SPATIO-TEMPORAL ASSESSMENT OF HEADWATER STREAMS IN THE SAN BERNARDINO NATIONAL FOREST

Jose Angel Mora
California State University - San Bernardino, 006135840@coyote.csusb.edu

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SPATIO-TEMPORAL ASSESSMENT OF HEADWATER STREAMS IN THE SAN
BERNARDINO NATIONAL FOREST

A Thesis
Presented to the
Faculty of
California State University,
San Bernardino

In Partial Fulfillment
of the Requirements for the Degree
Master of Science
in
Earth and Environmental Sciences

by
Jose Angel Mora
December 2019
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Approved by:

Jennifer Alford. Committee Chair, Geography
Erik Melchiorre, Committee Member
James Noblet, Committee Member
ABSTRACT

As the demand for freshwater resources increases due to increasing human populations, degradation of available resources, and climatic changes it will become increasingly important to understand the factors that impact the physicochemical characteristics of surface water resources over space and time. This study assessed a headwater stream over the course of a year in the San Bernardino National Forest that serves as both surface and groundwater resources for the Santa Ana River Watershed region, the largest and most populated watershed in Southern California. Streams were monitored bi-weekly during dry periods and weekly during wet periods from April 2018 through April 2019 for dissolved oxygen (DO), flow rate, temperature, conductivity, turbidity, pH, nitrate (NO$_3^-$), and ammonium (NH$_4^+$) with additional lab assessments for total dissolved solids (TDS), E. Coli (EC) and total coliform (TC). Findings illustrated that across the study sites NO$_3^-$, NH$_4^+$ and TDS exceeded federal and regional water quality standards for a majority of the sampling events (>60 percent). Additionally, NO$_3^-$, DO and flow rates were elevated in the wet season, while conductivity, NH$_4^+$ TDS, pH, TC and EC were elevated during the dry season.
ACKNOWLEDGEMENTS

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CHAPTER ONE
INTRODUCTION

Literature Review

The protection of water resources is a paramount concern as growth in the global human population and related landscape changes continue to adversely impact the quality and quantity of water resources across multiple geographical scales (Peters and Meybeck, 2000; Zhang et al., 2010; Park et al., 2011; and others). As water traverses the landscape it may be primarily impacted by both natural and anthropocentric based inputs and from the development of infrastructure that physically directs water to more populated regions, resulting in disruptions to water quality, quantity, and natural hydrologic flows (Varol et al., 2012; Northington and Webster, 2017; Trudeau and Richardson, 2015). Inputs to surface water resources are typically associated with surface runoff that flows through agricultural, forested, and urban land types (Tong and Chen, 2002; Alford, 2014; St-Hilaire et al., 2015; Huang et al., 2013 and others). Landscape activities that contribute pollution to surface waters may include crop and livestock production, industrial discharges, failing septic systems, and increases in impervious surfaces (i.e. houses, roads, and parking lots). These activities also create longitudinal hydrologic impacts at the pollution source and downstream. This spatial context often results in highly variable characteristics in water quality as one moves from the headwaters to the mouth of the hydrologic network.
(Alford, 2014; Arnold and Gibbons, 1996; Mallin et al., 2009; Schueler, 1994; Shaw et al., 2014). In addition to human activities, climatic changes have resulted in prolonged drought conditions that disrupt available water resources (Tigkas et al., 2012; Allen et al., 2011). As a result of the variability in potential impacts to water resources, it is becoming increasingly important to identify the extent to which both natural and anthropocentric factors influence water quality. In the United States alone, there are over 3.5 million miles of rivers and streams, however, only 31.4% of them have been assessed indicating that little is known about the quality of water resources available to support both ecological and human activities (USEPA, 2017).

Documented observations that associate land types and activities with specific water quality metrics have resulted in common trends in water quality across multiple studies (Alford et al., 2016; Carpenter et al., 1998; Vega et al., 1998; Peters and Meybeck, 2009; and others). For example, pollution from agricultural land types are often associated with soil erosion that contributes excessive organic carbon, nutrients, and sediments to nearby waterways because of livestock activities and the presence of barren land between crop harvesting and planting (Smith et al., 2013; Mallin and Cahoon, 2003; Mallin et al., 2009; Tong and Chen, 2002). Across urban areas, stormwater runoff tends to contribute excessive heavy metals, orthophosphates, and debris to surface waters typically related to oil and brake dust from cars and litter on the landscape (Chester and James, 1996; Tong and Chen, 2001; Mallin et al., 2009).
Additionally, increases in impervious surfaces (i.e. roads, buildings, parking lots) have been linked to hydrologic disruptions and increases in pollution inputs because such surfaces impede water from infiltrating into the soil. This may lead to increasing surface flows that transport high concentrations of pollutants to nearby surface waters during and after rain events (Chester and James, 1996 and Brabec et al., 2002). Landscape activities may also be driven by regulatory changes. In the Mississippi River, the largest drainage basin in the United States, water quality changed dramatically after the adoption of artificial fertilizers causing a rapid increase in nitrogen and phosphorus concentrations that eventually discharged into the Gulf of Mexico. Application of these nutrients on agricultural land caused a variety of environmental issues such as eutrophication throughout the hydrologic network resulting in water quality impairments at the pollution source and downstream (Turner and Rabalais, 1991; Rabotyagov et al., 2014; USEPA, 2018 and others).

Both natural and anthropogenic factors have also been associated with potential impacts to the quality of water resources needed to support human health and socioeconomic activities. In the Indus River plain of Pakistan, groundwater has exceeded the World Health Organization’s (WHO) guidelines for arsenic (<10 μg/L) because of the natural microbial reduction of sedimentary iron oxyhydroxides. Trends suggest that this natural process has reduced groundwater quality, a primary drinking water resource, putting more than 13 million people’s health at risk (Naseem and McArthur, 2018). The exponential
growth in human population has adversely impacted water resources by placing high demands on infrastructure, increasing agricultural production in rural areas, and magnifying impervious surfaces in urbanizing areas. The rapid urbanization around China’s Grand Canal in the Yantze River Delta illustrates the relationship between urbanization and water quality degradation from the lack of infrastructure and uneven distribution of wastewater treatment facilities. Yu et al. (2012), observed that both agriculture and urban canal sections exhibited similar impairments related to excessive nutrient runoff, potentially impacting both aquatic and human health. Findings also illustrate that the urban canal sections exhibited high concentrations of metals such as mercury, copper, and iron from local industrial activities including, but not limited to, copper recycling and power generation plants. As noted by Solomon (2009), when fish are exposed to excessive metals, it breaks down their biochemical regulatory functions leading to aquatic dead zones. In Southeastern North Carolina, Cahoon et al. (2006) noted that coastal watersheds with high densities of septic systems located near steep slopes, and poor soil conditions were statistically correlated with fecal coliform contamination in nearby waterways. Findings suggest that pollution inputs were associated with human waste from septic systems which eventually lead to closure of shellfish waters and public beaches. Other studies suggest that beach closures from fecal coliform bacteria are common after a significant rain event. This typically occurs because runoff from point (i.e. wastewater treatment plants) and nonpoint sources (i.e. pet waste), coupled with aging or failing
infrastructure carry contaminants into surface water, increasing health risks for both wildlife and humans (Kleinheinz et al., 2009; Cahoon et al., 2006; Linwood, 2008; Yu et al., 2012). Human consumption of seafood and exposure to waters with excessive fecal coliform, Escherichia coli (E. Coli) and other pathogens may result in waterborne viruses that may cause pneumonia, respiratory and urinary tract infections in humans (Harwood et al., 2014).

The locations of specific land types and activities within the hydrologic network are also of particular interests, especially as they relate to tributary and headwater streams. Headwater streams serve as the beginning of the surface water network and constitute the greatest total stream length across the hydrologic unit. Alexander et al. (2007), notes that activities that impair water quality in headwater streams may result in adverse impacts to both surface water quality and groundwater quantity across the entire hydrological network. In Wisconsin, the Fox River, a principal tributary to the Green Bay, was listed in the EPA’s National Priorities List in 1998 due to industrial operations contaminating 240,000 cubic yards of sediments across a 39-mile stretch and to this day, extensive cleanup and stream restoration is still ongoing. In the Coastal Plain region of North Carolina, Mallin and Cahoon (2003) observed that the production of swine and turkey in Concentrated Animal Feeding Operations (CAFOs) contributed the greatest input of nutrients into the streams of the Cape Fear River Basin. These examples reveal not only the spatial extent of such impacts to
surface waters, but also the temporal complexities with mitigating further impacts to water resources (USEPA, 2017).

More recently, climatic conditions have been identified as a contributing factor in water resource deficiencies highlighting the need for alternative resource management strategies. Li et al. (2017) observed that extreme drought conditions led to 43.3% and 57.1% water reduction volumes, water acidification, and hypereutrophic conditions in Lake Alexandrina and Lake Albert in Australia, which drastically reduced water resources available for drinking, irrigation and recreation. In Western Europe, Van Vliet and Zwolsman (2008) observed that the Meuse River had a decrease in water flow and water quality during the 1976 and 2003 drought events. During both drought events, the river experienced high temperatures, low river flows, eutrophication (i.e. excessive nutrients), and an increase in the concentration of metals such as nickel and barium. In the U.S., droughts have led to mandatory water conservation practices, significant crop revenue loss, and water rate increases for consumers (Moss et al., 2015; Howitt et al., 2015; Loaiciga and Renehan, 1997). Such conditions create disparities between how water resources are allocated, used, and protected to meet the needs of human activities and ecological services.

Severe droughts and intense but short-lived precipitation can also impact the biodiversity, agricultural industry, and infrastructure growth. This is particularly true in the United States state of California, which is the second largest and most populated state with an estimated 39 million residents across a
423,970 km² landscape. In addition, California produces approximately 50.13 billion dollars of agricultural resources for the United States and exports an estimated 20.56 billion dollars in agricultural products globally (Census, 2018; CDFA, 2019). The majority of West Coast's annual precipitation is dependent on a few precipitation events that can release an estimated 30 to 50% of the annual precipitation to the West Coast contributing to its water supply (NOAA, 2019; Dettinger et al., 2011; Dettinger, 2013; and others). These precipitation events derive from atmospheric rivers that are constantly moving and transporting large amounts of water vapor and high winds from the Pacific Ocean into the United States' West Coast. When the atmospheric rivers encounter mountainous terrain (e.g. San Bernardino Mountains) they create orographic precipitation in the form of rain or snow. Large atmospheric river storms can be extremely dangerous causing flooding, debris, and mud flows, but the absence of these short lived storms could lead to long and unpredictable periods of droughts. California went through such a prolonged drought during 2012-2016, but received large quantities of precipitation during the 2018-2019 wet season. Atmospheric rivers released high quantities of precipitation in a short period of time across California causing mudslides and flash floods, but also contributing to the water resources (NOAA, 2019). The storms greatly benefited the state and contributed much needed precipitation to the Santa Ana River Basin, the largest watersheds in Southern California.
Recent droughts forced many regions of the state to withdraw groundwater from their aquifers at rates that exceeded recharge, causing a variety of significant problems such as a decrease in the water table and land subsidence (Faunt et al., 2016; Langridge et al., 2015; Xiao et al., 2017; and others). For example, farmers used groundwater as their main water source causing areas near the Tulare Basin to sink 13 inches and areas near the California Aqueduct to sink 12.5 inches during the drought (National Aeronautics and Space Administration (NASA) (NASA, 2015). Ecological impacts from the extended drought have also been significant. During the drought, a decrease in the suitable habitat available for the endangered southern steelhead trout caused an eighty-four percent decrease in the trout population (Dagit et al., 2017). As prolonged droughts are becoming more frequent and unpredictable it will be vital to understand the extent to which pollution inputs related to human activities impact surface water resources prior to reaching recharge basins to avoid groundwater contamination.

In the Santa Ana River Basin in Southern California, groundwater is a primary water resource to millions of people with surface water contributions primarily occurring seasonally. Research has shown that there are contaminants in the Santa Ana’s underground aquifers that originated from industrial, agricultural, and recreational point and nonpoint sources. A United States Geological Survey (USGS) surveyed 247 wells in 1968-1969 and 1977-1978 throughout the SARB for contaminants that included nitrate-nitrogen, dissolved
solids, chloride, calcium, magnesium and boron. The survey showed that nitrogen-nitrate concentrations were more evenly distributed throughout the upper basin, but there was a number of wells in the lower basin that exceeded the criteria. These wells were located in agricultural lands where high amounts of fertilizers were actively being used in excess (USGS, 1979). In San Bernardino, there are five major contaminant plumes with different contaminants that include inorganics, nitrates, pesticides, and perchlorates. The Muscoy and Newmark contamination plumes are located near Shandon Hills in San Bernardino, CA and its main contaminants are trichloroethylene and perchloroethylene. Efforts from the EPA and local agencies have begun and the extraction and treatment of the groundwater has shown some improvements in the water quality (SAWPA, 2015).

Although some efforts are being made to address water quality in the Santa Ana Basin, there still remains a growing need to implement management plans that are elastic and inclusive to the cumulative effects of climatic change and the natural and anthropocentric sources of pollution inputs. When considering how to sustain water resources for current and future generations, California is of particular interest because it encompasses a dynamic landscape characterized by various climates, ecosystems and densely populated areas that are often spatially misaligned with water resources (SWP, 2019). Geographically, the main sources of water are located in the northern and eastern mountain ranges, but population densities and related resource demands are more
prominent in the southern and western regions of the state (Israel and Lund, 1995). These patterns have resulted in the development of extensive infrastructure that primarily conveys water resources from the Sierra Mountains to agricultural and urban landscapes hundreds of miles away. During the process, natural hydrological flows are often disrupted resulting in desertification of once hydrated landscapes (CDWR, 2019). According to the California Department of Water Resources (CDWR) there are over 1,250 dams in California that are used to store and control the flow of water (CDWR, 2018). To distribute water from these dams, a 444-mile long California Aqueduct was constructed from the Sacramento-San Joaquin Delta to Los Angeles and Riverside Counties, where the majority of the state’s population and water demand resides.

Despite these engineered tactics, water infrastructure has not mitigated major reductions in water resources during periods of prolonged drought. The last major drought in California lasted five years from 2012-2016 resulting in many water shortages, and concerns throughout the state that eventually lead Governor Brown to declare a drought state of emergency in 2014 (Chappell, 2014, USGS, 2018). During the historic drought, the annual state runoff was significantly lower compared to normal years and during the peak of the drought, the mean annual temperature was at its highest while the mean annual precipitation was at its lowest (CDWR, 2017; Dagit et al., 2017). When such conditions occur, groundwater resources are utilized to support various human activities. To increase groundwater resources, percolation basins have been
implemented on the landscape to capture surface water and replenish underground aquifers during the wet seasons. These basins can be used during the dry season and during droughts, however, the quality of water prior to entering these basins is not well documented indicating that water pulled from these basins for distribution to local communities may be impaired. Although expensive, wastewater recycling and desalination have also been considered to mitigate growing water resource needs, however, the cost is often shifted to consumers often causing economic and resource deficiencies in low income communities, further escalating resource disparities and access (Choy et al., 2014; Task Group Report, 1963, SBVMWD, 2019).

Study Purpose and Objectives

The highly variable sources of pollution inputs and the vast amount of water resources needed to support both anthropocentric and ecological activities warrants the need to understand how human activities and natural processes impact surface water resources. This is particularly true of headwater streams, especially those that contribute surface water to groundwater recharge basins. These basins have become increasingly prominent on the landscape to meet human water resource needs, especially during drought conditions. The primary objectives of this study are to (1) illustrate, spatiotemporally, the physicochemical characteristics of multiple water quality metrics at first order, headwater, tributaries and a downstream site prior to entering a recharge basin, (2) determine the extent to which extreme seasonal patterns (wet vs. dry seasons),
including drought and atmospheric rivers conditions, influence the physicochemical characteristics of surface waters and (3) understand statistically significant relationships between the physicochemical characteristics of surface water resources throughout the study site. Findings may support water resource management strategies that aim to mitigate adverse impacts to surface water resources so that they can support both human activities and ecological services for current and future generations.
CHAPTER TWO

STUDY SITE

Although considerable research has focused on water resource trends across various geographical scales, there is limited research on surface water quality of headwater tributaries located within the Santa Ana River Basin (SARB). This watershed is of particular interest because it drains the largest (6,860 square kilometers) and most populated (six million) watershed in Southern California (SAWPA, 2015). Waterman Creek is a headwater tributary of SARB located along highway 18 in the San Bernardino National Forest, California, United States. The canyon has steep topography and its geology is composed of young alluvial fan and landslide deposits with high permeability and low porosity and gneiss bedrock with low permeability and low porosity (USGS, 2001). Weather patterns in the catchment represents a Mediterranean Climate with hot and dry summers and cold and wet winters. Most of the precipitation patterns in this region occur from October to April, but close to 90% of the annual precipitation falls between December and February, as was the case during this study period (SCSC, 2019).

The study site contains three catchments; two contain headwater tributaries and the third location represents the downstream convergence of these headwaters. Each of the catchment stream segments are surrounded by a variety of natural and anthropogenic activities that include forest, agriculture, commercial and residential buildings and related impervious surfaces (i.e. roads,
parking lots) and various infrastructure (i.e. septic systems, natural gas pipelines) and recreational activities (Figure 1). The western catchment (i.e. Catchment 1, HUC 22554838; 4.63 km²) forms a small first order stream segment (0.49 km), however, the catchment contains a substantial amount of impervious surfaces (e.g. roads and homes) when compared to the other catchments. The eastern catchment (i.e. Catchment 2, HUC 22554836; 3.14 km²) contains a first order stream segment (2.08 km) that traverses agricultural land and less impervious surfaces when compared to Catchment 1. The third and southernmost catchment (i.e. Catchment 3, HUC 22555344; 7.24 km²) begins where catchments 1 and 2 converge to form a second order stream known as Waterman Creek (EPA, 2019). Waterman Creek terminates into the San Bernardino Valley Municipal Water District’s percolation basin, which is used to recharge groundwater for use during dry seasons and extreme droughts.
Figure 1. Waterman Canyon Site Location.
CHAPTER THREE

METHODS

Water Quality Sampling

Water quality was monitored in situ and with additional samples processed in the lab from April 2018 to April 2019. Samples were collected bi-weekly during the dry season (i.e. May through September) and weekly during the wet season (i.e. October through April). Samples were collected at three points within the catchment area (15 km$^2$). Site one and two are located along two different first order tributaries, while site 3 is located at the confluence of these tributary streams (Figure 1). Additional samples were collected before, during, and after rain events. In situ, stream side monitoring included measurements of ammonium (mg/L), conductivity (μS/cm), dissolved oxygen (mg/L), pH, nitrate (mg/L), turbidity (NTU), and temperature (°C) using ion selective electrodes, probes, and a Vernier LabQuest 2 monitor similar to Khatoon et al. (2013), Schraga and Cloern (2017), Vega et al. (1998), and Varol et al. (2012). Total Dissolved Solids (TDS) grab samples were collected in 1 (L) brown opaque HDPE plastic bottles that were acid washed using EPA protocols. The acid wash included a wash with trace metal phosphate free laboratory detergent, rinsed with tap water, then washed with 50:50 HNO$_3$ and deionized (DI) water, and rinsed with DI water. Total Coliform and E. Coli were analyzed using U.S. EPA approved IDEXX methods, Colilert, Colilert-18, Colisure, and Quanti-Tray/2000.
Results were reported as most probable number per 100 milliliters (MPN/100mL) of water, which is comparable to the EPA colony forming units (cfu). Total coliform and E. Coli testing began in mid-May 2018 due to equipment availability. Grab samples were immediately placed on ice and refrigerated in the lab at 4 °C until analyzed. Data from field monitoring and lab results were recorded in Microsoft Excel.

**Water Quality Criteria**

The U.S. Environmental Protection Agency Recreational Water Quality and Aquatic Life Criteria, California State Water Resources Control Board, South Lahontan Region Objectives, and San Bernardino Mountains Hooks Creek Objectives were compared to individual samples and parameter means to determine if water samples were meeting federal criteria and state objectives (Table 1) (USEPA, 2012; WQCP, 2015). These criteria and standards represent the most local and regionalized standards what can be applied to this study site. Although the EPA approved IDEXX testing procedures for total coliform and E. Coli are reported in most probable number (MPN) when results are read in the lab, IDEXX indicates that results align with the EPA’s colony forming units (cfu) and these units are interchangeable (IDEXX, 2019; USEPA, 2003). The percentages of the total samples collected and exceeding the criteria and objectives were calculated for each site.
Table 1. Water Quality Criteria and Objectives

<table>
<thead>
<tr>
<th>Water Quality Metric</th>
<th>Unit</th>
<th>Standard</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature</td>
<td>C</td>
<td>&lt;25 C</td>
<td>CA State Water Board</td>
</tr>
<tr>
<td>Dissolved Oxygen (DO)</td>
<td>mg/L</td>
<td>&gt;4 mg/L</td>
<td>CA State Water Board, Lahontan Region</td>
</tr>
<tr>
<td>pH</td>
<td>------</td>
<td>6.5-8.5</td>
<td>CA State Water Board, Lahontan Region</td>
</tr>
<tr>
<td>Turbidity (Turb)</td>
<td>NTU</td>
<td>&lt;100 NTU</td>
<td>CA State Water Board (Fact Sheet)</td>
</tr>
<tr>
<td>Conductivity (Cond)</td>
<td>μS/cm</td>
<td>150-500 Range</td>
<td>EPA (Range)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>&lt;336 μS/cm (mean)</td>
<td>CA State Water Board (mean)</td>
</tr>
<tr>
<td>Nitrate (NO₃⁻)</td>
<td>mg/L</td>
<td>0.8-2.5 mg/L</td>
<td>San Bernardino Mountains Hooks Creek Objectives</td>
</tr>
<tr>
<td>Ammonium (NH₄⁺)</td>
<td>mg/L</td>
<td>0.02-0.4 mg/L</td>
<td>EPA Aquatic Life Criteria</td>
</tr>
<tr>
<td>Total Coliform (TC)</td>
<td>cfu/100mL</td>
<td>&lt;1,000 cfu/100mL</td>
<td>CA State Water Board Objectives</td>
</tr>
<tr>
<td>E. Coli</td>
<td>cfu/100mL</td>
<td>&lt;126 cfu/100mL</td>
<td>EPA Recreational Standards</td>
</tr>
<tr>
<td>Total Dissolved Solids (TDS)</td>
<td>mg/L</td>
<td>&lt;127 mg/L</td>
<td>San Bernardino Mountains Hooks Creek Objectives</td>
</tr>
</tbody>
</table>
Watershed Terrestrial and Hydrological Characteristics

To determine potential relationships between land use types and water quality, the 2016 Multiresolution National Land Cover Dataset was downloaded into ArcGIS 10.4 and clipped to the catchment areas (MRCL, 2019). Google Earth’s satellite imagery was also utilized to identify the percent of each land use type within the catchment, since the size of the catchment is small and there are no available land use cover data available for this area. This process included the creation of polygons that represented, residential lots, roads, agriculture land, forest and water features including streams and the recharge basin. The streams recharge basin, delineation, and catchments were determined using the USEPA’s WATERS KMZ geospatial layer (USEPA, 2017). Precipitation data was collected from Weather Underground using the Upper Waterman Canyon and Mountain weather stations, which is located upstream of the testing sites. Additionally, septic and sewer information was collected from the San Bernardino County Municipal Water District and the Crestline Sanitation District. This information was confirmed by ground truthing to further determine where dwelling with septic and sewer are located within each catchment.

Statistical Analysis

Applying methods similar to Alford (2016), Khatoon (2013), and Varol et al. (2012) descriptive statistics including mean, variance, and standard deviations, for each water quality parameters were calculated for each site during the study period. To understand statistically significant relationships among the
water quality parameters, SPSS Version 24 was used to create a Pearson’s correlation matrix for each sampling location that highlights statistically significant relationships among water parameter the 0.05 and 0.01 confidence levels. Parameters were tested for normality in SPSS using Shapiro-Wilks tests and observing skewness and kurtosis values. Water quality parameter sampling data not following a normal distribution were transformed using a natural log transformation in Microsoft Excel as previously applied by Mallin et al. (2016), USGS (2015) and Yuncong and Migliaccio (2011). Time series analysis was conducted using Microsoft Excel to illustrate changes in the physicochemical characteristics of the stream over time and to relate these trends to wet and dry seasons.
CHAPTER FOUR
RESULTS

Watershed Characteristics

To understand the temporal characteristics of precipitation, precipitation accumulations were aggregated for 24, 48 and 72 hours prior to a single sampling event. In general, higher frequencies (0.1-8.97 inches) of precipitation events occurred between November 2018 through April 2019 (Figure 2), while smaller precipitation (0.1-0.63 inches) events occurred 72 hours prior to multiple sampling dates in May 2018. These rain events were followed by a dry period that lasted until 11/30/2018. Sampling events in November 2018, December 2018, and throughout January were associated with the largest precipitation accumulations. It should be noted that during the May 2018 to November 2018 period, there was a prolonged drought period for the study site and one of the worst fire seasons in California history, although no fires were in close proximity to the study site. In contrast, the November 2018 to March 2019 period was one of the most extreme precipitation events characterized by several atmospheric rivers creating the highest precipitation accumulations in nearly a decade.
Figure 2. Total Precipitation for 24hrs, 48hrs, and 72 hrs. (in.).
In relation to landscape characteristics, barren land represented a majority of the catchments (Figure 3). Catchment 3 had the highest percentage of impervious surfaces (i.e. 31%), while Catchment 2 had the highest percentage of evergreen forests (i.e. 39%). In relation to specific catchment features (Figure 4), Catchment 1 had the highest number of dwelling units (i.e. 211), septic (i.e. 153) and sewer (i.e. 58) systems, with Catchment 2 having the second highest number of these features and Catchment 3 having the lowest across the three catchments.
Figure 3. Land Use and Land Cover Catchment Characteristics.
Figure 4. Catchment Infrastructure Characteristics.
Descriptive Statistics and Physiochemical Correlations

The descriptive statistics, recommended water quality criteria/objectives, and the number of testing events exceeding the standards for the overall data collected at the three sampling sites are illustrated in Table 2. Four water quality parameter means exceeded the criteria and objectives outlined in Table 1 including nitrate (NO$_3^-$) (10.1 mg/L), ammonium (NH$_4^+$) (0.99 mg/L), total coliform (1162 cfu/100mL), and total dissolved solids (TDS) (200 mg/L). A majority of parameters (i.e. conductivity, NO$_3^-$, NH$_4^+$, pH, total coliform, E. Coli, and TDS) have individual samples that failed to meet their criteria and objectives. As shown on Table 2, the mean conductivity does not exceed the CA State Water Board mean objective (<336 μS/cm), but seven individual samples did not meet the EPA range standards (150-500 μS/cm). TDS had a mean (200 mg/L) and seventy four samples that exceeded the San Bernardino Mountains Hooks Creek objectives. NO$_3^-$ had a mean (10.1 mg/L) and eighty-nine individual samples that exceeded the San Bernardino Mountains Hooks Creek Objectives (0.8-2.5 mg/L). NH$_4^+$ had a mean (.9902 mg/L) and fifty-one individual samples that did not meet the EPA Aquatic Life Criteria (0.02-0.4 mg/L). The mean pH (8.09) was within the CA State Water Board objective (6.5-8.5), but six individual samples did not meet the objective. For bacteria, the total coliform mean (1162.5 cfu/100mL) and forty-eight individual samples exceeded the CA State Water Board objective (1000 cfu/100mL) and the E. Coli mean (46.84 cfu/100mL) was within EPA standards but six individual samples did not meet the EPA standards. Total coliform
(679975) and E. Coli (15164) had the greatest variation followed by conductivity (9169) and TDS (4483). It should be noted that there was a period during the dry season and the beginning of the wet season (July through August) when site 3 was not flowing, therefore during this period there was no data collected for the site.
Table 2. Descriptive Statistics for all Water Quality Data Combined

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Variance</th>
<th>Criteria</th>
<th># and % Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow m/s</strong></td>
<td></td>
<td>.04</td>
<td>2.2</td>
<td>.58</td>
<td>.41</td>
<td>.17</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>DO mg/L</strong></td>
<td></td>
<td>5.1</td>
<td>13.2</td>
<td>9.6</td>
<td>1.8</td>
<td>3.3</td>
<td>&gt;4.0 mg/L</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>Temp. C</strong></td>
<td></td>
<td>9.4</td>
<td>21.4</td>
<td>14.2</td>
<td>2.8</td>
<td>8.3</td>
<td>&lt;25 C</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>Conductivity μS/cm</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>150-500 Range</td>
<td>7 (6.7%)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>&lt;336 μS/cm (mean)</td>
<td></td>
</tr>
<tr>
<td><strong>NO₃⁻ mg/L</strong></td>
<td></td>
<td>.50</td>
<td>40.1</td>
<td>10.1</td>
<td>8.1</td>
<td>66</td>
<td>0.8-2.5 mg/L</td>
<td>89 (90.1%)</td>
</tr>
<tr>
<td><strong>NH₄⁺ mg/L</strong></td>
<td></td>
<td>.00</td>
<td>10.7</td>
<td>.99</td>
<td>1.8</td>
<td>3.6</td>
<td>0.02-0.4 mg/L</td>
<td>51 (54.3%)</td>
</tr>
<tr>
<td><strong>Turbidity NTU</strong></td>
<td></td>
<td>.00</td>
<td>53</td>
<td>10.9</td>
<td>8.9</td>
<td>79</td>
<td>&lt;100 NTU</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td></td>
<td>1.00</td>
<td>30</td>
<td>8.1</td>
<td>4.4</td>
<td>19</td>
<td>6.5-8.5</td>
<td>6 (5.9%)</td>
</tr>
<tr>
<td><strong>TC cfu/100mL</strong></td>
<td></td>
<td>66.3</td>
<td>2419</td>
<td>1162</td>
<td>824</td>
<td>679975</td>
<td>&lt;1,000 cfu/100mL</td>
<td>48 (48.5%)</td>
</tr>
<tr>
<td><strong>EC cfu/100mL</strong></td>
<td></td>
<td>.00</td>
<td>1119.9</td>
<td>46</td>
<td>123</td>
<td>15164</td>
<td>&lt;126 cfu/100mL</td>
<td>6 (6.1%)</td>
</tr>
<tr>
<td><strong>TDS mg/L</strong></td>
<td></td>
<td>52</td>
<td>372</td>
<td>200</td>
<td>66.9</td>
<td>4483</td>
<td>&lt;127 mg/L</td>
<td>74 (84.1%)</td>
</tr>
</tbody>
</table>
Table 3 displays the overall correlation of all the data from Waterman Creek. Flow was statistically significant and positively correlated to DO and statistically significant and negatively correlated to temperature, TC, and E. Coli. Flow’s positive correlation ($r=0.61$) and statistical significance ($p<0.01$) to DO indicates that as flow increases, DO increases. Flow was negatively correlated ($r=-0.50$) and statistically significant ($p<0.01$) to temperature meaning that as temperature decreased, flow increased. DO was negatively correlated to temperature ($r=-0.73$; $p<0.01$), TC ($r=-0.23$; $p<0.05$), and E. Coli ($r=-0.25$; $p<0.05$) showing that as temperature, TC, or E. Coli increases, DO decreases. Temperature was positively correlated with TC ($r=0.26$; $p<0.01$) and E. Coli ($r=0.25$; $p<0.05$) and negatively correlated with conductivity ($r=-0.27$; $p<0.01$). Conductivity was positively correlated to pH ($r=0.26$; $p<0.01$). Nitrate was negatively correlated to TC ($r=-0.31$; $p<0.05$) and TDS ($r=-0.36$; $p<0.01$). Total Coliform was positively correlated to E. Coli ($r=0.57$; $p<0.01$) and TDS ($r=0.42$; $p<0.01$) showing that as total coliform increases, E. Coli and TDS increases. Lastly, E. Coli was positively correlated with TDS ($r=0.43$; $p<0.01$).
Table 3. Covariance Correlations Matrix for All Sampling Sites. All Parameters Log Transformed.

<table>
<thead>
<tr>
<th></th>
<th>Flow</th>
<th>DO</th>
<th>Temp.</th>
<th>Cond.</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>Turb.</th>
<th>pH</th>
<th>TC</th>
<th>EC</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>0.61**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>-0.50**</td>
<td>-0.73**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cond.</td>
<td>-0.168</td>
<td>-0.10</td>
<td>-0.27**</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>-0.08</td>
<td>0.16</td>
<td>-0.25</td>
<td>-0.168</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>0.03</td>
<td>0.14</td>
<td>-0.09</td>
<td>0.06</td>
<td>-0.04</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turb.</td>
<td>-0.13</td>
<td>-0.18</td>
<td>0.20</td>
<td>0.09</td>
<td>-0.00</td>
<td>-0.08</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-0.04</td>
<td>-0.008</td>
<td>0.10</td>
<td>0.26**</td>
<td>-0.09</td>
<td>-0.10</td>
<td>0.11</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>-0.24*</td>
<td>-0.23*</td>
<td>0.26**</td>
<td>0.08</td>
<td>-0.31*</td>
<td>0.04</td>
<td>0.09</td>
<td>-0.05</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>-0.24*</td>
<td>-0.25*</td>
<td>0.25*</td>
<td>0.16</td>
<td>-0.11</td>
<td>0.09</td>
<td>-0.02</td>
<td>-0.11</td>
<td>0.57**</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>TDS</td>
<td>0.05</td>
<td>-0.06</td>
<td>0.11</td>
<td>0.02</td>
<td>-0.36**</td>
<td>0.17</td>
<td>-0.05</td>
<td>-0.14</td>
<td>0.42**</td>
<td>0.43**</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
Catchment 1: Descriptive Statistics and Physiochemical Correlations

Catchment 1 represents the second largest percent of impervious surfaces and the largest number density of dwelling units (n=211) with four water quality parameters means exceeding the criteria and objectives, as outlined in Table 1. This includes NO$_3^-$ (9.8 mg/L), NH$_4^+$ (0.81 mg/L), total coliform (1389 cfu/100mL), TDS (192 mg/L). A majority of parameters, (i.e. NO$_3^-$, NH$_4^+$, pH, total coliform, E. Coli, and TDS) have individual samples that failed to meet their criteria and objectives. TDS has a mean (192 mg/L) and twenty eight samples that exceeded the San Bernardino Mountains Hooks Creek objectives. NO$_3^-$ has a mean (9.8 mg/L) and thirty-four individual samples that exceeded the San Bernardino Mountains Hooks Creek Objectives (0.8-2.5 mg/L). NH$_4^+$ has a mean (0.81 mg/L) and seventeen individual samples that did not meet the EPA Aquatic Life Criteria (0.02-0.4 mg/L). The mean pH (8.18) was within the CA State Water Board objective (6.5-8.5), but five individual samples did not meet the objective.

For bacteria, the total coliform mean (1388 cfu/100mL) and twenty-three individual samples exceeded the CA State Water Board objective (1000 cfu/100mL) and with E. Coli the mean (41.1 cfu/100mL) was within EPA standards but two individual samples did not meet the EPA standards. Total coliform (687421) and E. Coli (4968) had the greatest variance followed by conductivity (5792) and TDS (2586).
Table 4. Descriptive Statistics of Water Quality Data for Catchment 1 Samples.

<table>
<thead>
<tr>
<th>Descriptive Statistics WC1</th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Variance</th>
<th>Criteria/ Standards</th>
<th># and % Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow m/s</td>
<td>38</td>
<td>.04</td>
<td>1.1</td>
<td>.48</td>
<td>.34</td>
<td>.12</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DO mg/L</td>
<td>37</td>
<td>5.6</td>
<td>12.7</td>
<td>9.4</td>
<td>1.9</td>
<td>3.5</td>
<td>&gt;4 mg/L</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Temp. C</td>
<td>38</td>
<td>9.9</td>
<td>21.4</td>
<td>14.7</td>
<td>3.2</td>
<td>10.5</td>
<td>&lt;25 C</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Conductivity μS/cm</td>
<td>38</td>
<td>159</td>
<td>485</td>
<td>291</td>
<td>76.1</td>
<td>5791</td>
<td>150-500 Range &lt;336 μS/cm (mean)</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>NO₃⁻ mg/L</td>
<td>35</td>
<td>2.0</td>
<td>40.1</td>
<td>9.8</td>
<td>8.4</td>
<td>70</td>
<td>0.8-2.5 mg/L</td>
<td>34 (94.4%)</td>
</tr>
<tr>
<td>NH₄⁺ mg/L</td>
<td>34</td>
<td>.00</td>
<td>10.7</td>
<td>.81</td>
<td>1.9</td>
<td>3.5</td>
<td>0.02-0.4 mg/L</td>
<td>17 (48.5%)</td>
</tr>
<tr>
<td>Turbidity NTU</td>
<td>37</td>
<td>.00</td>
<td>31.4</td>
<td>10.1</td>
<td>8.1</td>
<td>66</td>
<td>&lt;100 NTU</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>pH</td>
<td>38</td>
<td>5.8</td>
<td>8.2</td>
<td>7.2</td>
<td>.52</td>
<td>.27</td>
<td>6.5-8.5</td>
<td>5 (13.2%)</td>
</tr>
<tr>
<td>TC cfu/100 mL</td>
<td>37</td>
<td>82.3</td>
<td>2419</td>
<td>1388</td>
<td>829</td>
<td>687421</td>
<td>&lt;1,000 cfu/100mL</td>
<td>23 (62.2%)</td>
</tr>
<tr>
<td>EC cfu/100 mL</td>
<td>37</td>
<td>2.0</td>
<td>410</td>
<td>41</td>
<td>70.5</td>
<td>4967</td>
<td>&lt;126 cfu/100mL</td>
<td>2 (5.4%)</td>
</tr>
<tr>
<td>TDS mg/L</td>
<td>31</td>
<td>88</td>
<td>284</td>
<td>192</td>
<td>50.8</td>
<td>2586</td>
<td>&lt;127 mg/L</td>
<td>28 (90.3%)</td>
</tr>
</tbody>
</table>
Table 5 illustrates correlation between the physicochemical parameters and samples for WC1. Table 5 illustrates that flow has a positive correlation with DO ($r=0.74$; $p<0.01$) and nitrate ($r=0.52$; $p<0.01$) and a negative correlation between temperature ($r=-0.70$; $p<0.01$), conductivity ($r=-0.38$; $p<0.05$), TC ($r=-0.41$; $p<0.05$), E. Coli ($r=-0.44$; $p<0.01$), and TDS ($r=-0.49$; $p<0.01$). This shows that as flow increased, DO and nitrate increased and as flow increased temperature, conductivity, TC, E. Coli, and TDS decreased and vice versa. DO had a positive correlation with nitrate ($r=0.63$; $p<0.01$) and a negative correlation with temperature ($r=-0.88$; $p<0.01$), pH ($r=-0.45$; $p<0.01$), TC ($r=-0.50$; $p<0.05$), E. Coli ($r=-0.35$; $p<0.05$), and TDS ($r=-0.65$; $p<0.01$). Temperature has positive correlations with conductivity ($r=0.37$; $p<0.05$), pH ($r=0.45$; $p<0.01$), TC ($r=0.53$; $p<0.01$), E. Coli ($r=0.38$; $p<0.05$), and (r=0.56; $p<0.05$) and a negative correlation with nitrate ($r=-0.57$; $p<0.01$). Conductivity has a positive correlation with ammonium ($r=0.47$; $p<0.01$), TC ($r=0.35$; $p<0.05$), and E. Coli ($r=0.61$; $p<0.05$) and a negative correlation with nitrate ($r=-0.39$; $p<0.05$). Nitrate has two negative correlations with TC ($r=-0.41$; $p<0.05$) and TDS ($r=-0.55$; $p<0.01$), illustrating that as NO$_3^-$ increases, TC and TDS decreases. pH has a positive correlation with TDS ($r=0.43$; $p<0.05$) and TC has a positive correlation with both E. Coli ($r=0.46$; $p<0.05$) and TDS ($r=0.36$; $p<0.01$). Finally, E. Coli and TDS are positively correlated ($r=0.36$; $p<0.05$).
### Table 5. Covariance Correlations Matrix for WC1. All Parameters Log Transformed.

<table>
<thead>
<tr>
<th></th>
<th>Flow</th>
<th>DO</th>
<th>Temp.</th>
<th>Cond.</th>
<th>NO₂</th>
<th>NH₄⁺</th>
<th>Turb.</th>
<th>pH</th>
<th>TC</th>
<th>EC</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>.74*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>-.70</td>
<td>-.88*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cond.</td>
<td>-.38</td>
<td>-.31</td>
<td>-.57*</td>
<td>-.31</td>
<td>.37*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO₂</td>
<td>.52*</td>
<td>.63*</td>
<td>-.57*</td>
<td>-.39*</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH₄⁺</td>
<td>.06</td>
<td>.07</td>
<td>-.08</td>
<td>.47*</td>
<td>-.14</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turb.</td>
<td>-.22</td>
<td>-.13</td>
<td>.11</td>
<td>-.05</td>
<td>-.15</td>
<td>-.20</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-.25</td>
<td>-.45*</td>
<td>.45*</td>
<td>.15</td>
<td>-.06</td>
<td>-.004</td>
<td>-.09</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>-.41</td>
<td>-.50*</td>
<td>.53*</td>
<td>.35*</td>
<td>-.41*</td>
<td>.05</td>
<td>.24</td>
<td>.16</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>-.44</td>
<td>-.35*</td>
<td>.38*</td>
<td>.61*</td>
<td>-.28</td>
<td>.26</td>
<td>-.03</td>
<td>.06</td>
<td>.46*</td>
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</tr>
<tr>
<td>TDS</td>
<td>-.49*</td>
<td>-.65*</td>
<td>.56*</td>
<td>.21</td>
<td>-.55</td>
<td>.12</td>
<td>.06</td>
<td>.43*</td>
<td>.36*</td>
<td>.36*</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
Catchment 2: Descriptive Statistics and Physiochemical Correlations

Catchment 2, which is located in the eastern catchment of the canyon contains an organic farm and a smaller number of dwelling units (n=35 vs. 211), when compared to catchment 1 and it has four water quality parameters with means that exceeded the criteria and objectives outlined in Table 1. This includes NO$_3^-$ (8.36 mg/L), NH$_4^+$ (1.1 mg/L), total coliform (1068 cfu/100mL), TDS (187 mg/L). A majority of parameters, including conductivity, NO$_3^-$, NH$_4^+$, pH, total coliform, E. Coli, TDS, and turbidity has individual samples that failed to meet their criteria and objectives. As shown on Table 6, the mean conductivity (298 μS/cm) does not exceed the CA State Water Board mean objective (<336 μS/cm), but two individual samples did not meet the EPA range standards (150-500 μS/cm). TDS has a mean (187 mg/L) and twenty five samples that exceed the San Bernardino Mountains Hooks Creek objectives. NO$_3^-$ has a mean (8.4 mg/L) and thirty-three individual samples that exceeded the San Bernardino Mountains Hooks Creek Objectives (0.8-2.5 mg/L). NH$_4^+$ has a mean (1.1 mg/L) and twenty individual samples that did not meet the EPA Aquatic Life Criteria (0.02-0.4 mg/L). The mean pH (7.17) was within the CA State Water Board objective (6.5-8.5), but one individual sample did not meet the objective. For bacteria, the total coliform mean (1068 cfu/100mL) and seventeen individual samples exceed the CA State Water Board objective (1000 cfu/100mL) and with E. Coli the mean (68 cfu/100mL) was within EPA standards, but three individual samples did not meet the EPA standards. Total coliform (606180) and E. Coli (34075) has the greatest variance followed by conductivity (6710) and TDS (4158).
Table 6. Descriptive Statistics of Water Quality Data for Catchment 2 Samples.

<table>
<thead>
<tr>
<th>Descriptive Statistics WC2</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N</td>
<td>Min</td>
<td>Max</td>
<td>Mean</td>
<td>Std. Deviation</td>
<td>Variance</td>
<td>Criteria/ Standards</td>
<td># and % Exceeding</td>
</tr>
<tr>
<td>Flow m/s</td>
<td>41</td>
<td>.06</td>
<td>1.2</td>
<td>.49</td>
<td>.32</td>
<td>.10</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>DO mg/L</td>
<td>40</td>
<td>5.1</td>
<td>12.7</td>
<td>9.3</td>
<td>1.8</td>
<td>3.1</td>
<td>&gt;4 mg/L</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Temp. C</td>
<td>40</td>
<td>10.0</td>
<td>20.4</td>
<td>14.1</td>
<td>2.9</td>
<td>8.3</td>
<td>&lt;25 C</td>
<td>0 (0%)</td>
</tr>
<tr>
<td>Conductivity μS/cm</td>
<td>41</td>
<td>197</td>
<td>547</td>
<td>297</td>
<td>81.9</td>
<td>6710</td>
<td>150-500 Range &lt;336 μS/cm (mean)</td>
<td>2 (4.8%)</td>
</tr>
<tr>
<td>NO₃⁻ mg/L</td>
<td>39</td>
<td>1.7</td>
<td>23.3</td>
<td>8.4</td>
<td>6.3</td>
<td>40.2</td>
<td>0.8-2.5 mg/L</td>
<td>33 (84.6%)</td>
</tr>
<tr>
<td>NH₄⁺ mg/L</td>
<td>37</td>
<td>.00</td>
<td>7.9</td>
<td>1.1</td>
<td>1.7</td>
<td>3.1</td>
<td>0.02-0.4 mg/L</td>
<td>20 (54.1%)</td>
</tr>
<tr>
<td>Turbidity NTU</td>
<td>39</td>
<td>.50</td>
<td>53</td>
<td>11.9</td>
<td>10.1</td>
<td>101</td>
<td>&lt;100 NTU</td>
<td>3 (7.7%)</td>
</tr>
<tr>
<td>pH</td>
<td>38</td>
<td>6.2</td>
<td>7.8</td>
<td>7.2</td>
<td>.35</td>
<td>.12</td>
<td>6.5-8.5</td>
<td>1 (2.6%)</td>
</tr>
<tr>
<td>TC cfu/100mL</td>
<td>37</td>
<td>66.3</td>
<td>2419</td>
<td>1068</td>
<td>778</td>
<td>606180</td>
<td>&lt;1,000 cfu/100mL</td>
<td>17 (46%)</td>
</tr>
<tr>
<td>EC cfu/100 mL</td>
<td>37</td>
<td>1.0</td>
<td>1119</td>
<td>68</td>
<td>184</td>
<td>34075</td>
<td>&lt;126 cfu/100mL</td>
<td>3 (8.1%)</td>
</tr>
<tr>
<td>TDS mg/L</td>
<td>32</td>
<td>52.0</td>
<td>304</td>
<td>187</td>
<td>64</td>
<td>4158</td>
<td>&lt;127 mg/L</td>
<td>25 (78.1%)</td>
</tr>
</tbody>
</table>
Table 7 shows that flow was positively correlated to DO ($r=0.58; p<0.01$) and $\text{NO}_3^-$ ($r=0.54; p<0.01$) indicating that as flow increases, the concentrations of DO and $\text{NO}_3^-$ increase. DO was positively correlated to $\text{NO}_3^-$ ($r=0.79; p<0.01$) and negatively correlated to temperature ($r=-0.59; p<0.01$) and TDS ($r=-0.55; p<0.01$) meaning that as DO increases, $\text{NO}_3^-$ increases. This also means that as the water temperature increased, there was less DO present. Temperature had a positive correlation with TDS ($r=0.56; p<0.01$) and a negative correlation with $\text{NO}_3^-$ ($r=-0.65; p<0.01$) suggesting that higher stream temperatures were associated with higher TDS and lower $\text{NO}_3^-$ concentrations. Conductivity is positively correlated with $\text{NH}_4^+$ ($r=0.41; p<0.05$) and EC ($r=0.412; p<0.05$) and negatively correlated with $\text{NO}_3^-$ ($r=-0.45; p<0.01$) indicating that as conductivity increases $\text{NH}_4^+$ and EC increases and $\text{NO}_3^-$ decreases. $\text{NO}_3^-$ is negatively correlated with TDS ($r=-0.62; p<0.01$), therefore as $\text{NO}_3^-$ increases TDS decreases. Turbidity was positively correlated with TDS ($r=0.39; p<0.05$), but it was a weak association. Finally, TC was strongly correlated to E. Coli ($r=0.66; p<0.01$) indicating that as TC increases, E. Coli increases.
Table 7. Covariance Correlations Matrix for WC2. All Parameters Log Transformed.

<table>
<thead>
<tr>
<th></th>
<th>Flow</th>
<th>DO</th>
<th>Temp.</th>
<th>Cond.</th>
<th>NO$_3^-$</th>
<th>NH$_4^+$</th>
<th>Turb.</th>
<th>pH</th>
<th>TC</th>
<th>EC</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>DO</td>
<td>.583$^*$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>-.311</td>
<td>-.590$^*$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cond.</td>
<td>-.143</td>
<td>-.204</td>
<td>.182</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_3^-$</td>
<td>.541</td>
<td>.792$^*$</td>
<td>-.649</td>
<td>-.452$^*$</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>.086</td>
<td>-.127</td>
<td>-.013</td>
<td>.415</td>
<td>-.190</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turb.</td>
<td>-.200</td>
<td>-.274</td>
<td>.296</td>
<td>-.016</td>
<td>-.229</td>
<td>-.084</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>-.280</td>
<td>-.284</td>
<td>.215</td>
<td>.311</td>
<td>-.225</td>
<td>.207</td>
<td>.027</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
<td>.101</td>
<td>-.065</td>
<td>.232</td>
<td>.309</td>
<td>-.193</td>
<td>-.006</td>
<td>-.046</td>
<td>.083</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC</td>
<td>.136</td>
<td>-.197</td>
<td>.135</td>
<td>.412$^*$</td>
<td>-.222</td>
<td>.114</td>
<td>-.175</td>
<td>-.033</td>
<td>.663$^*$</td>
<td>1</td>
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</tr>
<tr>
<td>TDS</td>
<td>-.401$^*$</td>
<td>-.556$^*$</td>
<td>.578$^*$</td>
<td>.175</td>
<td>-.628$^*$</td>
<td>.048</td>
<td>.399</td>
<td>.28</td>
<td>.02</td>
<td>.09</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
Catchment 3: Descriptive Statistics and Physiochemical Correlations

Catchment 3, which is located in the southern section of the canyon, is a second order tributary and the closest site to the Waterman Percolation Basin. This site had four water quality parameters with means that exceeded the criteria and objectives outlined in Table 1. This included NO$_3^-$ (10.6 mg/L), NH$_4^+$ (1.12 mg/L), conductivity (340 μS/cm), TDS (229 mg/L). A majority of parameters, including conductivity, NO$_3^-$, NH$_4^+$, total coliform, E. Coli, and TDS had individual samples that failed to meet their criteria and objectives. As shown in Table 8, the mean conductivity (341 μS/cm) exceeds the CA State Water Board Objective (<336 μS/cm) and five individual samples did not meet the EPA range standards (150-500 μS/cm). TDS had a mean (229 mg/L) and twenty-one samples that exceeded the San Bernardino Mountains Hooks Creek Objectives. NO$_3^-$ had a mean (10.6 mg/L) and twenty-two individual samples that exceeded the San Bernardino Mountains Hooks Creek Objectives (0.8-2.5 mg/L). NH$_4^+$ had a mean (1.12 mg/L) and fifteen individual samples that did not meet the EPA Aquatic Life Criteria (0.02-0.4 mg/L). For bacteria, the total coliform mean (966 cfu/100mL) and eight individual samples exceeded the CA State Water Board Objective (1000 cfu/100mL) and with E. Coli the mean (23 cfu/100mL) was within EPA standards but one individual sample does not meet the EPA standards. Total coliform (703531) and conductivity (17151) have the greatest variance followed by TDS (6500) and E. Coli (1979). Turbidity (68.1) and NH3+ (63.4) also have significant variances as well.
### Table 8. Descriptive Statistics of Water Quality Data for Catchment 3 Samples

<table>
<thead>
<tr>
<th></th>
<th>N</th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Std. Deviation</th>
<th>Variance</th>
<th>Criteria/ Standards</th>
<th># and % Exceeding</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Flow m/s</strong></td>
<td>26</td>
<td>.29</td>
<td>2.2</td>
<td>.87</td>
<td>.50</td>
<td>.25</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td><strong>DO mg/L</strong></td>
<td>24</td>
<td>8.0</td>
<td>13.2</td>
<td>10.6</td>
<td>1.4</td>
<td>1.9</td>
<td>&gt;4 mg/L</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>Temp. C</strong></td>
<td>26</td>
<td>9.4</td>
<td>18.9</td>
<td>13.5</td>
<td>2.2</td>
<td>4.8</td>
<td>&lt;25 C</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>Conductivity μS/cm</strong></td>
<td>26</td>
<td>239</td>
<td>644</td>
<td>340</td>
<td>130</td>
<td>17151</td>
<td>150-500 Range &lt;336 μS/cm (mean)</td>
<td>5 (19.2%)</td>
</tr>
<tr>
<td><strong>NO₃- mg/L</strong></td>
<td>23</td>
<td>.50</td>
<td>28.2</td>
<td>10.6</td>
<td>7.9</td>
<td>63.4</td>
<td>0.8-2.5 mg/L</td>
<td>22 (95.7%)</td>
</tr>
<tr>
<td><strong>NH₄+ mg/L</strong></td>
<td>22</td>
<td>.00</td>
<td>10.2</td>
<td>1.1</td>
<td>2.2</td>
<td>4.7</td>
<td>0.02-0.4 mg/L</td>
<td>15 (68.2%)</td>
</tr>
<tr>
<td><strong>Turbidity NTU</strong></td>
<td>26</td>
<td>1.0</td>
<td>30</td>
<td>10.7</td>
<td>8.3</td>
<td>68.1</td>
<td>&lt;100 NTU</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>pH</strong></td>
<td>26</td>
<td>6.6</td>
<td>8.4</td>
<td>7.6</td>
<td>.54</td>
<td>.29</td>
<td>6.5-8.5</td>
<td>0 (0%)</td>
</tr>
<tr>
<td><strong>TC cfu/100mL</strong></td>
<td>25</td>
<td>76.2</td>
<td>2419</td>
<td>966</td>
<td>838</td>
<td>703530</td>
<td>&lt;1,000 cfu/100mL</td>
<td>8 (32%)</td>
</tr>
<tr>
<td><strong>EC cfu/100mL</strong></td>
<td>25</td>
<td>.00</td>
<td>209</td>
<td>23</td>
<td>44.4</td>
<td>1979</td>
<td>&lt;126 cfu/100mL</td>
<td>1 (4%)</td>
</tr>
<tr>
<td><strong>TDS mg/L</strong></td>
<td>25</td>
<td>94</td>
<td>372</td>
<td>228</td>
<td>80.6</td>
<td>6500</td>
<td>&lt;127 mg/L</td>
<td>21 (84%)</td>
</tr>
</tbody>
</table>
Table 9 shows that flow is negatively correlated with temperature ($r=-0.41; p<0.05$) and TDS ($r=-0.66; p<0.01$) meaning that as flow decreases, temperature and TDS increases. DO has a strong positive correlation with NO$_3^-$ ($r=0.66; p<0.01$) and a negative correlation with temperature ($r=-0.42; p<0.05$) and TDS ($r=-0.51; p<0.05$) illustrating that as DO increases, NO$_3^-$ increases and temperature and TDS decreases. Temperature is positively correlated with conductivity ($r=0.62; p<0.01$), TC ($r=0.46; p<0.05$), and TDS ($r=0.47; p<0.05$). Conductivity was positively correlated with TC ($r=0.46; p<0.05$) meaning that as conductivity increases, TC increases. NO$_3^-$ is negatively correlated to TDS ($r=-0.44; p<0.05$), therefore as NO$_3^-$ increases, TDS decreases. NH$_4^+$ was positively correlated to pH ($r=0.51; p<0.05$). Lastly, TC is positively correlated with E. Coli ($r=0.47; p<0.05$) indicating that as TC increases, E. Coli increases.
Table 9. Covariance Correlations Matrix for WC3. All Parameters Log Transformed.

<table>
<thead>
<tr>
<th></th>
<th>Flow</th>
<th>DO</th>
<th>Temp.</th>
<th>Cond.</th>
<th>NO$_3$</th>
<th>NH$_4^+$</th>
<th>Turb.</th>
<th>pH</th>
<th>TC</th>
<th>EC</th>
<th>TDS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>DO</td>
<td>.309</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
<tr>
<td>Temp.</td>
<td>- .413</td>
<td>- .419</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cond.</td>
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<td>- .335</td>
<td>.616&quot;</td>
<td>1</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NO$_3$</td>
<td>.231</td>
<td>.665&quot;</td>
<td>- .295</td>
<td>- .405</td>
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<td></td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>NH$_4^+$</td>
<td>.240</td>
<td>- .290</td>
<td>.051</td>
<td>.057</td>
<td>.399</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Turb.</td>
<td>.096</td>
<td>.183</td>
<td>- .121</td>
<td>- .241</td>
<td>.166</td>
<td>- .234</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pH</td>
<td>- .301</td>
<td>- .215</td>
<td>.271</td>
<td>- .077</td>
<td>- .390</td>
<td>.507</td>
<td>- .102</td>
<td>1</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>TC</td>
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<td>.458&quot;</td>
<td>.464&quot;</td>
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<td>- .245</td>
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</tr>
<tr>
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<td>.315</td>
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<td>.055</td>
<td>- .116</td>
<td>.470&quot;</td>
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<tr>
<td>TDS</td>
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<td>- .512</td>
<td>.470&quot;</td>
<td>.394</td>
<td>- .438&quot;</td>
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<td>- .139</td>
<td>.317</td>
<td>.022</td>
<td>- .246</td>
<td>1</td>
</tr>
</tbody>
</table>

** Correlation is significant at the 0.01 level (2-tailed).
* Correlation is significant at the 0.05 level (2-tailed).
Temporal and Seasonal Trends

Seasonal trends during the study period were highly variable due to prolonged dry periods (i.e. drought) followed by intense precipitation events often characterized by atmospheric rivers. Extensive periods of no precipitation resulted in low base flows in WC1 and WC2 and no surface flows in WC3. Trends for conductivity, total coliform (TC) and E. Coli (EC) exhibit the most variability across catchments 1 and 2. Since these are tributary headwaters, water quality impairments that occur in these stream segments may impact water resources across the entire hydrological network. As such, the temporal trends associated with these parameters and precipitation events are illustrated in figures 5 - 7.

Figure 5 illustrates conductivity results for site 1 (WC1) and 2 (WC2) and the accumulated precipitation 24 hours prior to sampling. Conductivity was higher during the early portions of the study period (i.e. May, June), followed by the dry season where concentrations were fairly consistent until the beginning of the wet season, which began in early November. The first November precipitation event resulted in a small change in conductivity concentrations at both sites. During the wet season, no significant changes occurred with the largest rain event in January (1.55 inches), however, an increase was observed shortly after this precipitation event related to smaller precipitation events. No significant differences were observed between WC1 and WC2 during both the dry and wet
seasons indicating that trends may be similar across the entire watershed and catchment characteristics may not be a factor in the observed variability.

Figure 6 shows that TC is highly variable across both sites during both dry and wet sampling periods. A majority of the sampling events that exceeded the CA State Water Board Objectives (1,000 cfu/100mL) occurred in the dry season when compared to the wet season at both sampling locations, however, WC1 tends to have higher total coliform concentrations (avg. 1933.1 cfu/100 mL) when compared to WC2 (avg. 1473 cfu/100 mL). In January, during and shortly after the first and largest rain event (1.55 inches), both sites experience a significant increase in concentrations, however, WC1 (>2419.6 cfu/100 mL) has a higher increase compared to WC2 (1553.1 cfu/100 mL). Overall, WC1 has higher total coliform concentrations mean (1388.9 cfu/100 mL) when compared to WC2 (1068.6 cfu/100 mL) indicating that landscape characteristics and surface and subsurface hydrological characteristics may be influencing these trends.

Figure 7 illustrates that in the beginning of the dry season, there was a significant increase in E. Coli at both sites following small rain events in May (0.02 in.). Higher E. Coli concentrations were detected at WC2 when compared to WC1. Over the dry season, characterized by low flows (August 2018-November 2018), E. Coli concentrations were relatively low and consistent with only one of the samples exceeded the EPA Recreational Standards. The first rain event after the dry period occurs in early December.
(0.01 in.), which slightly increased E. Coli counts at both sites. The sampling
days with the highest precipitation during the study period occurs in January
and E. Coli concentrations were within the EPA Recreational Standards
during these events. E. Coli was less variable in the wet season when
compared to the dry season, however, some individual sampling events did
not meet the EPA Recreational Standards in the dry season.
Figure 5. Conductivity and Precipitation Trends.
Figure 6. Total Coliform and Precipitation Trends.
Figure 7. E. Coli and Precipitation Trends.
Figures 8 and 9 illustrate the means for each parameter during the wet and dry seasons. As illustrated on figure 8, flow rate was greater in the wet season for both sites. During the dry season, when mean temperatures were higher, the mean concentration of DO decreased, but during the wet season the opposite was observed showing that temperature and DO are inversely correlated. The NO$_3^-$ and DO means are highest during the wet season and lowest during the dry season suggesting that NO$_3^-$ and DO are positively correlated just as described with Pearson’s correlation for both sites. NH$_4^+$ and pH means are slightly greater in the dry season but remained steady. Turbidity means are not consistent between sites since WC1 had a higher turbidity during the wet season, while WC2 has a higher turbidity during the dry season. Figure 9 shows that conductivity concentrations were higher during the dry season when compared to the wet season for both sites. The bacteria counts for both parameters at both sampling sites are significantly higher during the dry season compared to the wet season. This supports findings in the Pearson’s analysis that bacteria concentrations are positively correlated to temperature and negatively correlated to flow rate. Lastly, TDS concentrations were slightly higher during the dry season.
Figure 8. Wet, Dry Season Means for WC1 and WC2: Flow, DO, Temperature, NO$_3^-$, NH$_4^+$, Turbidity and pH.
Figure 9. Wet, Dry Season Means for WC1 and WC2: Conductivity, Total Coliform, E. Coli and TDS.
CHAPTER FIVE
DISCUSSION

Water Quality Parameters

In this study, three sites were analyzed in three catchments to determine the relationships between the physicochemical parameters under investigation and how these may relate to seasonal and landscape differences in both headwater tributaries and in surface water quality prior to entering the groundwater recharge basin. Catchment 1 (i.e. WC1) has the highest amount of dwelling units, Catchment 2 (i.e. WC2) contains agricultural activities and some impervious surfaces, and Catchment 3 (i.e. WC 3) has the highest amount of impervious surfaces and it is located at the confluence of these two first order tributary streams and represents the last point of sampling prior to surface waters entering the groundwater recharge basin. During the study period, there were extreme weather patterns that included prolonged dry periods (i.e. droughts) creating low base flow events, precipitation periods characterized by heavy rains (i.e. atmospheric river), and smaller events that resulted in higher stream flow (i.e. storm flows). During periods of drought, base flow conditions caused WC3 to go dry for an extended period of time (July-November), but WC1 and WC2 were flowing. Although it is beyond the scope of this study, this likely means that base flow from WC1 and WC2 were percolating into the subsurface, contributing to lateral groundwater flows. In contrast, during heavy and prolonged precipitation
rainfall accumulations from WC1 and WC2, in addition to direct atmospheric contribution, supported surface flows at WC3. This is of interest because NO$_3^-$ was observed to be elevated during the wet seasons, with some individual samples exceeding regional water quality objectives (Table 1). This trend suggests that during precipitation events, surface flows are contributing higher concentrations of pollution inputs to the groundwater recharge basin potentially impacting groundwater quality. High concentrations of NO$_3^-$ are of concern because they can introduce excessive nutrients into the water column causing the depletion dissolved oxygen (i.e. hypoxic conditions) that threaten aquatic species and human health (Smith et al., 2013; Fink & Mitsch, 2004; Mallin & Cahoon, 2003 and others).

To ensure that the water quality of the stream was within the federal criteria and state objectives, various parameters were tested and compared to the U.S. Environmental Protection Agency Recreational Water Quality and Aquatic Life Criteria, California State Water Resources Control Board, South Lahontan Region Objectives, and San Bernardino Mountains Hooks Creek Objectives. Various parameters had a mean that exceeded the criteria and objectives (e.g. NO$_3^-$, NH$_4^+$, TC, and others) while other parameters had individual samples that exceeded the criteria and objectives (e.g. Cond., pH, E. Coli, and others). The first catchment contains the highest number of dwelling and sewer units and the second highest percentage of impervious surfaces. WC1 is located in this catchment and it was the site with the highest mean
concentration (1389 MPN/100mL) and the highest number of individual samples (n=23) that exceeded the objective for TC. WC1 was also the site with the second highest concentration (41.1 MPN/100mL) and individual samples (2) that exceeded the E. Coli criteria. Lastly, it was the site that had the highest individual samples that exceeded the criteria and objectives for NO\textsubscript{3}\textsuperscript{-}, TDS, and pH.

Catchment two had some ongoing agricultural activities in close proximity to the creek and upstream of WC2. WC2 had the highest mean concentration of E. Coli (68.7 MPN/100mL) and it had the highest number of individual samples that exceeded the criteria and objectives for E. Coli, NH\textsubscript{4}\textsuperscript{+}, and turbidity. Lastly, catchment three was in the southern portion of the canyon where it would form a second order tributary when the two upper first order tributaries would meet. WC3 had the highest percentage of impervious surfaces but it is important to note that WC3 was not flowing for an extended period of time (July-November) during the dry season. Therefore, there was limited data that was collected from this site. Based on the data that was collected, WC3 had the highest mean concentrations of NO\textsubscript{3}\textsuperscript{-}, conductivity, TDS, and NH\textsubscript{4}\textsuperscript{+} as well as the highest individual samples exceeding the conductivity objectives. Based on the fact that the stream flow varies by season, some parameters were observed to have significant differences between the wet and dry seasons. These types of seasonal variability in the physicochemical properties of perennial streams have also been observed by Mallin et al. (1999), Alford et al. (2014), and others.
**Seasonal Variations**

When considering seasonal variations (i.e. wet vs. dry), it was observed that in the wet season, the mean NO$_3^-$ and DO concentrations were greater compared to the dry season and they were positively correlated to each other. This means that when NO$_3^-$ concentration increases, the DO concentration increases as well. Flow rate was another parameter that had a mean that was greater during the wet season. During the dry season TC, E. Coli, conductivity, and TDS concentrations as well as temperature were greater than in the wet season. Data also showed that TC and E. Coli and temperature and TDS were positively correlated meaning that when one parameter increased the other increased as well. Pearson’s correlation also displayed that DO and temperature were negatively correlated. Therefore, in the wet season when temperatures were lower there was a higher concentration of DO in the stream and in the dry season when temperatures increased there was a lower concentration of DO similar to Vega et al. (1998), Khatoon et al. (2013), Varol et al. (2012) and others. Other correlations that were of importance included the negative correlations of NO$_3^-$, flow rate, and DO to TDS.

**Nitrate**

Nitrate was the parameter that had the highest number of individual samples (90.1%) that exceeded its objective across all three sampling locations. Nitrate is a form of nitrogen that can be naturally found in the environment (e.g. animal waste and plant and animal decomposition) and it can also come from
anthropogenic activities (e.g. wastewater systems, fertilizer use). Excess nitrate levels can lead to eutrophic conditions and impacts on aquatic health (Carpenter, 1998; Peters and Meybeck, 2009; LQ2, 2018). In this study, most of the individual exceedances observed were collected at WC1 which is located in the catchment with the highest number of dwelling, septic, and sewer units as well as the second highest percentage of impervious surfaces. The wet season experienced higher average concentrations of nitrate compared to the dry season, which is similar to the study findings observed by Barakat et al. (2016) in the Oum Er Rbia River in Morocco. Studies have shown that impervious urban surfaces are often areas that produce and transport high amounts of nonpoint nitrate pollution in times of storm and heavy rainfall. The sources of the nonpoint nitrate pollution have been associated with runoff from fertilizers, pet waste, and unsewered developments (Tong and Chen, 2002; Carpenter, 1998; Barakat et al., 2016).

**Total Coliform and E. Coli**

The presence of TC and E. Coli in streams and water bodies have often been linked to storm water runoff, agricultural manure runoff, and poorly performing septic systems (EPA, 2019; Cahoon, 2006). E. Coli is used as an indicator for pathogenic bacteria that could impact human health (Cahoon, 2006; LQ2, 2018). The mean concentrations for E. Coli were within the EPA’s criteria (<126 CFU/100mL) but all three sites had individual samples that exceeded the criteria. WC2 is the site that has the most individual samples exceeding the
criteria (3) followed by WC1 (2). Both sites are in catchments that have agricultural activities, impervious surfaces and dwelling units that may collectively contribute to the concentrations of E. Coli. In this study, seasonal variations were observed with TC and E. Coli since there was higher mean concentrations of TC and E. Coli in the dry season compared to the wet season. Past literature has shown similar trends and it has been suggested that higher E. Coli concentrations could come as a result of warmer temperatures and less storm flows (Heaney et al., 2015; Wilson et al., 2007).

Conductivity and TDS

Conductivity and TDS are parameters that are used to determine the amount of salinity present in water. Sources of soluble salts that enter freshwater ecosystems can be natural (e.g. rocks and soils) or anthropogenic (fertilizers, organic matter, and road salts) (Barakat et al., 2016). Studies have shown that conductivity has a strong correlation with alkalinity in water ecosystems (Stewart, 2001; Kney and Brandes, 2007). WC3 was the only site that was not within the conductivity mean criteria (<336 μS/cm) and it was the site with the most individual samples that were not within the EPA range (150-500 μS/cm), however, WC1 (i.e. 6,710) and WC2 (i.e. 5,791) displayed the highest variability in conductivity, although most samples were within the recommendations (Table 1). TDS, across all sampling sites have mean concentrations that exceeded the TDS objective (<127 mg/L) and > 65 percent of individual samples exceeding the objective. TDS and conductivity had higher concentrations during the dry season
during base flow events coupled with increasing temperature. Both parameters had a significant positive correlation to temperature meaning that when temperatures increase, TDS and conductivity increase. TDS had significant negative correlations to NO$_3^-$, flow rate, and DO. The complexity of TDS could be related to the complex geology and agricultural runoff.

Results of this study are useful to water resource planners and managers, especially in regions where increasing drought conditions and a growing human population continue to place highly variable strains on water resources and related infrastructure. In California, during periods of heavy precipitation and snow accumulation water is transported through various infrastructures to enable large quantities of water to be stored in groundwater basins for the purpose of using it in times of drought. Recharge basins are an effective way of capturing surface water long enough for it to infiltrate into the groundwater basins. Unfortunately, surface water are highly susceptible to multiple terrestrial and atmospheric sources of contamination that may introduce various pollution inputs to groundwater basins potentially leading to human health and other environmental and economic risks (i.e. contamination of soil and related agriculture production). In the Santa Ana River Watershed alone, studies have shown that there are groundwater basins that are contaminated with nitrates, perchlorates, pesticides, and others (SAWPA, 2015; USGS, 1979; East Valley Water District, 2014). Groundwater contamination can be devastating to communities who depend on groundwater since it reduces the amount of water
resources often leading to increases in water pricing in communities where incomes are below the state median household income levels. This is particularly true in the City of San Bernardino where a majority of residential communities are considered disadvantaged (<85% below state median household incomes) as defined by the CA Department of Water Resources Economically Distressed Communities Mapping Tool (CDWR, 2019). Typically, communities within this classification do not have the financial means to tackle issues associated with public health, education, and resource management. Findings of this research may highlight the need to monitor the potential seasonal and longer-term impacts from impaired surface water entering the recharge basins. The treatment and mitigation of contaminants can be lengthy and expensive due to the complexity of contaminants and the costs associated with the treatment is transferred to the ratepayers (Public Policy Institute of Technology, 2019; Kavanaugh, 1995). This often leads to an increase in operational costs and maintenance for water providers to meet the federal requirements related to the Safe Drinking Water Act. As a result, water rate increases in disadvantaged communities can be detrimental to the community since they have limited resources to address community needs, including public health, infrastructure, and natural resource management. Since San Bernardino is a disadvantaged community who is almost fully dependent on groundwater resources, it is important to understand how natural and anthropogenic activities could affect the quality of water since it
is directly linked to the quantity of water resources (City of San Bernardino, Water Department, 2015).
CHAPTER SIX

CONCLUSION

The primary goals of this research were to illustrate the physicochemical characteristics of multiple water quality metrics at headwater tributaries, to determine the extent of the seasonal patterns (wet vs. dry seasons), and to understand statistically significant relationships between the physicochemical characteristics of water resources throughout the study site. The research demonstrates that there were parameters (e.g. conductivity, nitrate, TC, TDS, etc.) that had mean concentrations and individual samples that exceeded the criteria and objectives set by federal and state regulations. Significant differences between seasonal patterns were observed as some parameters (e.g. DO, Nitrate, E. Coli, TC) had higher mean concentrations in the wet season compared to the dry season and vice versa showing the importance of water quality testing year round. Lastly, there were statistically significant relationships between different parameters (e.g. DO and Temperature, TC and E. Coli, Flow and TDs, etc.) that illustrate how one physicochemical characteristics relates to another resulting in variable surface water quality across the three catchments observed during this study.

This study illustrates the importance of year round water quality testing in headwater streams of the San Bernardino Mountains since they are the beginning of the hydrologic unit and they cover the highest percentage of stream
length across the hydrologic unit. Additionally, the study site is of importance because it is located in the headwater of the largest and most populated river basin in California. The steep topography that characterizes this geographical location experiences orographic effects that allow it to receive higher accumulation of annual precipitation when compared to other reaches of the SARB. As the exposed surface water resources traverse through different landscapes, it can be vulnerable to a variety of point and nonpoint sources of pollution that could eventually be introduced into groundwater basins. As weather patterns continue to become more unpredictable, California will continue to experience periods of dry and prolonged droughts and periods of high precipitation. The lack of available data that illustrates relationships between extreme seasonal patterns, land use types and water quality and quantity across California and beyond potentially affects the resilience of communities to adapt to present and future challenges. In a region where the majority of the residential communities are considered disadvantage, clean up and mitigation of contaminants in surface and groundwater can be difficult, costly, and even devastating. Therefore, management practices need to be implemented by citizens and decision makers to protect the limited water resources in the SARB at the local and basin scale.
REFERENCES


California Department of Water Resources. Dams Within Jurisdiction of the State of California. **2018.**


Dettinger, M. D. Atmospheric Rivers as Drought Busters on the U.S. West Coast. **2013**.


Rabotyagov, S. S.; Kling, C. L.; Gassman, P. W.; Rabalais, N. N.; Turner, R. E.
The Economics of Dead Zones: Causes, Impacts, Policy Challenges, and
a Model of the Gulf of Mexico Hypoxic Zone. *Rev. of Environ. Econ. and

Ralph, F. M.; Neiman, P. J.; Wick, G. A.; Gutman, S. I.; Dettinger, M. D.; Cayan,
D. R.; White, A. B. Flooding in California’s Russin River: Role of
Atmospheric Rivers. *Atmos. Sci.* **2006**.

San Bernardino Valley Municipal Water District. What We Do.

Santa Ana Water Project Agency. *Upper Santa Ana River Watershed Integrated
Regional Water Management Plan*. **2015**.

Schraga, T.; Cloern, J. Water Quality Measurements in San Francisco Bay by the

**1994**, 1, 3, 100-111.

Shaw, S. B.; Marrs, J.; Bhattarai, N.; Quackenbush, L. Longitudinal Study of the
Impacts of Land Cover Change on Hydrologic Response in Four
Mesoscale Watersheds in New York State, USA. *J. of Hydro.* **2014**, 519,
12-22.

Smith, A. P.; Western, A. W.; Hannah, M. C. Linking Water Quality Trend with
Land Use Intensification in Dairy Farming Catchments. *J. of Hydro.* **2013**,
476, 1-12.


U.S. Census Bureau.


U.S. Environmental Protection Agency, E. Coli and Enterococci.


