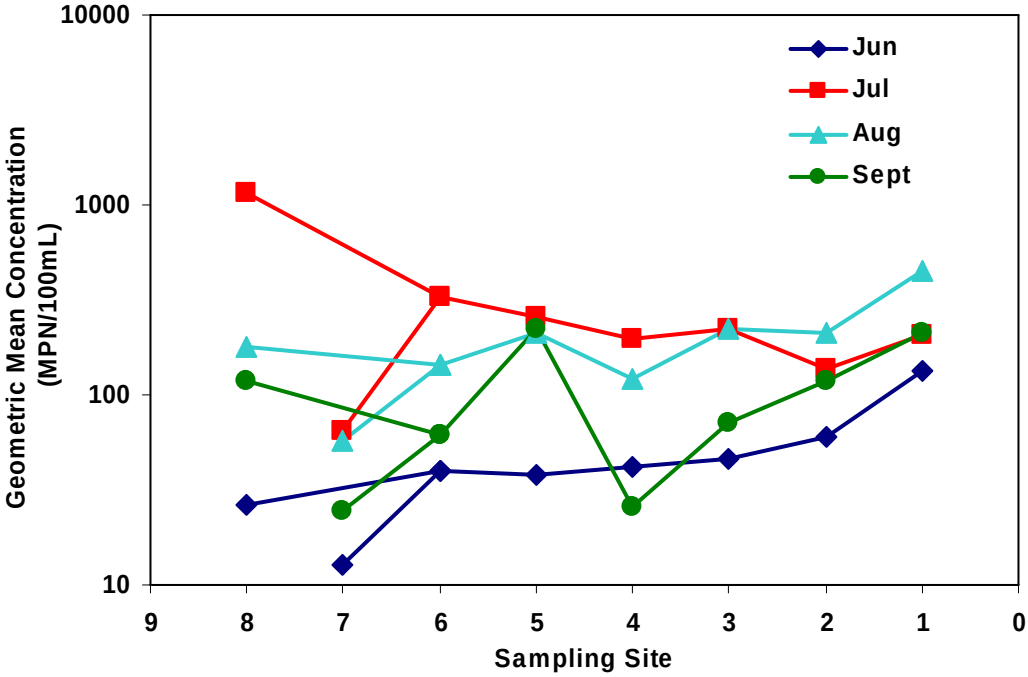

Figure 5.9—Geometric mean of all (both AM and PM) monthly *E. coli* concentrations analyzed for each sampling site.

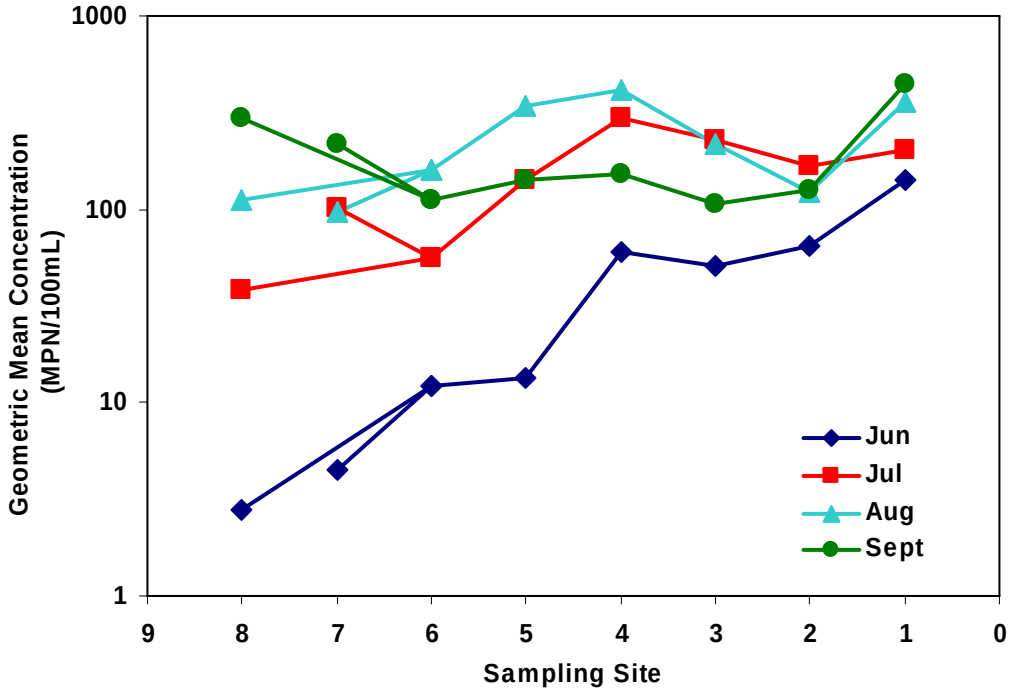

Figure 5.10—Geometric mean of all (both AM and PM) monthly enterococci concentrations analyzed for each sampling site.

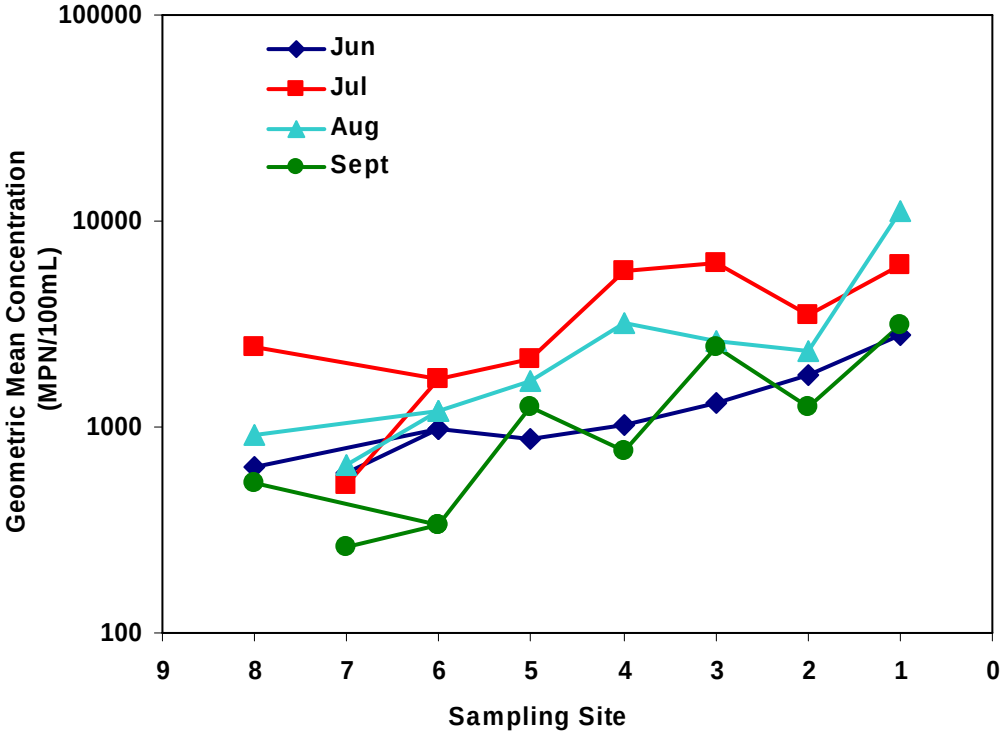

Figure 5.11—Geometric mean of all (both AM and PM) monthly total coliform concentrations analyzed for each sampling site.

decrease in streamflow and high bacteria loss rates within the stream (the loss rate with be discussed later). Figure 5.9 indicates that the relatively high concentrations of *E. coli* at sampling site 8 with respect to the other sites.

Figure 5.10 shows interestingly high enterococci concentrations observed in the upper reaches (Sampling sites 8 and 7) in September. In addition, the downstream sampling site 1 showed consistently high concentrations throughout the study period. The persistent elevated concentrations at sampling site 1 are likely due to a consistent source or sources between sampling sites 2 and 1. One suspected source is the large number of birds that are attracted by the zoo, which is located along this reach.

Figure 5.11 shows that in general the total coliform concentrations decrease for all observed months from site 8 to site 6, perhaps due to the inflow of lower concentrations observed in Burr Fork. From site 6 to site 4 the concentrations increase (except in August), with a significant increase noted from 5 to 4 and 2 to 1. The observed significant increase from site 5 to 4 and 2 to 1 was also found by Glenne and West (1981) as presented in Figure 3.6 (their sites 10 to 9 and 2 to 1 corresponded to the sites 5 to 4 and 2 to 1, respectively). The sampling sites, Taggart's Grill and Maryfield Drive, selected by Jensen et al. (2003) in 2001, roughly (~1 km) correlate to sampling site 5 and 3 respectively. The Jensen et al. (2003) report does not show the substantial increase along this reach (Figure 5.12), possibly indicating that the source is not consistent from year to year or that the sites are too spatially separated to compare results. On the other hand, the fecal coliform data reported by Jensen et al. (2003) appear to shows similar relatively high concentrations during the months of July and August (Figure 5.13).

The timing of increased concentration from site 5 to 4 is very interesting in that this study shows the concentration increase only in July and August, whereas Glenne and West (1981) observed the increase in April, June, and August. This may further substantiate that the total coliform and enterococci are due to animals that may be occupying the area during particular months whereas a groundwater source would likely be consistent and increasing the concentration with less diluting streamflow in September.

Other observations from Figures 5.11 and 3.6 are a consistent decrease in the lower reach (between corresponding sites: 3 and 2 for this study and the 1981; and from

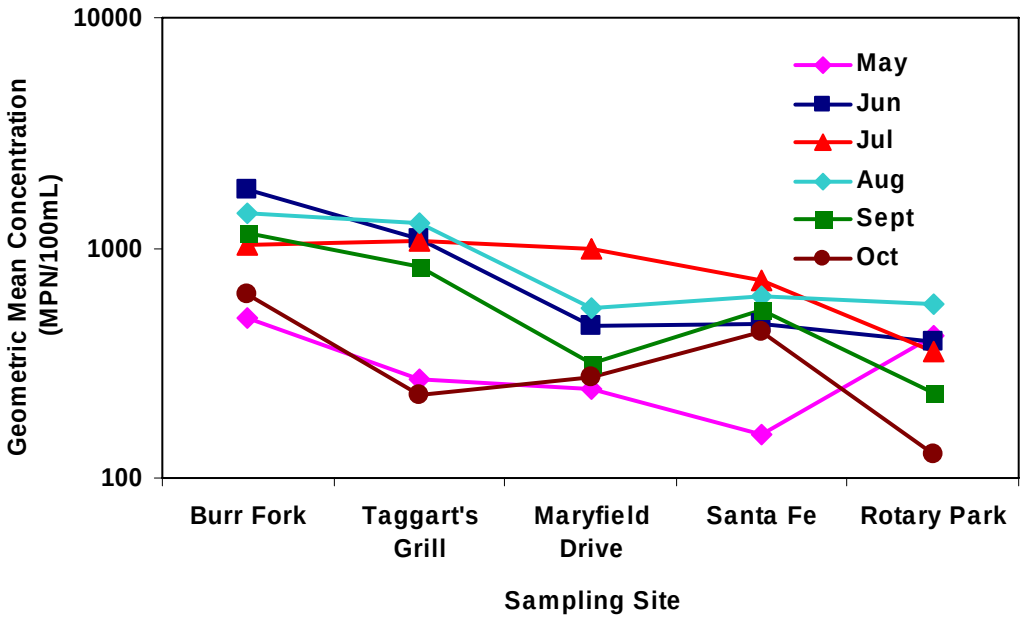

Figure 5.12—Total coliform concentrations at each sampling site from May to October 2001 (figure produced using data from Jensen et al. (2003)).

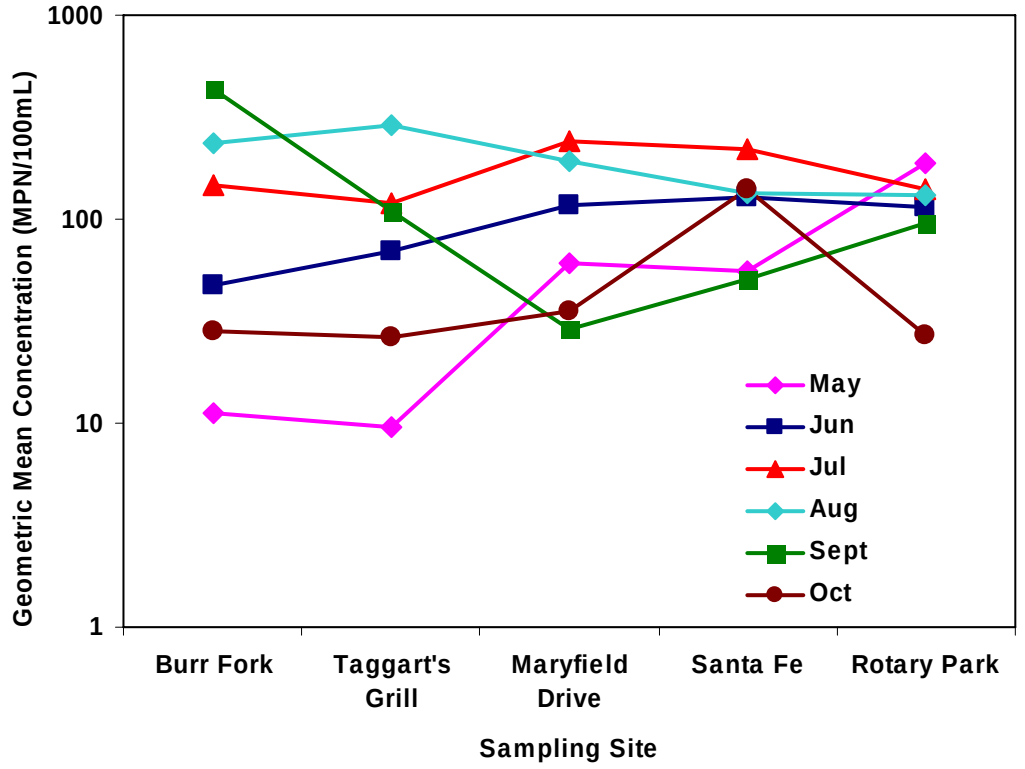

Figure 5.13—Fecal coliform concentrations at each sampling site from May to October 2001 (figure produced using data from Jensen et al. (2003)).

Santa Fe to Rotary Park for the 2001 study). This supports the evidence that there is influent groundwater diluting the concentrations along this reach over the entire sampling period.

5.2.1.1 Comparison to Water Quality Regulations

The state of Utah water quality regulations has recently changed from relying on both total coliform and fecal coliform as indicator bacteria to solely *E. coli*. The allowable 30-day geometric mean concentration and maximum concentration allowed in any sample is 206 and 940 (No. per 100mL), respectively (Utah Division of Administrative Rules, 2006). Figure 5.14 shows a moving 4-week (~30-day)

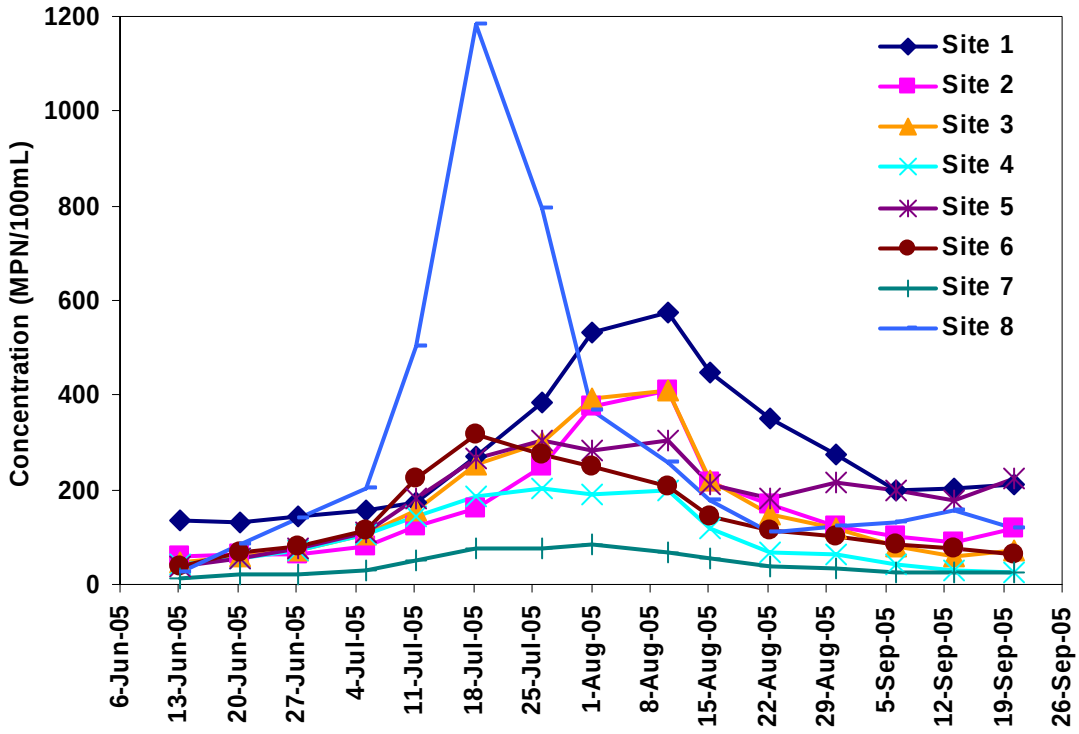

Figure 5.14—Weekly variation of moving 30-day geometric mean of the *E. coli* concentration at each sampling site.

geometric mean of *E. coli* concentrations at each sampling site. Figure 5.14 shows that every sampling site except 7 and 4 exceeded the 30-day geometric mean criterion. The exceedences show a seasonal variation likely due to increases in human, pet, and wildlife activity in and around Emigration Creek. Overall the upper sampling sites show peak concentrations near mid July while the lower sampling sites show peak concentrations around the first part of August. This is likley due to increase recreational activity in July (this reasoning will be supported later) in the upper reaches and the decrease in streamflow or dilution near the end of the summer in the lower reaches.

The second criterion, which requires the *E. coli* concentration to be less than 940 (No. per 100mL) for any individual sample, was exceeded by 24% of samples taken at sampling site 8. This result is illustrated by the extremely large peak in Figure 5.14. This criterion was also exceeded in 7% and 10% of the samples taken at sites 2 and 1, respectively. Sampling site 8 is downstream of a hiking trail that parallels the creek quite closely (5-10 m) with open crossing that required walking through the stream in several locations. Increased use of this trail by hikers and their dogs may be causing these high concentrations at sampling site 8. The high concentrations at sampling site 2 may be due to the upstream dog park and the high concentrations at sampling site 1 may be the attenuation effect from site 2 in addition to the birds that are attracted by the zoo upstream of sampling site 1.

The historic maximum allowable 30-day geometric mean concentration of total coliform for Emigration Creek was 5000 (No. per 100 mL) (Utah Division of Administrative Rules, 2005). Figure 5.15 shows a moving 30-day geometric mean of the total coliform concentrations for each sampling site. Figure 5.15 shows that

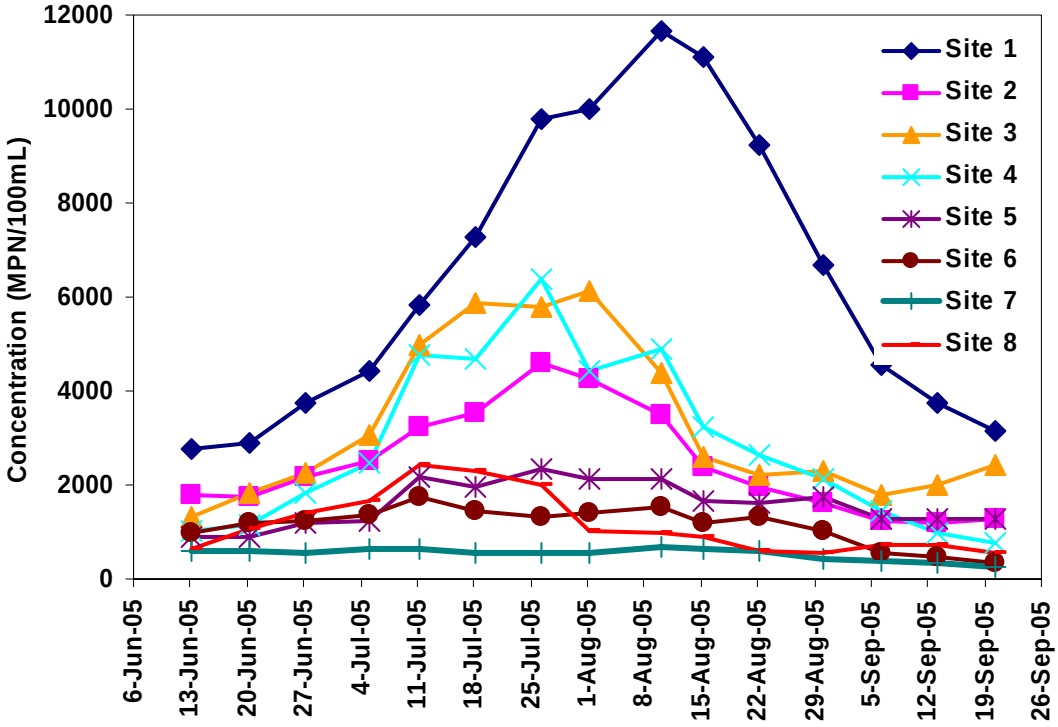

Figure 5.15—Weekly variation of moving 30-day geometric mean of the total coliform concentration at each sampling site.

sampling site 1 had the greatest exceedence that began in mid July and persisted until the first part of September. Exceedence at this site is likely due to the large number of birds that are attracted by the water features at the zoo which is located along the reach from sampling site 2 to 1 and attenuating effects from sampling site 2. In addition sampling sites 4 and 3 also exceeded the historic criterion mainly from mid July to mid August. As explained previously, drastic changes were observed in the water quality constituents between sampling site 5 and 4, which included a large increase in total coliform. The total coliform may be attenuating from sampling site 4 to 3 or additional increases in total coliform may be occurring from sampling site 4 to 3.

Although the State of Utah does not have bacteriological numeric requirements associated with enterococci the USEPA has recommended it as a good indicator of fecal

contamination in fresh and marine water. The USEPA has suggested criteria based upon an illness rate (USEPA, 2002). Using the same illness rate associated with the state of Utah *E. coli* criterion in Emigration Creek (10 illnesses per 1000 people), the enterococci regulatory criterion would be a 30-day geometric mean of 54 (No. per 100mL) and a maximum single sample concentration of 246 (No. per 100mL). Figure 5.16 shows a moving 30-day geometric mean of enterococci concentrations at each sampling site. This figure shows that every sampling site exceeded the hypothetical 30-day geometric mean criterion with a general increase in concentrations through June and July and levels off through August with the hypothetical exceedences persisting up to the last samples taken in the end of September. The hypothetical maximum allowable

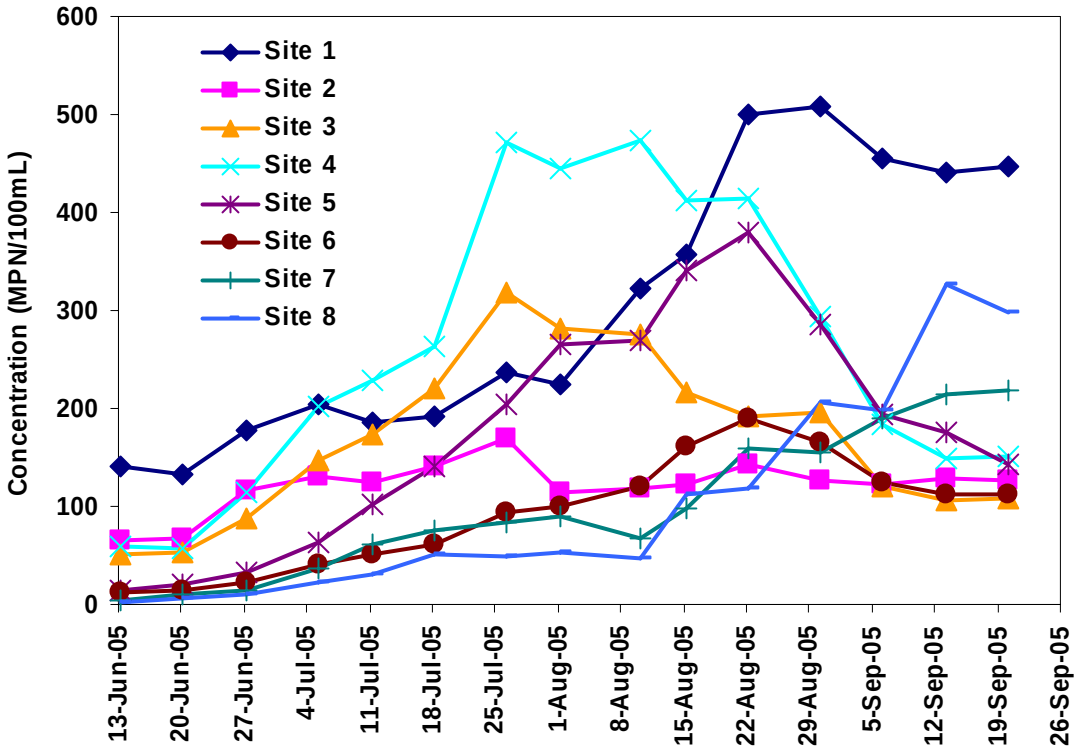

Figure 5.16—Weekly variation of moving 30-day geometric mean of the enterococci concentration at each sampling site.

concentration of 246 (No. per 100mL) was exceeded in more than 10% of the samples at each sampling site. It is interesting that sampling site 4, which did not exceed the *E. coli* criterion for any of the samples, exceeded this hypothetical maximum criterion in 55% of the samples and sampling site 1 exceeded this maximum criteria in 45% of the samples. The high concentrations at sampling site 4 have been discussed earlier, but the continued persistence of high concentrations at sampling sites 8, 7, and 1 may possibly be explained if the sources upstream of these sites are consistent (and independent of flow) and so as the streamflow decreases the instream concentration becomes greater. The exceedences for the other sites appear to increase through the end of June and into July and then decrease through August and into September.

Along with the bacteriological constituents the chemical constituents were compared to the State of Utah water quality criteria for Emigration Creek. After analyzing samples on July 18 it was determined that the ammonia concentrations at all the sampling sites were near the detection limit of the probe (0.01mg/L) and far below the State of Utah water quality criterion (~1 mg/L). A set of samples was tested the week of August 22 and again the concentrations were near the detection limits. In addition the nitrate concentrations were very low, less than 0.6 mg/L which is well below the State of Utah water-quality guideline of 4 mg/L (Utah Division of Administrative Rules, 2006).

5.2.2 Variation in Flux

Figure 5.17 shows the *E. coli* flux results presented as monthly geometric means for each sampling site. From Figure 5.17 it appears that for June and August the *E. coli*

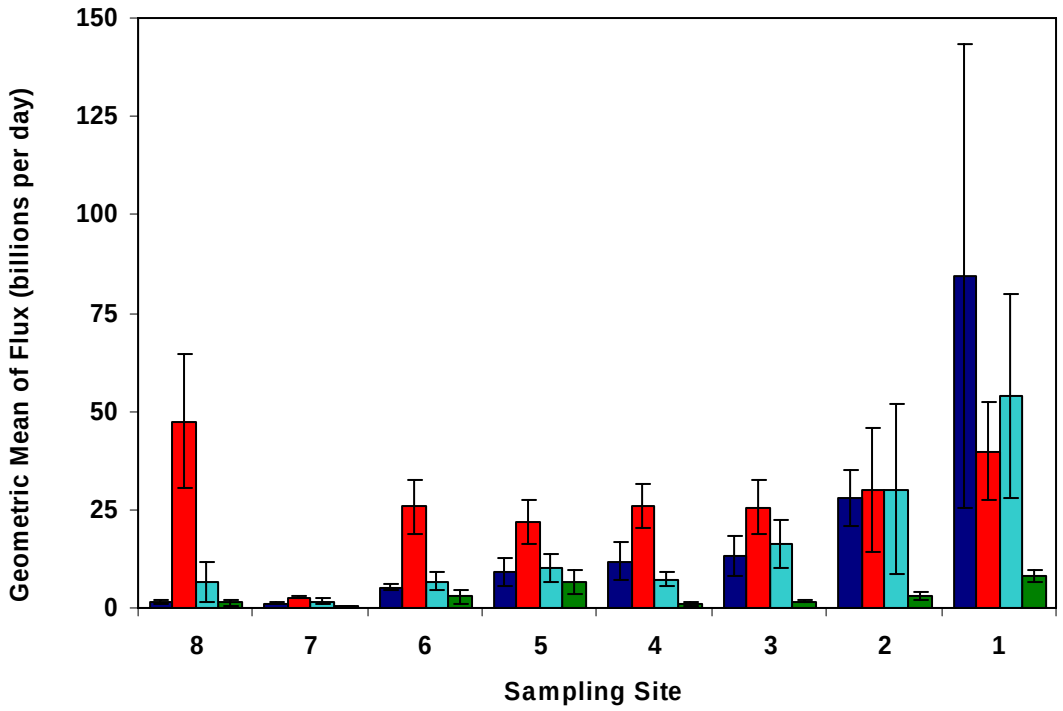

Figure 5.17—Geometric mean of *E. coli* flux at the sampling sites for each month of the sampling period.

flux trend is quite similar from upstream to downstream, but in July a significant amount of *E. coli* was entering the stream above sampling site 8 and in addition was persistently high down to sampling site 3. One reason for this may be the increased human activity within Emigration Canyon during July. This reasoning is supported by the increases in *E. coli* flux for the samples taken the day after the holiday weekends of July 4 and July 24 (see Figure 5.18).

For the months of June, August, and September the *E. coli* flux pattern is similar to the total coliform and enterococci flux, with the exception of the observed large increase in total coliform and enterococci flux from sampling site 5 to 4, in that they all increase downstream with significant increases in the lower two reaches. Noteworthy is

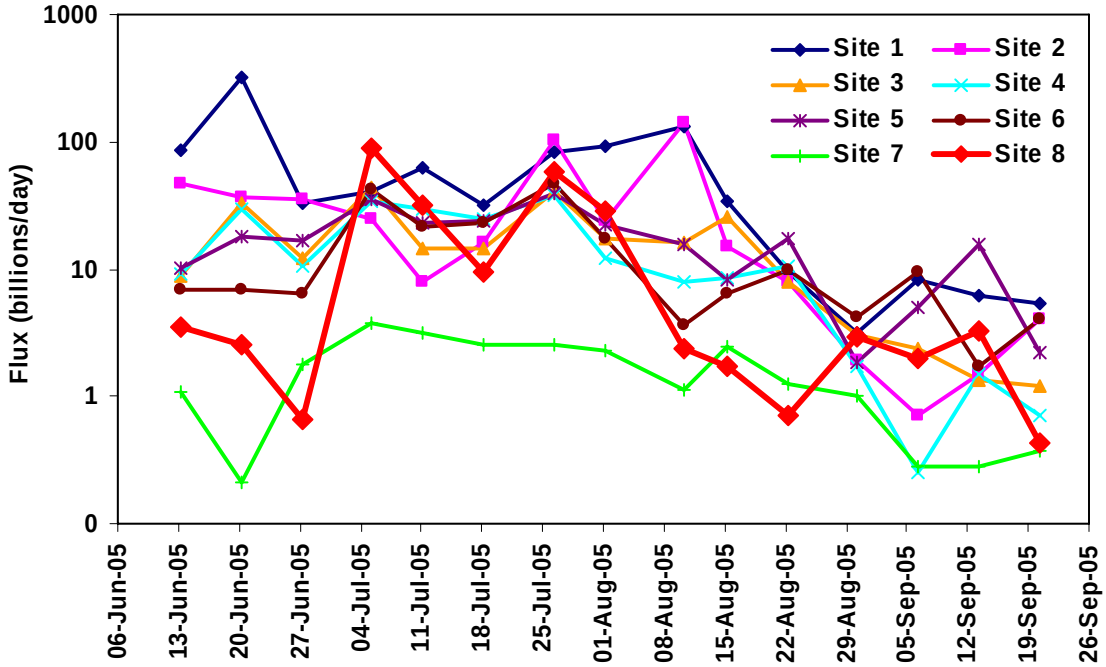

Figure 5.18—Calculated *E. coli* flux during the morning (AM) sampling run at each sampling site over the entire length of the study.

the increase in *E. coli* flux from sampling site 6 to 5. This increase does not appear significant in Figure 5.17 but because the streamflow is so low (in August and September) this small difference has a large impact on the concentration as shown in Figure 5.9. This increase in *E. coli* flux is likely due to a consistent source upstream of sampling site 5 that does not vary with season.

Figure 5.19 shows the geometric mean of enterococci flux for each month. The general trends are similar to the total coliform fluxes shown in Figure 5.20 (less one order of magnitude). This may indicate that the total coliform and enterococci have similar sources. Of significance was the large increase from sampling site 5 to 4 for all months sampled, except September, and the decrease in concentration from sampling site 4 to 3 for the months of July and August. Variability as represented by the error

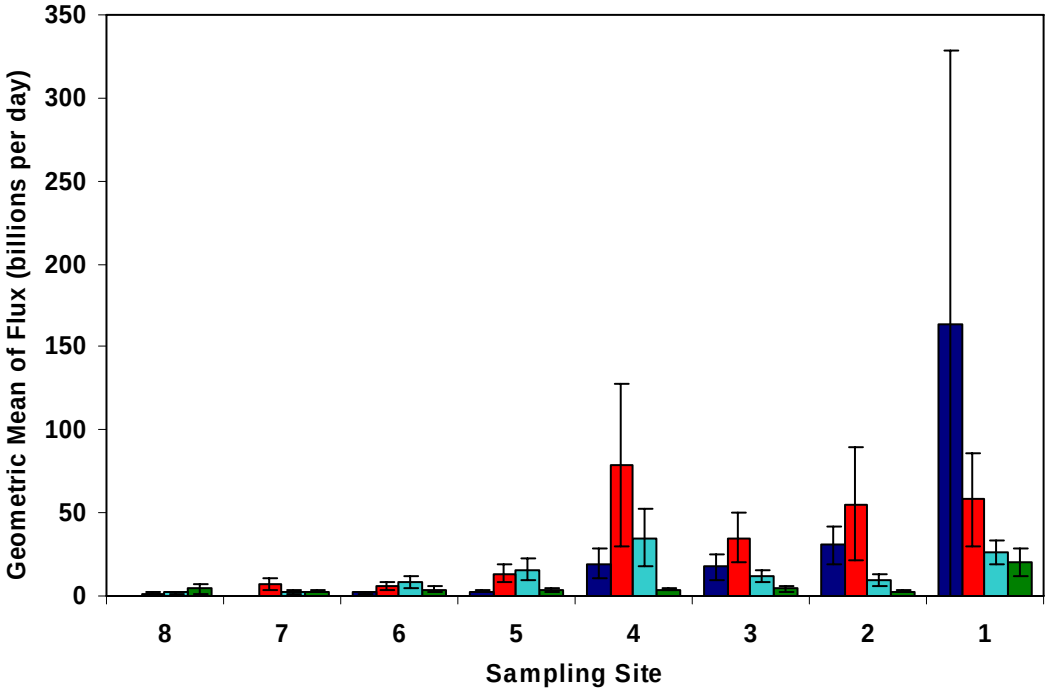

Figure 5.19—Geometric mean of enterococci flux at the sampling sites for each month of the sampling period.

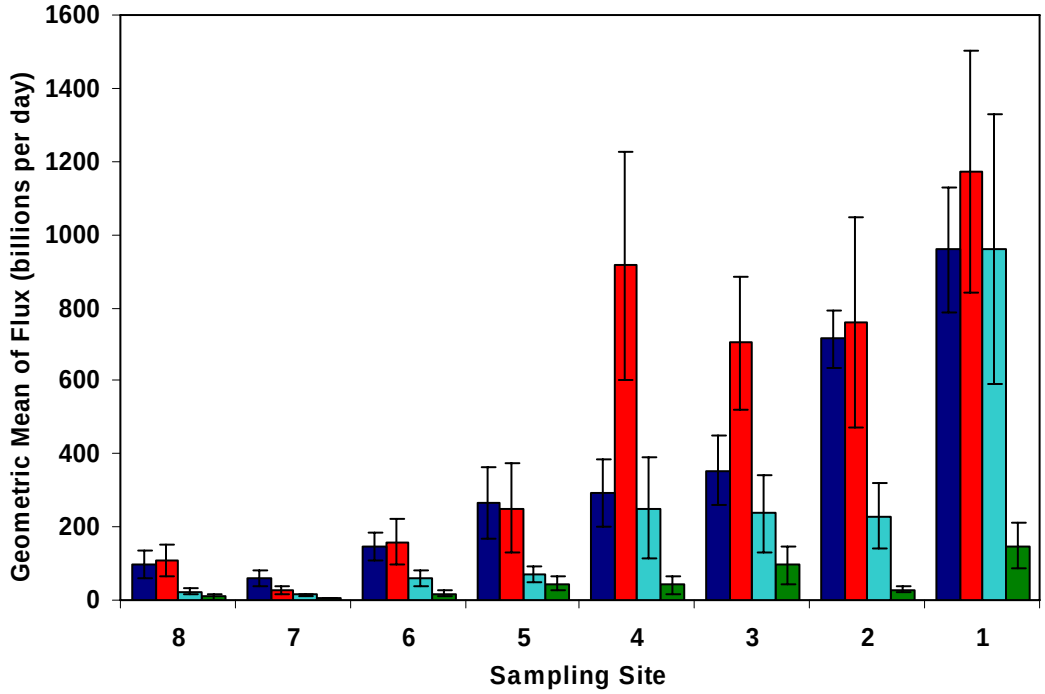

Figure 5.20—Geometric mean of total coliform flux at the sampling sites for each month of the sampling period.

bars (one-half of a standard deviation) increased in magnitude as the magnitude of the flux increased. This variability may indicate the larger sources vary with time.

The Glenne and West (1981) study had comparable observations. The highest fluxes for the present study were mainly found in July followed by June (see Figure 3.7). The Glenne and West (1981) study did not sample during July but showed June fluxes to be generally higher than the other months observed. The substantial increase from sampling sites 5 to 4 and 2 to 1 of the present study was also reported in the 1981 study.

5.3 Diurnal Variation

Over the course of the study several diurnal patterns were observed. These observations were made by plotting the results from the morning and afternoon sampling events (Figure 5.21). Each bacteriological constituent exhibited a diurnal pattern with the highest concentrations occurring during the morning sampling time. The driving force behind this diurnal pattern is suspected to be due mainly to the diurnal pattern of sunlight radiation, temperature, or diurnally varying input sources.

Increased exposure to sunlight radiation and increased temperatures elevate the bacteria die-off rate (Chapra, 1997). The change in pH does not appear to have an effect because the pH is more extreme during the morning than in the afternoon which would cause the die-off rate to increase during the night which is not observed. Lastly, it is probably that nocturnal animals may be more active near the creek during the night and early morning than throughout the day.

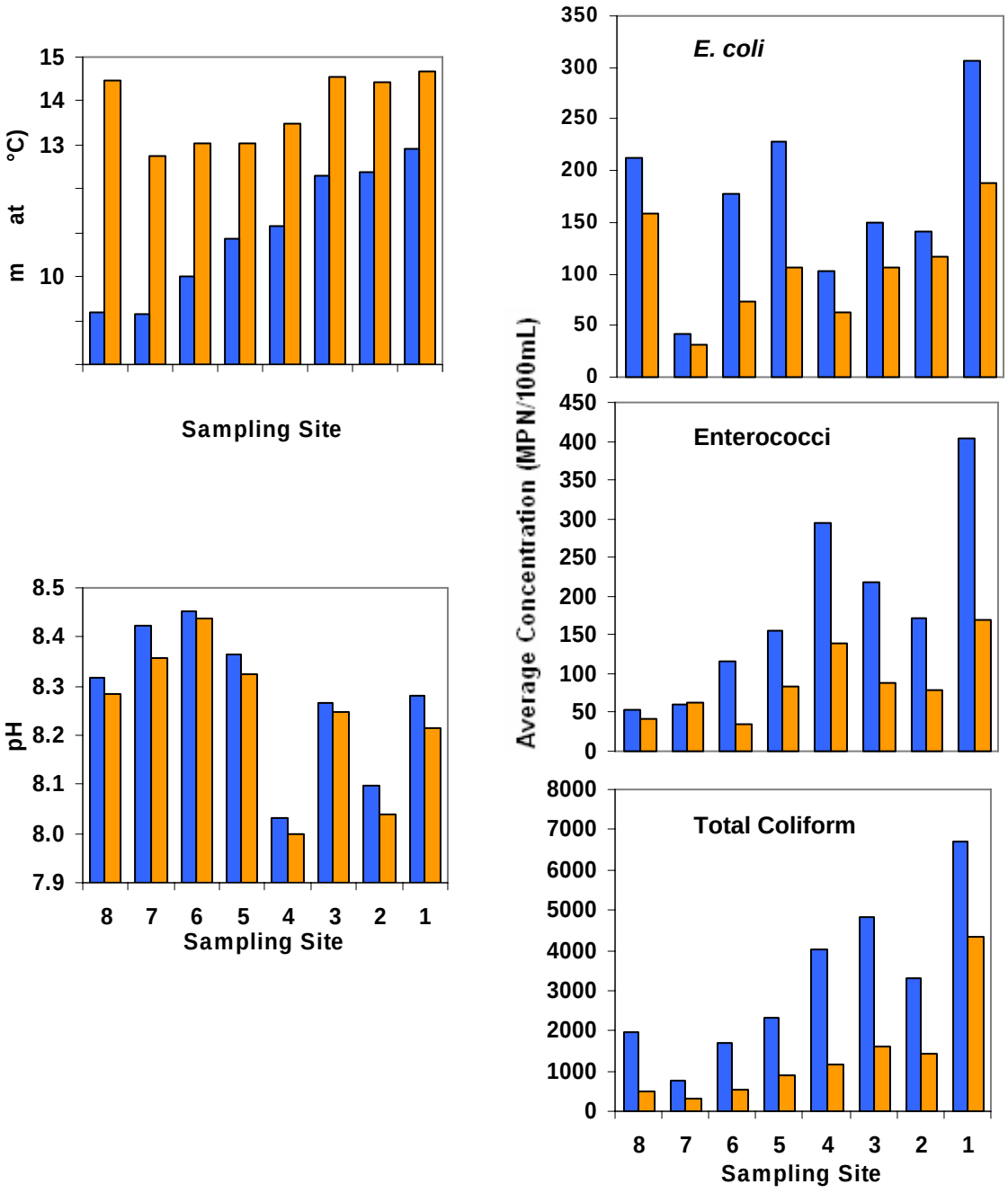

Figure 5.21—Diurnal variation in the various water quality parameters.

Previously a pooled variance one tailed *t*-test statistical test was preformed on the fecal coliform data from the Jensen et al. (2003) 2001 study (see Table 1.1). For this study the same statistical test showed that the *E. coli* concentrations observed during the morning and afternoon sampling times were found to be statistically different at a significance level of 95% ($\alpha = 0.05$). Table 5.1 shows the basic statistics and results of the *t*-test. At a 0.05 level of significance the *t* value obtained is less than the critical *t* and the *p* value is less than the level of significance therefore the average *E. coli* concentration is lower for the afternoon sampling time than the morning sampling time. This difference can also be observed by plotting all the data against their respective cumulative probabilities as in Figure 5.22. Included in Figure 5.22 are lines for each sampling time constructed based on the mean and standard deviation of the logarithmic data. The difference in the morning and afternoon distributions is graphically shown, with the morning sampling time concentrations being higher than the afternoon concentrations for any given cumulative probability.

Table 5.1—t-Test of log transformed *E. coli* data at the morning and afternoon sampling times.

	Morning	**Afternoon**
Mean	2.17	1.98
Variance	0.25	0.32
Observations	120.00	112.00
Pooled Variance		0.28
t		-2.76
p Value		0.003
t Critical one-tail		-1.65

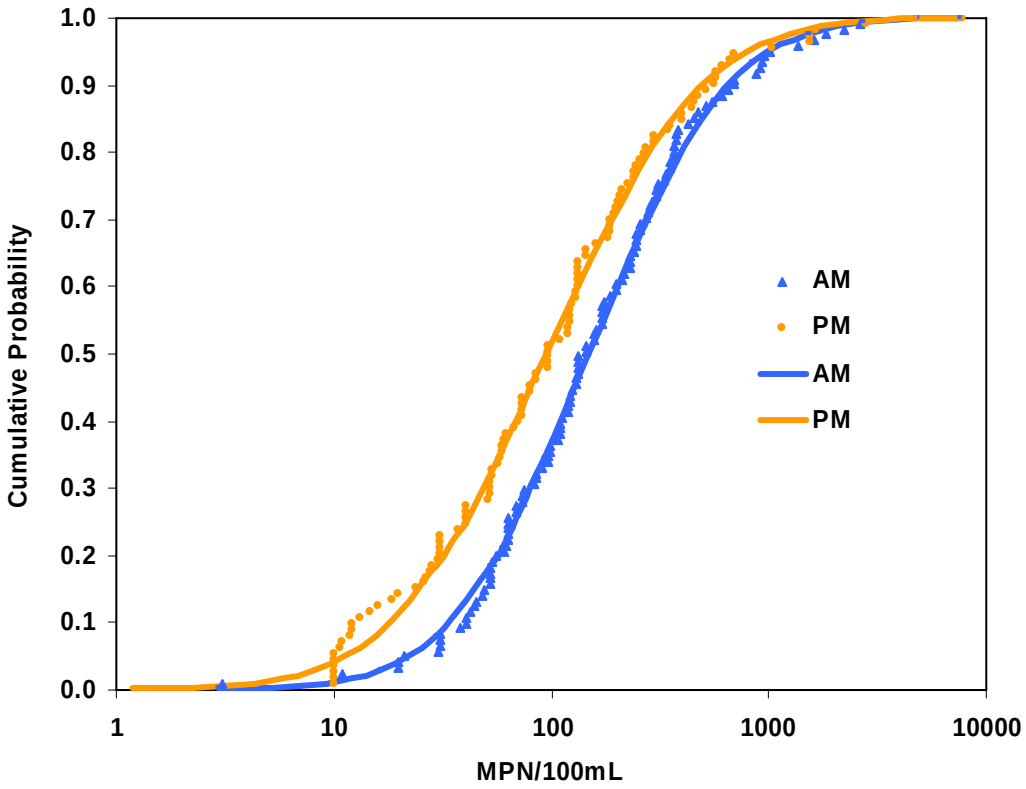

Figure 5.22—Difference in cumulative probabilities for the morning and afternoon *E. coli* concentrations.

5.4 Bacteria Attenuation

From the bacterial tracer test performed October 13, 2005 the DA001 (tracer bacteria) breakthrough and tailing concentration curves were plotted for all the sampling sites. The sampling sites A through H (a shown in Figure 4.2) covered a 6.3 km stream reach in the upper part of Emigration Creek. Each point in Figure 5.23 represents the concentration of tracer bacteria at the time the sample was collected relative to the beginning of the bacteria tracer injection upstream. Figure 5.23 indicates that as the tracer bacteria were transported downstream the bacterial plume length increased and the overall concentrations decreased. The amount of dilution determined

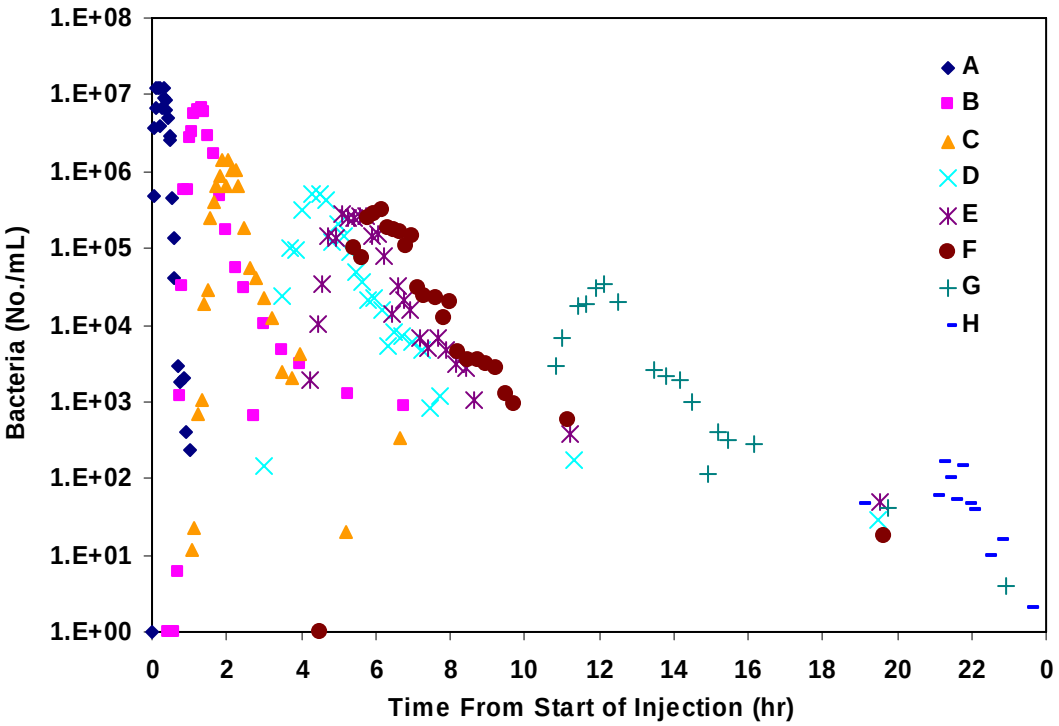

Figure 5.23—Measured concentration of tracer bacteria at each sampling site in time.

by the USGS dissolved (bromide) tracer preformed October 12, 2005 was a factor of 3 from site B to site C due mainly to the influent stream Burr Fork (see Figure 4.2), and from site C to site H the USGS bromide tracer test indicated a dilution factor of only 2, most likely due to influent groundwater. The amount of dilution observed by the USGS bromide tracer study did not account for the order of magnitude decrease in bacteria concentration observed in the bacteria tracer study. This indicated that attenuation processes caused the significant decrease in the concentration of the bacteria.

In order to determine the magnitude of attenuation for the tracer bacteria, a simple first order reaction rate equation (eq. 5-1) was used to determine a bulk attenuation rate constant (k) for the entire study reach.

$$\frac{N}{N_0} = e^{-kT} \tag{5-1}$$

In this equation N_0 represents the total number of bacteria injected into the stream and N represents the total number of bacteria that passed each respective sampling site, thus the ratio of N/N_0 is the ratio of bacteria passing each sampling site. N_0 and N were calculated simply using the area under the curves plotted in Figure 5.23 multiplied by the flow rate at each sampling site (determined and provided by the USGS using their dissolved tracer study preformed the day prior to the bacteria tracer) in the respective units. The constant k represents the bulk attenuation rate and T represents the amount of time that the bacteria had been traveling in the stream. This travel time was calculated for each sampling site using equation 5-2 (Chapra, 1997). In this equation T represents the average travel time, n represents the total number of samples, and c and t

$$T = \frac{\sum_{i=0}^{n-1}\left(c_i t_i + c_{i+1} t_{i+1}\right)\left(t_{i+1} - t_i\right)}{\sum_{i=0}^{n-1}\left(c_i + c_{i+1}\right)\left(t_{i+1} - t_i\right)} \tag{5-2}$$

represent the concentration and time (from injection) for each sample. Figure 5.24 shows N/N_0 versus the calculated travel time of the bacteria plume for each sampling site. In addition Figure 5.24 shows the best-fit line representing the equation 5-1 using 7 of the 8 sampling sites (sampling site H was not used because the front of the bacteria

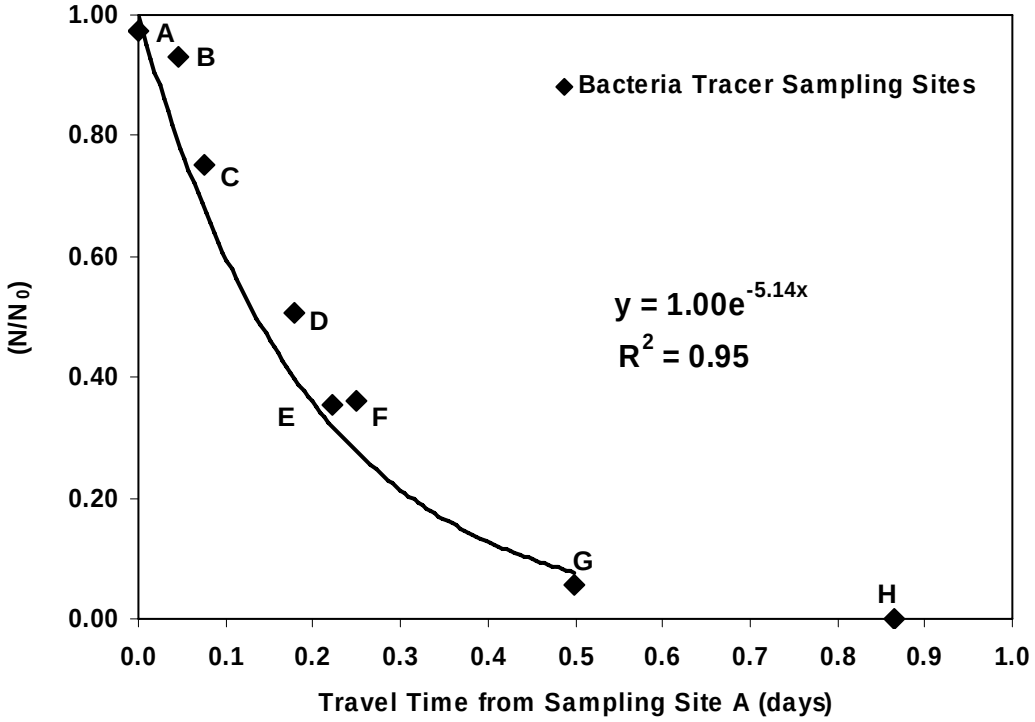

Figure 5.24—Determination of the loss coefficient *k* using the best fit line.

plume was not captured). From this best-fit exponential line the bulk attenuation rate (*k*) was shown to be 5.14 day^{-1}.

Using the total number of bacteria passing each sampling site, instead of concentration, in the first order reaction equation (eq. 5-1) the changes due to dispersion and dilution are accounted for. A similar mathematical approach has been used in other studies (Easton et al. 2005, Moore et al. 1988) to determine bacteria loss in time.

The bulk attenuation or loss rate determined in this study (5.14 day^{-1}) was much greater than other published loss rates (Easton et al., 2005; Moore et al. 1988), which ranged from below 0.1 to 3.14 day^{-1}. The likely reason for this is that the methodology of this study differs from any previous study researched in that other studies (Easton et

al., 2005; McFeters and Stuart 1972), which monitored the change in bacteria using in-place vessels that were permeable to the natural stream water but which retained the tracer bacteria placed in the vessel. These studies monitored bacteria over time (days) at one specific location along a stream or river. In contrast this study monitored changes of bacteria within the natural stream and allowed movement of bacteria down gradient with the streamflow. In addition the previous studies used culturing methods to determine the concentration of bacteria, which means that the bacteria observed must be live and viable. In contrast, this method (ferrographic capture) used to determine the concentrations did not require that the cell be alive and viable, only that the cell wall of the bacteria be intact. This further substantiates the high loss rates observed in this study compared to previous studies because it included all bacteria both live and dead cells whereas the other studies only observed live cells.

The disparity in loss rates begs the question of what could be causing dramatic attenuation of the tracer bacteria. A number of factors are considered to cause bacteria loss. Chapra (1997) describes three factors: natural mortality and salinity, light, and settling. Natural mortality and salinity effects were considered in the previous studies (Easton et al., 2005; McFeters and Stuart 1972). So in the worst case even if the effects of natural mortality and salinity were determined to cause the tracer bacteria cells to die and break down the cell walls (so they would not be considered in ferrography) these losses still would not account for the high loss rate observed in this study. The effects of light, namely ultraviolet light, may have been filtered out by the vessels used in previous experiments, but ultraviolet light was likely not much of a factor in this experiment because much of the creek was shaded due to the thick surrounding

vegetation. In addition, no noticeable differences were observed between reaches traveled during the day (A to B, B to C, and C to D) and reaches traveled during the evening, night, and morning (D to E, E to F, F to G, and G to H). Effects of settling within Emigration Creek are likely insignificant due to the constant agitation of the streamwater by the cobble stones and rocks within the streambed. Based upon the results obtained and this discussion it seems apparent that other processes are causing the rapid removal of the tracer bacteria within Emigration Creek. Translation in itself would not be a likely cause for such a significant loss but the processes associated with it such as filtration in bed sediment likely would result in the removal of bacteria. Loss rates due to filtration determined using polystyrene microspheres (Li et al., 2004) roughly the size of bacteria (1 μm) resulted in greater loss rates than observed in this study. This suggests that the bacteria may be filtered out by the portion of streamflow that flows through the bed sediment. Attachment (or sticking) of bacteria to surfaces within the streamflow path in addition to predation of bacteria by protests may also be likely attenuation processes. Both attachment and predation of the same bacteria used in this study were observed in a groundwater study by Zhang et al. (2001). In addition to the Zhang et al. (2001) study the phenomenon of attachment is supported by the extended tail observed in this study. Figure 5.25 shows the breakthrough-tailing curve for sampling site F, which was typical for most of the sampling sites. The steep breakthrough curve followed by the long extended tail is possibly the result of attachment and slow detachment of the bacteria within the stream, respectively. In contrast the extended tail may be also be due to slow release from eddies along Emigration Creek.

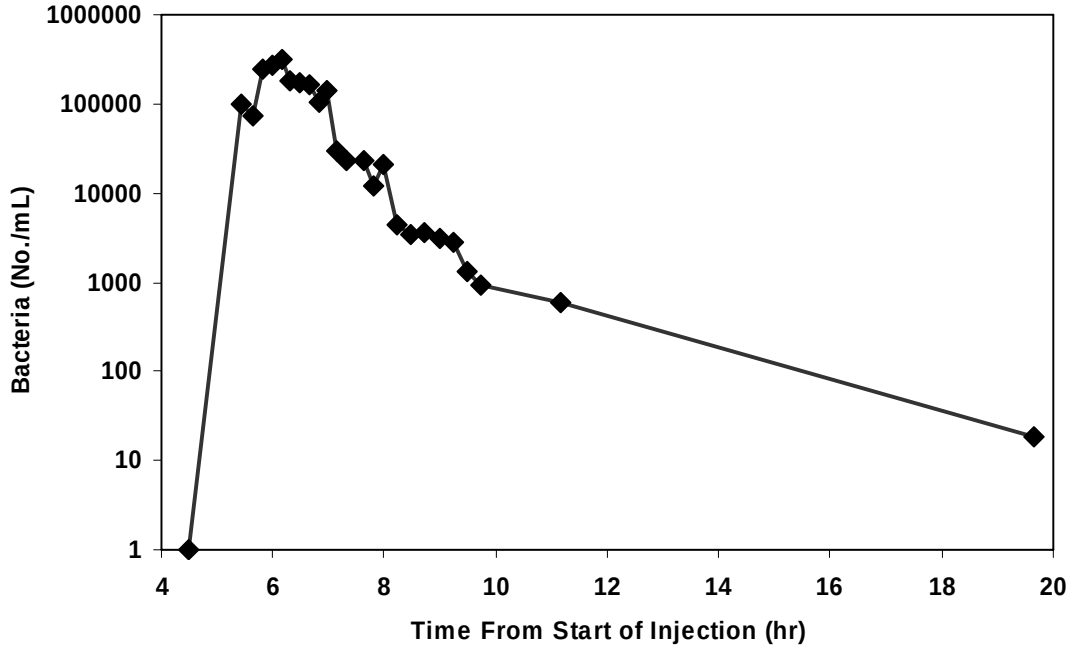

Figure 5.25—Typical breakthrough and tailing curve (site F).

5.5 Synthesis of Results

A plug-flow point source model was used to estimate the *E. coli* average monthly and average warm season input loadings along each study reach of Emigration Creek. This model was based on observed warm season flux (in billions per day) of *E. coli* passing each sampling site and the attenuation rate determined by the bacteria tracer experiment. First-order decay kinetics (eq. 5-1) were applied in the plug-flow model to produce the following relationship, which was applied to all stream reaches:

Loads within each reach were represented by a single, no-flow point source load entering the stream just downstream of each sampling location. Assuming instantaneous complete mixing between the stream and the no-flow point-source load gives the following equation (eq. 5-3) for bacterial flux at the next downstream station:

$$Load_{IN} = \frac{Flux_{DS}}{e^{-k\frac{X}{U}}} - Flux_{US} \quad (5\text{-}3)$$

$Load_{IN}$ is the amount of bacterial load (in billions/day) that hypothetically would be entering the creek at an infinitely small distance downstream of the upstream sampling site. $Flux_{DS}$ is the observed flux (in billions/day) passing the downstream sampling site. $Flux_{US}$ is the observed flux (in billions/day) passing the upstream sampling site. k is the attenuation rate constant determined by the bacteria tracer study (k = 5.14 day^{-1}). X and U are the stream reach length (m) and the velocity of the streamflow (m/day).

Many assumptions were made in using this model to estimate representative point-source loads. One main assumption is that the tracer bacteria (DA001) are similar to *E. coli.* The differences in survivability between these types of bacteria were beyond the scope of this study. Another assumption is that the loss rate obtained is constant over the entire stream reach and during all the modeled months. The attenuation rate probably varies with streamflow with lower streamflows likely, resulting in higher attenuation rates; thus, the attenuation rate is likely more representative for lower streamflows similar to October. Figures 5.9, 5.10, and 5.11 show that the variability between sampling sites greatly increases in September. This variability may be due to greater attenuation rates in September.

Stream velocity (determined using the travel time from the bacteria tracer for each reach) was also assumed be constant over the modeled months. This assumption

would also be more valid for the low flow months of August and September than for June and July.

Despite the simplistic model and necessary assumptions, the model was able to provide seemingly reasonable relative loading magnitudes for each reach. Figure 5.26 shows these monthly and average *E. coli* inputs for each reach. The results show that the input loads generally increase downstream and that there are significant loads in July within the reaches 5 to 3. Both of these trends are possibly attributed to increased anthropogenic activity at these locations and times. The results also suggest significantly higher loads along every reach during the month of July. This indicates that the high flux rates observed in July at almost all the sampling sites were probably independent of the high flux rate at sampling site 8 and probably the result of increased loading all along the creek.

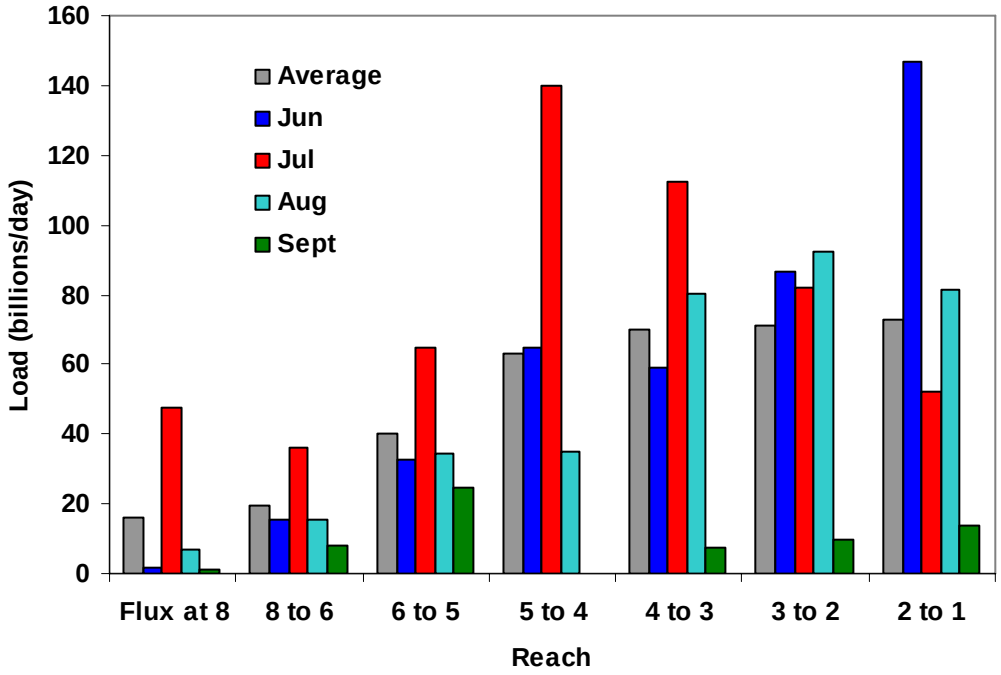

Figure 5.26—Modeled *E. coli* loading input along each reach.

The implication that such high bacteriological loadings can be occurring and then rapidly attenuating increases the difficulty of locating bacteriological pollutant sources. For example, Figure 5.27 shows a hypothetical situation where the decrease in the *E. coli* concentration at sampling sites downstream of sampling site 8 is determined using the attenuation rate of 5.14 day^{-1} and based on the highest concentration observed at sampling site 8 which was 2828/100mL. This example illustrates that if a regulatory agency were collecting samples at sampling site 5, the out of compliance *E. coli* concentrations in the reach upstream would go unnoticed. This implies that in streams with high attenuation rates, spatially closer sampling sites would be required to locate the bacteriological pollutant sources and determine the status of the entire stream reach with respect to the regulatory bacteriological water quality standards.

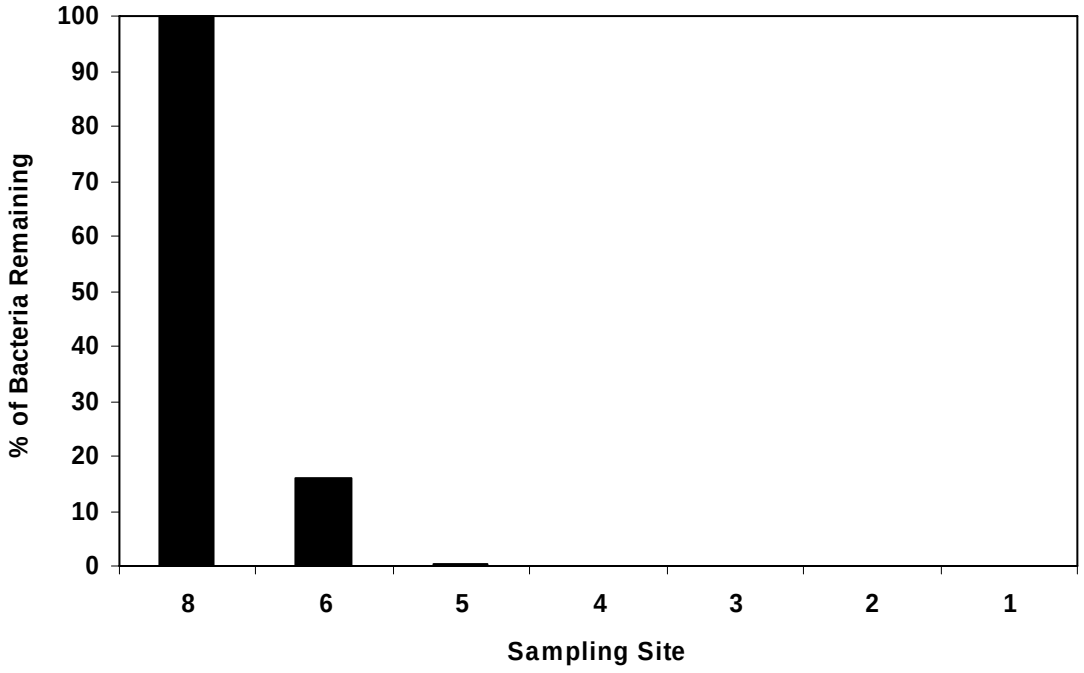

Figure 5.27—Hypothetical perpetuation of *E. coli* downstream of sampling site 8 (based on the highest concentration observed at sampling site 8, which was 2828/100mL and an attenuation rate of $k = 5.14 day^{-1}$).

CHAPTER 6

CONCLUSIONS

The goals of this study were to (1) determine the spatial and temporal distribution of concentration and loading of bacteriological and chemical fecal-contamination indicators and (2) document spatial variations in bacteria attenuation along the main channel of Emigration Creek. The first goal was partially achieved monitoring over a 4-month, warm season period the total coliform, *E. coli*, enterococci, nitrate, ammonia, and chloride concentrations in Emigration Creek and measuring streamflow during sample collection to determine the bacteria and chemical constituent flux differences along the rural-to-urban stream transect. The first goal was fully achieved in addition to the second by conducting a bacteria tracer, which quantified bacteria attenuation and in conjunction with the warm season monitoring results helped to identify bacteria loading sources and magnitudes using a simple model.

From the data obtained, spatial, temporal, and diurnal trends were observed in both the concentration and flux of the bacteriological and chemical constituents. Spatially the concentrations and fluxes for *E. coli*, enterococci, total coliform, chloride and nitrate in addition to the temperature, conductivity, and the streamflow rate all generally increased from upstream to downstream. The two most upstream sampling sites (8 and 7) showed very different water quality types. Sampling site 8 showed high

E. coli and total coliform concentrations and fluxes. Sampling site 7 showed higher enterococci concentrations and fluxes than sampling site 8. The high results obtained for sampling site 8 are suspected to be related to recreational activity in the upper reach of the canyon which is accessed using a trail that parallels the creek upstream of sampling site 8. This was supported by the increase in *E. coli* flux at sampling site 8 for the samples collected following July 4th and July 24th (major holidays celebrated in Utah). The high levels of enterococci observed at sampling site 7 are suspected to be related to a different source type or differences in the fate and mode of transport of bacteria to the creek upstream of the sampling site.

There were significant overall increases in enterococci, total coliform, nitrate, and chloride concentrations and fluxes from sampling site 5 to 4. Interestingly the increase was not consistently observed in the *E. coli* concentration or flux. The measured streamflow rate between sampling sites 5 and 4 showed substantial increase, which is due to groundwater, as no significant influent streams were observed throughout most of the sampling period. The observed constituent increase and influent groundwater raised suspicion that they may be related. From observing the monthly flux of total coliform and enterococci it was evident that the bacterial source was not consistent over time meaning that either the groundwater source reduced as the study progressed or the contamination is from surface sources that were more prominent in the summer than early fall.

From sampling site 3 to 2 a groundwater input became apparent. This input was recognized by: an increase in streamflow with no other noticeable surface water inputs

along this reach, a decrease in the bacterial concentration due to dilution, and a decrease in the water temperature likely due to the colder groundwater.

From sampling site 3 to 2 and 2 to 1 large increases in both the concentration and flux of the bacteriological constituent were observed. The high concentrations and fluxes at sampling site 2 may be due to the upstream dog park and the high concentrations and fluxes at sampling site 1 may be the attenuation effect from site 2 in addition to the birds that are attracted by the zoo upstream of sampling site 1.

Temporal changes were observed over the study period. The streamflow rate of Emigration Creek changed dramatically over the course of the study period, ranging from 0.40 m^3/s in June to around 0.05 m^3/s in September. The highest concentrations of the bacteriological constituents were observed in July and August. This is likely due to the increased recreational activity within Emigration Canyon. Interestingly the enterococci concentrations in the upper and lower reaches of the study reach were comparatively higher for the month of September. The *E. coli* flux showed a general increase from upstream to downstream throughout the study period with the exception of July, in which, the flux was comparatively very high at sampling site 8, 6, 5, 4, and 3 with respect to the other months. The results from the bacteria tracer show that the persistent loadings are likely not due just to the increase at sampling site 8 but are most likely due to increased loading between the sampling sites listed. In addition to the monthly variations, diurnal variations were also observed with greater bacteriological fluxes occurring during the morning sampling period.

The concentration levels of *E. coli* and total coliform in Emigration Creek exceeded the new (2006) and historic (2005) State of Utah bacteriological numeric

criteria. The majority of *E. coli* exceedences occurred from mid July to mid August at sampling sites 8, 6, 5, 3, 2, and 1. Enterococci concentration (currently not a regulatory criterion in Utah) results indicated that relatively high values (compared to USEPA recommendations) were observed from mid June until the end of the study period (late September) with excessive exccedences observed at site 4 which interestingly did not exceed the regulatory *E. coli* water quality standards.

The bacteria tracer preformed after the conclusion of the warm season monitoring (in October) indicated that the bacteria loss rate was larger than previous surface water studies have estimated. The breakthrough and tailing profiles possibly indicate that attachment of the bacteria is one source or bacteria removal in addition to filtration and predation of the bacteria all of which have been observed in groundwater studies.

Combining the attenuation rate and the long term monitoring results allowed a model to be produced that calculated the amount of *E. coli* loading entering the creek between each of the warm season monitoring sites. Due to the high attenuation rate this model indicated that bacterial loads were entering the creek in the lower reaches (from sampling site 5 to 1) especially in July. In addition the results from the model illustrated that the loading at the upper most sampling site had little effect on the lower sampling sites 4, 3, 2, and 1.

These findings are significant from a health and regulatory stand point because if a stream has a high bacteriological attenuation rate as observed along Emigration Creek and a significant (exceeded regulatory standards) source of bacteriological pollution is located far enough upstream from the sampling site used for regulatory

purposes the regulatory sample may indicate that the steam is within the regulatory constraints.

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