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Spatial and temporal analysis of fecal indicator bacteria concentrations in beach water in San Diego, California

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Abstract

With millions of yearly beach visitors in southern California, beach water quality represents an important factor in public health and ocean dependent economy. Fecal indicator bacteria (FIB) in water is much easier to measure than disease causing organisms but correlation exists between the two. For this reason, FIB concentrations are used to measure recreational water quality and related health risk of body contact with the water. The source of FIB is often related, but not limited, to surface runoff. This study analyzed beach water FIB concentrations at two San Diego beaches, Ocean Beach and Tourmaline Surfing Park, that are affected by the river and storm water discharges, and explored the land use in their adjacent watersheds. The study distinguished between wet and dry weather and compared bacterial concentrations against the watershed land use. Furthermore, the study analyzed temporal and spatial dynamics of bacterial concentrations during and after storm weather at Ocean Beach. Finally, the study examined the relationship between bacterial concentrations at seven sampling sites of San Diego River tributaries and the land use within the tributaries. Fecal indicator bacteria concentrations showed a significant rise during rainfall. Ocean Beach had significantly higher FIB concentrations during dry weather, compared to Tourmaline Surfing Park, with significantly higher FIB concentrations at the sampling location near the river discharge in wet weather. Bacterial concentrations generally decreased with the distance from the closest surface water discharge. The peak in FIB concentration rise was reached already on the first day of the storm weather at Tourmaline Surfing Park and on the second day at Ocean Beach. As little as 1 mm of rainfall was needed for a significant raise in bacterial concentrations in beach water. Watersheds with a higher percentage of residential and transport area had lower mean bacterial concentrations in beach water at the surface water discharge, compared to watershed with lower percent of residential and transport area. Higher percentage of land, used for parks or open space, undeveloped land, commercial and public services, recreation, industry and agriculture in the watershed, corresponded to higher mean indicator bacteria at the beach where the river discharges. No correlation was found between *Enterococcus* concentration in San Diego River and land use in the tributaries.

Popular Abstract

With millions of yearly beach visitors in southern California, beach water quality represents an important factor in public health and ocean dependent economy. Fecal indicator bacteria (FIB) in water is much easier to measure than disease causing organisms but the concentrations of both have a strong relationship. For this reason, FIB concentrations are normally used to measure recreational water quality and related health risk of body contact with the water. One of many possible sources of FIB is the water drained from the surface, including rivers and storm water systems. This study analyzed beach water FIB concentrations affected by the river and storm water discharges at two San Diego beaches, Ocean Beach and Tourmaline Surfing Park, and explored land use in the area of drainage. The study distinguished between wet and dry weather and compared bacterial concentrations against the watershed land use. Furthermore, the study explored how bacterial concentrations in water varied in space across the beach during and after the storm weather at Ocean Beach. Finally, the study examined the relationship between bacterial concentrations at seven

sampling sites of San Diego River tributaries and the land use within the tributaries. Fecal indicator bacteria concentrations quickly raised during the rainfall. Ocean Beach had much higher FIB concentrations during dry weather, compared to Tourmaline Surfing Park, with very high FIB concentrations at the sampling location near the river discharge in wet weather. Bacterial concentration generally decreased with the distance from the closest surface water discharge. Indicator bacteria concentration was the highest on the first day of the storm weather at Tourmaline Surfing Park and on the second day at Ocean Beach. As little as 1 mm of rainfall was needed for a significant raise in bacterial concentrations in beach water. Watersheds with a higher percentage of residential and transport area had lower mean bacterial concentrations in beach water where the storm water drains discharge, compared to areas with lower residential and transport area percentage. Higher percentage of land used for parks or open space, undeveloped land, commercial and public services, recreation, industry and agriculture in the watershed corresponded to higher mean indicator bacteria at the beach where the river discharges. None of the land use groups was found to contribute to higher *Enterococcus* concentration in San Diego River.

Table of Contents

List of Abbreviations

CFU	Colony Forming Unit
FIB	Fecal Indicator Bacteria
ENT	*Enterococcus*
FC	Fecal Coliform
TC	Total Coliform
GM	Geometric Mean
MPN	Most Probable Number
OB1	Ocean Beach Sampling Site 1
OB2	Ocean Beach Sampling Site 2
OB3	Ocean Beach Sampling Site 3
OB4	Ocean Beach Sampling Site 4
T1	Tourmaline Sampling Site 1
T2	Tourmaline Sampling Site 2

List of Tables

List of Figures

1 Introduction

Californian beaches yearly attract more than 150 million visitors who enjoy swimming, surfing, wading and diving, therefore ensuring public and coastal environment health is a high priority. Efforts are being made to better understand the sources and dynamics of beach water microbial pollution. Most of the beach water quality issues in California is caused by a surface runoff or discharge. Water testing is focused on storm drains, rivers, streams and lagoons which have been shown to be transporting pollutants from inland areas (Sercu et al. 2011, Izbicki et al. 2009). In the past, there have been measures in place to prevent or divert pollutants from reaching the ocean during the summer season, however, beach water is still affected by some surface water runoff sources (Department of Environmental Health 2017a). Winter in Southern California is the period of more rainfall and bigger storms offering bigger swells. Surfers, eager for good surfing, can therefore be exposed to pollutants entering the sea water through the released storm drain discharges during the winter. Tens of thousands of California all year-round swimmers can contract a respiratory or a gastrointestinal illness from just one swim in polluted sea water affected by rainy weather (Heal the Bay 2017). In most extreme cases, deaths believed to be a result of a contact with the sea water shortly after rainfall in Southern California have been reported (Beachapedia, 2017). Concentration of total coliform (TC), fecal coliform (FC) and *Enterococcus* (ENT), commonly known as fecal indicator bacteria (FIB) in water is much easier to measure than disease causing organisms but they are positively correlated (USGS Office of Water Quality 2016). For this reason, FIB concentrations are normally used as indicators of recreational water quality impairment. Associated health risk depends on the source of fecal pollution and it is therefore important to understand where FIB is coming from (Colford et al. 2007).

It is possible to draw general conclusions about water impairment from the literature serving as guidelines when dealing with coastal environment protection and public health. However, the literature review also suggests we should always look closely at the characteristics of the local environment when addressing beach water quality issues. Spatial and temporal variation of bacterial concentration in the sea water is specific to a particular beach and the adjacent watershed. Ackerman and Weisberg (2003) and Griffith et al. (2010) have compared the frequency of exceedance of the state recreational water standard and the distance from the runoff outlet. This study gives new information about FIB concentrations in relation to the exact location and the distance from the surface water discharges, as well as the rainfall needed for the significant raise of FIB concentrations and a temporal analysis of the peak concentrations depending on location. Understanding how the land use and the activities in a particular watershed affect the coastal water is crucial for education and prevention of surface water pollution.

Fast growing southern California population with over 6% growth in San Diego County since 2010 (World Population Review 2016) is putting stress on the costal environment. To assess the health risk of swimming in the ocean during the wet season Schiff et al. (2016) have conducted a study on two sentinel beaches in San Diego, California, during two winter seasons. Surfer Health Study focused on the water quality and the related health outcomes of surfers who regularly swam at the two beaches. While the study distinguished the two beaches and different weather conditions, the objective was to explore relationship between FIB and health issues of swimmers. The study did not focus on spatial or temporal variation of fecal indicator bacteria. This thesis was based on Schiff et al. (2016) data and focused on the beach water bacterial dynamics and possible land use related sources of water impairment. It analyzed the concentration of *Enterococcus*, total coliform and fecal coliform in beach water at Ocean Beach and Tourmaline Surfing Park in San Diego and a possible effect of land use in the two adjacent watersheds, differing by size, land use, as well as the type of drainage. The thesis looked into how the bacterial concentrations raise and drop in the space and time in relation to the rainfall events and made a comparison of the two study beaches.

1.1 Objectives

This thesis had three main objectives: the first objective was to compare two beaches in San Diego, California with the adjacent watersheds. The thesis compared the beach water fecal indicator bacterial concentrations between Ocean Beach and Tourmaline Surfing Park and the land use in their adjacent watersheds. The thesis distinguished between wet and dry weather and compared the bacterial concentrations against the watershed land uses. The second objective was to study the temporal and spatial dynamics of bacterial concentrations during and after storm weather at Ocean Beach. The third objective was to examine the relationship between bacterial concentrations at seven sampling sites of San Diego River tributaries and the land use within the tributaries.

The study answered the following research questions:

Did Ocean Beach have significantly higher fecal indicator bacteria concentrations compared to Tourmaline Surfing Park during dry and wet weather? Were fecal indicator bacteria significantly higher during wet weather compared to dry weather? What was the precipitation needed for a significant raise in fecal indicator bacteria and how did it differ between sampling locations?

Was there a relationship between fecal indicator bacteria concentrations and the distance to the closest surface runoff discharge?

How did indicator bacteria concentrations vary across the Ocean Beach during the storm days and the days immediately after the storm? Is there a difference in temporal variation of bacterial concentrations between Ocean Beach and Tourmaline Surfing Park?

Was there a relationship between Lower San Diego River land use and *Enterococcus* concentrations at the sampling locations in the tributaries?

2 Background

2.1 Fecal indicator bacteria as a proxy for pathogens

Concentration of total coliform, fecal coliform and *Enterococcus,* commonly known as fecal indicator bacteria, are used to measure the health risk of swimming in recreational waters in California. While FIB is normally non-pathogenic they are correlated with the presence of disease causing organisms in the water (USGS Office of Water Quality 2016). To protect visitors from waterborne diseases, Californian health authorities issue a number of water contact advisories or beach closures following rainfall or when the concentration of FIB in the beach water exceeds Ocean Water Contact Sport Standards (Wu and Jackson 2016; He and He 2008; State Water Resources Control Board 2013a). One of the most common causes of recreational waters being classified as impaired in USA is fecal bacteria from non-point sources (Soller et al. 2015). Beach management decisions are based on several studies showing raised FIB concentrations being correlated to gastrointestinal, respiratory and skin related illnesses (Halliday and Gast 2011; Colford et al. 2007; Fleisher et al. 2010). Fecal indicator bacteria appear to be good indicator during wet weather and a Surfer Health Study at Ocean Beach and Tourmaline Surfing Park found less evidence of correlation during dry weather. The study confirmed a strong positive association between increased incidence rate for gastrointestinal illness, diarrhea, sinus pain or infection, earache or infection, infected open wound and upper respiratory illness, and increased *Enterococcus*, total coliform and fecal coliform concentration levels during wet weather. However, during dry weather only, raised *Enterococcus* concentrations were associated with an increased infected wound rate (Schiff et al. 2016). A study of bathers and non-bathers in subtropical recreational marine waters with no known source of sewage contamination reports similar results finding a dose-response relationship between increased Enterococci exposure and skin related illness (Fleisher et al. 2010); however, no correlation was found for gastrointestinal and respiratory illnesses. The use of bacterial indicators as predictors of health risk of swimming in marine waters is based on a presumption that indicator bacteria persistence in marine waters is similar to the persistence of pathogens. However, Colford et al. (2007) claim the environmental conditions affect FIB survival and thus it is not always reliable indicator of health risk related to body water contact. For example, no correlation was found between FIB concentrations and illness risk in Mission Bay, California and the authors suggest this is due to the low percent of human fecal material at the study site (Gruber et al. 2005).

2.2 Sources of fecal indicator bacteria in beach water

The source of microbial pollution is not always clear and there are several coexisting factors that contribute to raised FIB concertation in beach water. The literature distinguishes between point sources of coastal marine water contamination, such as treated or untreated sewer discharges and non-point sources of contamination, such as urban, commercial, industrial surface runoff and natural vegetation areas runoff (Pandey et al. 2014). A leaky sewer is often found to be the source of human microbial contamination (Gruber et al. 2005; Sercu et al. 2011). Gruber et al. (2005) also suggest boat discharge and homeless as a potential direct human contamination sources of beach water. Indirect human sources can be irrigation runoff, restroom runoff and RV pump outs. While Papadakis et al. (1997) suggest that the beach visitors were the source of *Staphylococcus aureus* bacteria, found in beach sands, the evidence of the human feces source is not always clear (Kitts et al. 2010).

Several studies suggest urban storm water runoff as an important non-point source of FIB (Yamahara et al. 2007; Schiff et al. 2016; Shibata et al. 2004). For example, a study at Florida beach confirmed that the storm water system receives urban and a residential area runoff as the contamination source during a rain event, resulting in exceeded state standards for the recreational waters in terms of FIB concentration (Brownell et al. 2007). Sercu et al. (2011) proved that leakage from the sanitary systems to the storm drain was due to surcharge conditions in Santa Barbara, California. Regular leaking over longer periods contributes to fecal contamination of marine water at the storm drain discharge. While Weiskel et al. (1996) report that the septic systems were the largest FIB contributor to the watershed of Buttermilk Bay in Massachusetts, their effect to the bay water quality in their study was diminished through groundwater transport. They suggest the influence of fecal coliforms originating from a septic system on the coastal water quality depends on geology of the area and can have a more significant effect in areas with different topography and soil structure.

Natural streams and coastal lagoons have also been found to be contributors to the fecal indicator bacteria in coastal water (Ervin et al. 2014; Weiskel et al. 1996; Gruber et al. 2005; Izbicki et al. 2009). Non-point sources of pollution in streams can be applied manure and slurry on agricultrual land, sewage sludge and septic tank waste. Potential point sources can be runoff from yards and animal storage facilities, waste water treatment efluent, sewer overflows and leaking septic tanks (McDonald 1981; Obiri-Danso and Jones 1999). Cahoon et al. (2016) suggest that a so called interflow (rainfall enhanced shallow underground water washoff) contributes to the fecal coliform in surface water. Knee et al. (2008) compared different water bodies and found that the samples from the streams and the rivers more often contain *E. coli* and *Enterococci*, compared to the groundwater and the nearshore water at their study site in Hanalei Bay, Hawai`i. Considering a river flow and a groundwater flow, the rivers and the streams are likely to be the main source of FIB in the nearshore ocean water. However, Steets and Holden (2003) suggest that the discharge of fecal bacteria from the coastal lagoon has limited effect on the coastal water quality because of reduced microbial concentrations with mixing marine water. Evanson and Ambrose (2006) has made a similar conclusion, finding no significant FIB contribution from the wetland to the ocean water in their study of the wetland effect on the adjacent coastal water at Santa Ana river outflow in California. They compared total coliform to *E. coli* ratio and found that the wetland FIB differs from the FIB found in the surf zone. No significant effect on the surf zone was also confirmed by the comparison of exceedance of *Enterococcus* concentration standards in the wetland and the surf zone water.

A less obvious carrier of bacteria is groundwater (Gruber et al. 2005; Cahoon et al. 2016; Knee et al. 2008). It can enter coastal waters either by a direct groundwater discharge to the bay or a groundwater discharge to the stream discharging to the bay (Weiskel et al. 1996). However, Izbicki et al. (2009) determined the sources of fecal contamination in the urban streams and the nearshore ocean water in Santa Barbara, California and did not find the groundwater to be a considerable source of FIB.

Dogs, birds and other wildlife are important contributors to water impairment (Gruber et al. 2005; Cahoon et al. 2016; Kitts et al. 2010; Ervin et al. 2014). For example, Griffith et al. (2010) studied beaches with the outlets of watersheds that are not influenced by humans, and suggested that FIB concentrations (especially *Enterococcus* and *E. coli* concentrations) in the beach water can be raised by non-human sources to the level exceeding California’s water quality standards. Schiff et al. (2016) found avian and canine source markers in the surface water discharges of San Diego River and Tourmaline Creek.

Compared to other contributors on the beach, such as birds and humans, dogs were the largest source of bacteria in the beach water (Wang et al. 2010; Wright et al. 2009; Zhu et al. 2011). However, Converse et al. (2012) demonstrated significant gull contribution to high concentration of *Enterococcus* and *E. coli* in the beach water of Lake Michigan, with water quality improvement after the number of gulls on the beach was reduced. Kitts et al. (2010) and Weiskel et al. (1996) also concluded, that the main source of FIB in beach water are coming from birds.

Beach sand proved to be a favorable environment for FIB to persist and regrow with rewetting and so it can affect the water column with flushing bacteria in a high tide or a precipitation event (Halliday and Gast 2011; Lee et al. 2006). Several studies have shown that FIB concentrations were higher in the sand, compared to the water, thus microbes being transferred from the shoreline to the water column by either rising tide or precipitation (Bonilla et al. 2007; Yamahara et al. 2007; Shibata et al. 2004; Halliday et al. 2015). In a study of beach sand and water in Lake Michigan, the majority of the sand samples from the berm and backshore of the lake also had higher concentrations of *E. coli* and *Enterococcus*, compared to the sand samples submerged in the water. However, the authors found only *E. coli* concentrations of the berm sand strongly correlated with the concentrations in the water, but no correlation between the indicators from the backshore and the water concentrations (Cloutier et al. 2015). An experiment has shown that wet sand serves as a favorable environment for bacterial survival, compared to the sea water. A fecal event from a gull can cause *Enterococcus* to be spread over 3.1m^2 by pedestrian and natural transportation. Small and highly concentrated input can therefore affect reasonably big area and potentially water column (Bonilla et al. 2007). Additionally, beach sand covered with seaweed was found to contain high concentrations of FIB (Shibata et al. 2004). Izbicki et al. (2009) and Weiskel et al. (1996) claim kelp build up, guano and wreck in the beach sand are important contributors to raised FIB concentrations in nearshore water during the high tide washing of contaminated sand.

2.3 Rainfall and tidal impact on fecal indicator bacteria in beach water

Concentrations of FIB in beach water vary between dry and wet seasons, with concentrations often exceeding the regulatory standards after rainfall (Brownell et al. 2007; Liang et al. 2013). Heavy rain was related to a greater number of California’s water quality standards exceedances, compared to lighter rainfall. Larger storms enable fresh water bodies to cross a sand berm and discharge to the sea. Frequency of the water quality standard threshold exceedance drastically increases within 24 hours of the rainfall and gradually decreases during three days following the rainfall (Griffith et al. 2010; Izbicki et al. 2009). Ackerman and Weisberg (2003) confirmed that the number of beaches failing the water quality standard in Los Angeles County increases with every storm larger than 25 mm and most of the storms of 6 to 25 mm of rainfall. Fecal indicator bacteria concentration levels reached it's peak the first day after a large storm (>25mm) and the second day after a small storm. Raised bacterial concentrations then returned to the usual levels five days after a storm, regardless of the storm size. Numerous studies show drastic increase of bacterial concentrations in a water column during rainfall (Lee et al. 2006; Schiff et al. 2016; Riedel et al. 2015). Liang et al. (2013) found positive correlation between *E. coli* and fecal coliform concentrations, and rainfall one and three days prior sampling.

Similar to the beach water, rainfall has also impact on stream water bacterial concentrations. Weiskel et al. (1996) and Pandey et al. (2012) report increase in the fecal coliform concentration in a streamflow during wet weather, compared to dry weather. Crowther et al. (2003) suggest the reason for elevated bacterial concentrations in streams with high flow following rainfall, is increased surface runoff, extended stream network in the drainage area, bacteria transfer from the stream bed and a stronger water current preventing bacteria die-off.

High tide has been also found to influence the microbal concentrations in the sea water. Shibata et al. (2004) monitored marine water quality at two recreational beaches in Florida and found the highest concentrations of indicator bacteria along the shoreline at high tide.

2.4 Land use impact on streams and beach water quality

Some studies showed developed land has a negative effect on beach water quality, however undeveloped land can also contribute to a higher FIB concentration in the ocean. Yamahara et al. (2007) and Weiskel et al. (1996) showed higher concentration of FIB in the water at beaches surrounded by the areas with high percent of developed land or high density residential areas, where fecal coliforms are brought by the storm water, drained from impervious surfaces. Contrary, Griffith et al. (2010) found land within the respective undeveloped watershed can explain 73% of *Enterococcus* concentration variation in the sea water during wet weather.

Wu and Jackson (2016) studied the relationship between beach closures and the land use surrounding affected beaches as well as association of the beach closures with the land use change across United States. They found a significant positive correlation between the beach closures and the percentage of urban area, and significant negative correlation between the beach closures and the percentage of forrest. This study suggests urbanization, agricultural development and deforestation may contribute to the microbial contamination of marine waters.

Literature offers more information about FIB concentrations in fresh water in relation to land use. Similar to the impact on the sea water, studies showed rivers and streams are most affected by developed land and an intensive agriculture, although high FIB concentrations are sometimes found in soil samples of natural areas. Goto and Yan (2011) have studied the Manoa watershed on the Hawaiian island of Oahu. They found significantly higher concentrations of *E. coli*, *Enterococcus*, and *Clostridium perfringens* in the stream water of an urban area, compared to the stream water of a forest area. However, high concentrations of FIB were found in the soil troughout the watershed regardless of the land use, which indicates the soil could be a potential source of FIB in the water beside the sewage leaks, domestic animals and birds. Pandey et al. (2012) conclude concentrations of *E. Coli* in streams is positively correlated with the percentage of cropped land area, the area of manure application and barren land area. A negative correlation between *E. Coli* concentrations and land use was found for natural covered areas, wetlands, rivers, slopes and urban land. Bradshaw et al. (2016) showed that the concentrations of FIB in stream water and the sediment with predominant agricultural land use were higher, compared to the forested or wastewater pollution control plant land use. Crowther et al. (2002) found significant correlation between FIB concentrations in stream and livestock farming practices in the study of two catchment areas in Newport, England and Staithes, Wales. Intensive livestock farming has a strong positive correlation and extensive farming has negative correlation with mean fecal indicator concentrations. The weaker positive correlation between fecal indicator concentration and build-up areas is probably due to specifics of the study area being rural where the source of fecal bacteria is mostly agriculture. Crowther et al. (2003) also report significant dependancy of indicator bacteria from improved pasture and built-up areas being the main contributors to high bacterial concentrations in stream water.

Different studies offer some differences in conclusions regarding land use impact on water quality. This is likely due to differences in characteristics of the areas betweend different studies and the types of land uses included (or excluded). Studies analyzing mainly rural areas are offering different conclusions, compared to studies analysing mainly ubanized and developed land. The impact of watershed land use on surface water quality depends on the combination and intensity of land use. Meays et al. (2006) have compared *E. coli* concentrations from the stream water of multiple non urban watersheds near Vernon, British Columbia and found no significant differences between the major contributors of *E. coli* among the watersheds despite differing in the extent of forest, recreational, farmning/grazing and housing land use, though all of them are rural. The authors suggest it is due to the wildlife being the main contributor of bacterial concentrations in the surface waters.

Stream water quality therefore depends on watershed characteristics, such as land cover, soils, geology, topographic feature and catchment hydrology (Rothwell et al. 2010a, 2010b). Crowther et al. (2002) also suggest, that catchment area, the distribution of land use, topography and drainage influence fecal bacterial concentration in the stream water.

Concentration of FIB were found to be higher in surface runoff, compared to rivers and estuaries of the same watershed (Liang et al. 2013). This plays an important role as a potential non-point source of beach water contamination. In St. Lucie, Florida surface runoff quality was compared between 12 different land uses. The concentrations of FIB in the surface runoff water from the urban and cattle ranch land were higher, compared to forest and agriculutral surface runoff water. Among urban land uses, the residential surface runoff had higher concentration of FIB, compared to the surface runoff from golf land use. There is also a significant difference in the surface runoff water quality within different agricultural land use types. A plant nursery surface runoff had higher concetration of *E. coli* and fecal coliform, compared to a citrus and vegetable production land use, while Enterococci did not vary significantly (Liang et al. 2013). Tiefenthaler et al. (2011) found that the recreational land use heavily used by horses contributed significantly higher FIB concentrations to the storm water among several types of land uses, followed by, however not significantly, agricultural, urban and open space.

2.5 Spatial aspect of water contaminants

While concentration of indicator bacteria in coastal waters was found to be decreasing with distance from a surface water ourfall (Riedel et al. 2015; Cloutier et al. 2015), intensity of rainfall impacts the spatial distribution of bacterial concentrations in coastal waters. For example, Ackerman and Weisberg (2003) claim the storm size affects the water quality at the beach which depends on the distance from the runoff outlet. Sampling sites away from the outlet had bacterial concentrations exceeding the state standard following only large storms. Sampling sites nearby the runoff outlet had water quality standard exceeded with smaller storms, such as 6 mm of rainfall.

The watershed size proved to be correlated with the frequency of water quality threshold exceedance for FIB. During wet weather water samples from the beach at the large watersheds outflow exceeded the water quality threshold more than twice frequently compared to medium sized watersheds and more than four times frequently than small watersheds (Griffith et al. 2010). Pandey et al. (2012) also concluded that the concentration of *E. Coli* in the streams is positively correlated with the percentage of drained land area.

Bacterial concetrations in streams and rivers depend on water bodies proximity to contamination sources as well as rainfall intensity. In a study of data collected during 7 years in North Carolina, water samples representing different types of surface water bodies collected closer to central sewer or septic systems have proved to have higher concentrations of fecal coliform bacteria, compared to samples from other locations (Cahoon et al. 2016). Crowther et al. (2003) showed how rainfall affects the bacterial concentrations in the water comparing improved pasture land use (this land use showed the strongest positive relationship with bacterial concentration) spatial distribution and bacterial concentrations in the stream water and found dependency on base flow and high flow. At base flow the strongest correlation was at the closest proximity (<1 km or <2 km) of improved pasture land use to the subcactchment outlet. However, at high flow the relationship showed to be reverse, with the strongest correlation at locations further away (<5 km) from the subcatchment outlet and the weakest correlation at the closest locations (<1 km).

2.6 Statistical methods used in water quality and land use related studies

A wide range of statistical methods is used in the studies related to water quality and land use. Several studies used Pearson correlation coefficient to measure the relationship between the extent of various land uses and bacterial concentrations in water. For example, Wu and Jackson (2016) used Pearson correlation analysis for measuring multicollinearity among the percentage of land use classes. Pandey et al. (2012) used a Bivariate Persons correlation to measure the degree of association between bacteria and watershed indeces. Crowther et al. (2002, 2003) also examined the relationship between the bacterial concentrations and the percentage of different land uses using the Pearson correlation coefficient. To describe how land use is related to the water quality several studies apply different types of regression. In a study of the relationship between land use and the beach closures across US, Wu and Jackson (2016) used a Negative Binomal Regression model. Liang et al. (2013) explored the impact of mixed land-use practices on the microbial water quality with a logistic regression. Meays et al. (2006) used a generalized linear model to study spatial and annual variability in bacterial concentrations in multiple watersheds. Goto and Yan (2011) also used a linear regression to study effects of land uses on fecal indicator bacteria in the water and soil. Crowther et al. (2003) used a multiple regression with the stepwise selection procedure to model the relationships between the mean concentrations and the percentage of land use. Analysis of variance (ANOVA) is often used for the bacterial concentration comparison between multiple groups. Liang et al. (2013) as well as Knee and Encalada (2014) used ANOVA and Tukey's post-hoc test, while Tiefenthaler et al. (2011) used one-way ANOVA followed by Tukey-Kramer post hoc test for multiple comparisons. In the literature, Student's t-test is also used for bacterial concentration comparison. For example, Goto and Yan (2011) used it for their study of the land use effects on fecal indicator bacteria in the water and the soil; and Crowther et al. (2003) used it to compare the mean indicator concentrations under the base and the high flow. For spatial distribution and temporal trend Wu and Jackson (2016) used Mann-Kendall trend test and the seasonal Mann-Kendall trend test while Tiefenthaler et al. (2011) analyzed temporal patterns with a pollutograph.

3 Methods

3.1 Study Area

The study area covers Ocean Beach with the adjacent Lower San Diego River watershed, below El Capitan and San Vicente reservoirs; Tourmaline Surfing Park at the north end of Pacific Beach with the adjacent Tourmaline Creek watershed and the area of storm water system discharging to the Tourmaline Surfing Park. All locations are within San Diego County, California.

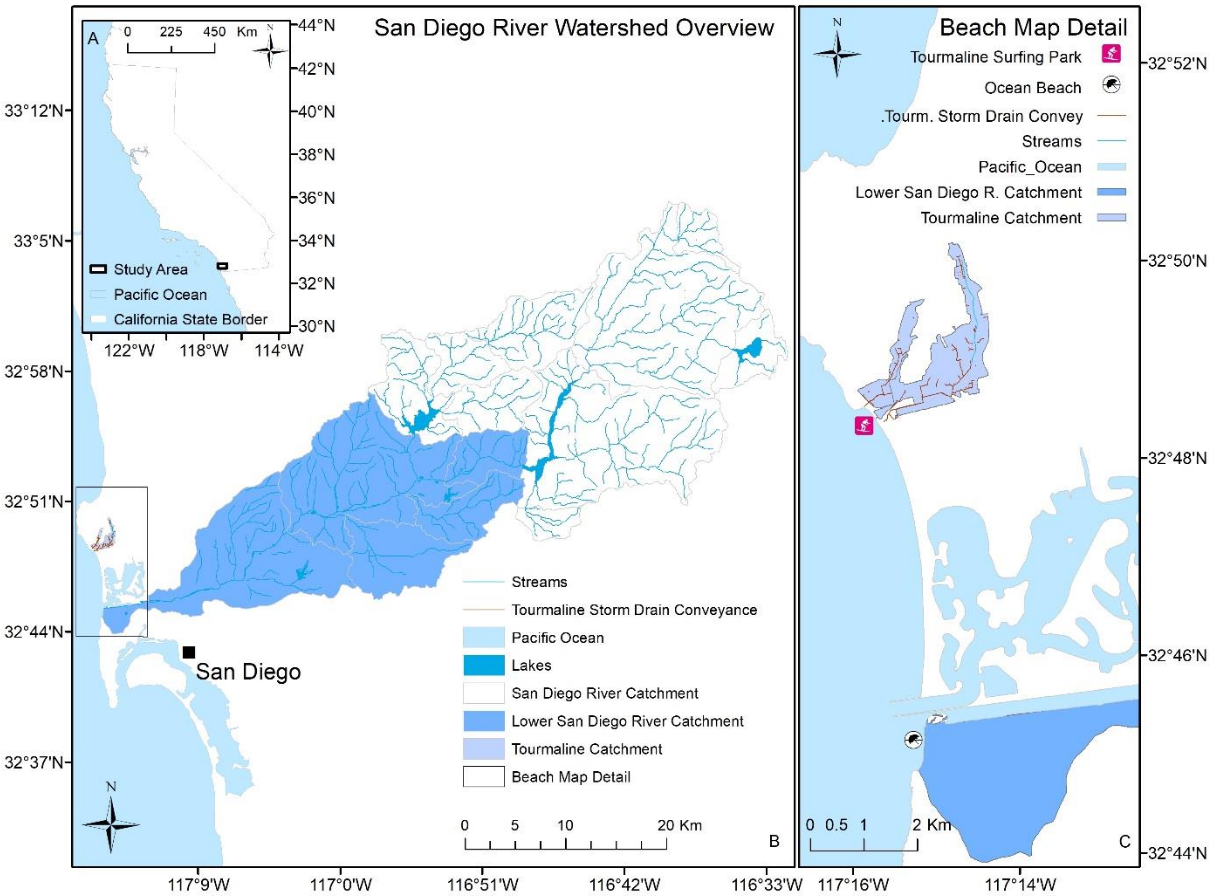

Figure 1. Study area location at State of California level (A), overview of study area (B), location of study beaches (C). Data source: SANDAG, Transportation and Storm Water department at City of San Diego.

3.1.1 Lower San Diego River watershed

San Diego River expands from Santa Cuyamaca Mountains on the east towards the west and drains into Pacific Ocean at Ocean Beach in San Diego. There are two major dams on the river, El Capitan and San Vincente, which did not discharge during the sampling period. The drainage area below the dams is the subject of this study and belongs to Lower San Diego River hydrologic area, which covers Santee, Coches, Mission San Diego, El Cajon and El Monte hydrologic sub-areas. The area covers approximately 45,000 hectares, of which residential land and parks or open space are the dominant uses. Annual precipitation in San Diego River watershed ranges from around 279 mm at the coast to around 889 mm around Cuyamaca and El Capitan Reservoir (Barker et al. 1994). Upper San Diego River watershed is the source of potable water for 760,000 people. The majority of the 520,000 San Diego River watershed residents live in the lower part of the watershed which is also the most affected by pollution (*Enterococcus*, fecal coliform, manganese, nitrogen, selenium, phosphorus). Sources of pollution in the watershed are urban and agricultural runoff, mining and sewage (Project Clean Water 2017).

3.1.2 Ocean Beach

Ocean Beach is popular for surfing during all seasons. It spans approximately 1.6 km south from San Diego River outflow broken down with a couple of rock breakwaters. There are restrooms, showers and fire pits located at the beach and dogs are allowed on leash early mornings and evenings (California Beaches 2017a). Unrelated to this and Schiff et al. (2016) study, City of San Diego samples beach water every six days on this beach. Water here is reported to be generally good (Department of Environmental Health 2017b). At the north end of Ocean Beach, where San Diego River flows into the ocean, is a Dog beach where dogs are allowed off leash at all times. Dog owners are responsible for control and clean-up of their dogs (The City of San Diego 2017). San Diego City samples water here every two days. The water quality generally meets the State health standards with occasional elevated bacterial counts (Department of Environmental Health 2017b). Sampling locations at Ocean Beach for this study are marked in Figure 2.

Figure 2. Overview of Ocean Beach with sampling locations. Base map source: Google Earth

3.1.3 Tourmaline Creek with storm water drainage

Tourmaline Creek with storm water drainage is a small area in La Jolla neighborhood which belongs to the Scripps hydrologic area within Penasquitos watershed. It mostly covers urban area of approximately 270 hectares. Storm water is discharged to the Pacific Ocean at Tourmaline Surfing Park, at the north end of Pacific Beach.

3.1.4 Tourmaline Surfing Park

Tourmaline Surfing Park is a popular spot for surfing during all seasons. It is located on the border of Pacific Beach and La Jolla neighborhoods. North of Tourmaline is a rocky beach with tide pools at the Linda Way Beach Access. There are barbeques, fire pits, restrooms and showers located at the park and dogs are allowed on leash early mornings and in the evenings (California Beaches 2017b). Tourmaline Creek discharges at this beach, however, the drain is diverted to a sewer during the summer. When discharged into the ocean, beach visitors are urged to avoid contact with runoff and ocean water at least 23 meters from the location where runoff enters the ocean. North of Tourmaline Creek discharge are two storm drain discharges into the ocean. Unrelated to this and Schiff et al. (2016) study, beach water here is sampled all year every week by the County of San Diego and the water quality is generally good (Department of Environmental Health 2017b). Sampling locations at Tourmaline Surfing Park for this study are marked in Figure 3.

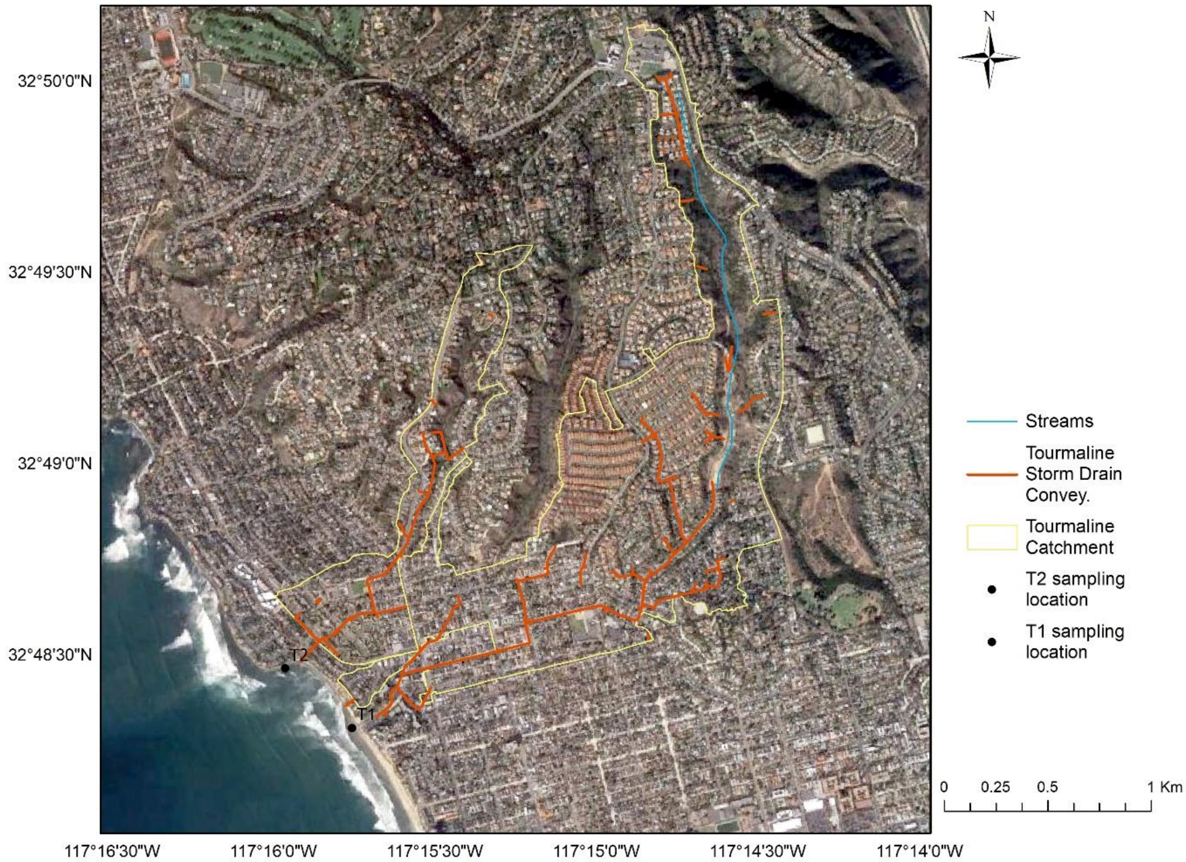

Figure 3. Tourmaline Creek and storm drain system draining to Tourmaline Surfing Park. Base map source: Google Earth

3.2 Data

3.2.1 Land Use Data

Land Use data was retrieved from the Regional GIS Data Warehouse at San Diego Association of Governments services (land use code definition in Appendix 1). This data set was last updated in 2015 using aerial photography, the County Assessor Master Property Records file, and other ancillary information. The land use information was reviewed by each of the local jurisdictions and the County of San Diego to ensure its accuracy. Data set is in the GRS80 Spheroid, California State Plane Coordinate System (feet), Zone VI, North American Datum 83 (NAD 83).

3.2.2 Watershed Data

San Diego River watershed data was retrieved from the Regional GIS Data Warehouse at San Diego Association of Governments services; original source of data is California Department of Forestry and Fire Protection. Hydrologic basins data set was retrieved in shape file format. This dataset was last updated in 2004. Data set is in California State Plane Coordinate System (feet), Zone VI, North American Datum 83 (NAD 83). Lower San Diego River hydrologic area (hereafter Lower San Diego watershed) was extracted from the Hydrologic basins dataset as a subset of San Diego River watershed.

Tourmaline Creek watershed and north Pacific Beach adjacent storm drainage catchment areas are part of the Catchment data set retrieved by email from Mr. Andre L. Sonksen at the Transportation and Storm Water department, City of San Diego. Data set is in California State Plane Coordinate System (feet), Zone VI, North American Datum 83 (NAD 83). The study area was extracted from the Catchment data set. Based on the literature and the Department of Environmental Health recommendation to beachgoers (Ackerman and Weisberg 2003; Department of Environmental Health 2017b; Heal the Bay 2006) catchments with outfalls within 50 m distance from the sampling site or between the sampling sites at Tourmaline Surfing Park were selected as the study area, hereafter Tourmaline watershed.

3.2.3 Digital elevation model (DEM)

A digital elevation model (DEM) with a spatial resolution of 10 meters (32.8 US survey foot) was retrieved from the Regional GIS Data Warehouse at San Diego Association of Governments services. The file contained 11463 x 14652 number of records from year 1970. Elevation data usually does not change much over time and despite being over 40 years old it is the official data from San Diego government. Further, for the purpose the data was used in this project (watershed delineation) and the accuracy used, the possible change in elevation over 40 years likely has insignificant effect on the end result (land use proportions).

3.2.4 Water Quality Data

Beach water quality data (*Enterococcus*, fecal coliform and total coliform concentrations) was obtained from Southern California Coastal Water Research Project (SCCWRP). Data was collected every day during two winter periods 15.1.2014-5.3.2014 and 2.12.2014-31.3.2015. Ocean receiving water samples were collected at four locations at Ocean Beach and two locations at Tourmaline Surfing Park every morning (8.30 ± 2 hrs) during the sampling period. The samples were collected in 1 L sterilized and sample rinsed bottles on incoming flow at 0.5 to 1.0 m depth just below the water surface. The samples were tested for concentration of *Enterococcus*, fecal coliforms, and total coliforms (Schiff et al. 2016). Sampling site coordinates in kmz file format were obtained from SCCWRP.

Water quality data (*Enterococcus* concentrations) from San Diego River upstream sites were retrieved from the Surfer Health Study report in the part of the Supplemental Investigation: Wet Weather Source Tracking Upstream in the San Diego River (Table 1). Samples were collected during one storm event from January 31 to February 1, 2016 (Schiff et al. 2016). There were 13 sampling sites in total, however, only seven samples from the major tributaries is used in this study as the sampling sites at the mainstream would produce drainage areas overlapping each other. Latitude and longitude of sampling locations were retrieved by email from SCCWRP.

Table 1. Enterococcus concentrations measured at Lower San Diego River tributaries during January 31 and February 1, 2016.

	Morena Boulevard	Alvarado Creek	Murphy Canyon	Forrest Creek	Sycamore Canyon Creek	Los Coches Creek	Upper Eucalyptus Hills
Enterococcus MPN/100ml	14400	1203	4396	18444	3619	30342	10250

3.2.5 Precipitation Data

Daily precipitation data for the study period was obtained from the Applied Climate Information System (SC-ACIS). Precipitation was measured at San Diego International Airport (Lindbergh) weather station. When data referred to "trace" amount observed (< .01 inch) in one day, the mark for "trace" was replaced with the value 0.009. This value was simply the matter of the author choice, being lower than 0.01. Data was converted from inch to mm and joined to FIB concentration table by date.

3.3 GIS Data Analysis

The original Land use data had detailed definitions of units with four-digit codes that serve the authorities for land management and administration (detailed description in Appendix 1). For the purpose of this study the data was reclassified (grouped) into 13 categories: Agriculture, Commercial and Public services, Residential, Recreation, Park or Open spaces, Extractive industry, Industry, Transport, Military, Landfill, Undeveloped land, Water bodies and Other land use. A summary of land use groups is presented in Table 2, more details on grouping can be found in Appendix 1. Although the impact on the environment of agriculture and industry depends on the intensity of their activities, only one category for each was defined as the proportion of their areas in this study is relatively small. The land use study area (hereafter land use) was extracted by clipping the original land use data with the area of Lower San Diego River hydrologic unit and defined Tourmaline watershed. Land use data table was joined with the new land use classification table by the original land use four-digit code. Data was then summarized by the newly defined land use categories retrieving total areas for each land use category.

Table 2. Summary of land use classification description (SANDAG 2007)

Land use	Description
Agriculture	Orchard or vineyard, intensive agriculture, field crops.
Commercial and public services	Commercial, wholesale, trade, shopping center, specialty commercial, automobile dealership, service station, other retail trade and strip commercial, office, public services, civic center, cemetery, religious facility, library, post office, fire/police station, mission, hospitals, other health care, schools, university, college, other public services.
Residential	Spaced rural residential, family residential, single room occupancy units, mobile home park with mostly permanent residents, group quarters, jail/prison, dormitory, military barracks, monastery, other group quarters facility, hotel, motel, resort hotel.
Recreation	Resort, commercial recreation, tourist attraction, stadium/arena, race track, golf course, golf course club, house, convention center, marina, Olympic training center, casino, other recreation.
Park or open space	Parks, open space, preserve, beach - passive, landscape open space, undevelopable natural area.
Extractive industry	Extractive industry.
Industry	Heavy industry, light industry, industrial park, general warehousing, public storage.
Transport	Airports, rail station/transit center, freeway, communications and utilities, parking lot, rail road, marine terminal, other transportation.
Military	Military use, military training, weapons facility.
Landfill	Junkyard/dump/landfill.
Undeveloped land	Vacant and undeveloped land.
Water bodies	Bay, lagoon, lake, reservoir, large pond.
Other	Indian reservation, under construction, specific plan areas, mixed use.

Lower San Diego River tributaries were delineated from the DEM using Spatial Analyst tools in ArcGIS 10.3.1. The sinks in DEM were filled and flow direction raster created, which was then used for tributary (watershed) delineation. Because the cells of the actual sampling locations did not accumulate a realistic watershed, cells with the highest flow accumulation within the radius of 300 meters from the sample location (received from SCCWRP) were defined as outflow points. Delineation of tributaries is presented in Figure 4.

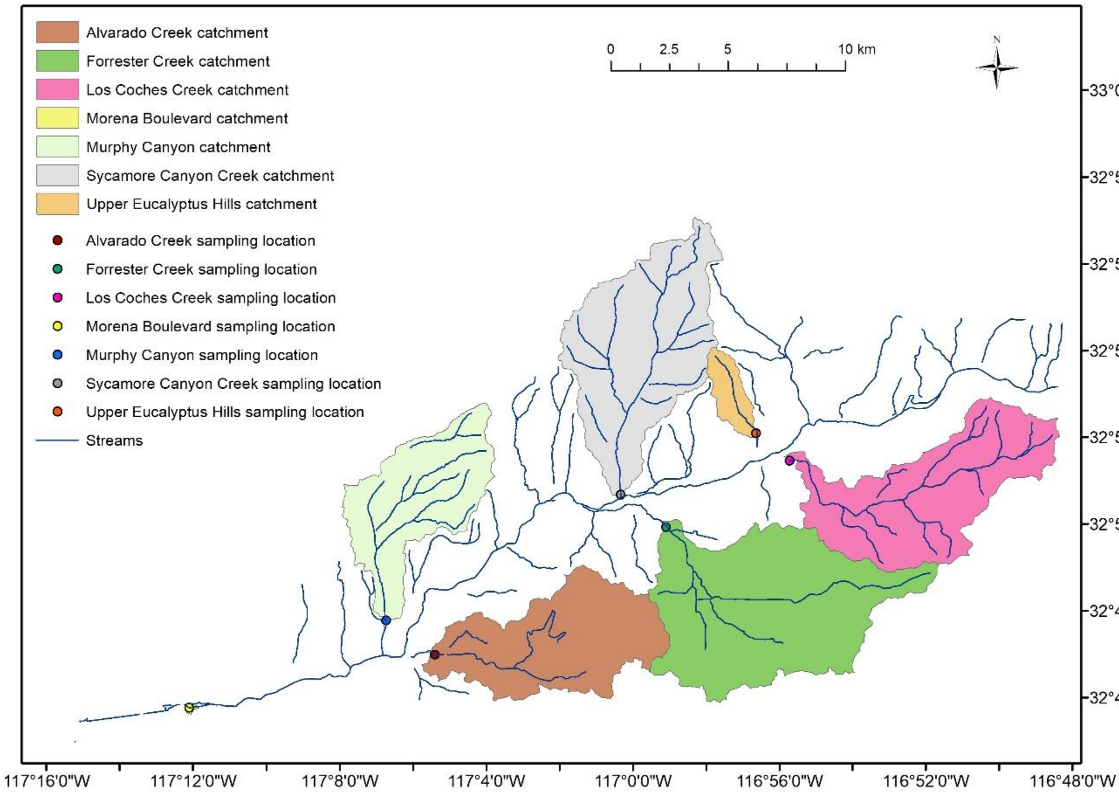

Figure 4. Delineated tributaries with defined outfall locations within 300 m of water quality sampling locations upstream of San Diego River.

3.4 Statistical Data Analysis

Despite the water sample data for FC, TC and ENT concentrations from Tourmaline and Ocean Beach were log10 transformed, the normal probability plots showed deviation from the reference line (Appendix 2). Logarithm transformation was used because it is also used in related research (Schiff et al. 2016, Crowther et al. 2002, Sercu et al. 2011). Sample geometric means were calculated from the arithmetic means of log10 transformed data. Geometric mean was chosen because it offers a compromise between arithmetic mean, which is highly sensitive to outliers, and median, that ignores outliers. Geometric mean is also used in the California's ocean recreational water quality standard. Data was grouped by (1) indicator bacteria, (2) wet and dry weather and (3) beach into a total of six sample groups: dry *Enterococcus*, total coliform and fecal coliform groups for Tourmaline Surfing Park, dry *Enterococcus*, total coliform and fecal coliform groups for Ocean Beach, wet *Enterococcus*, total coliform and fecal coliform groups for Tourmaline Surfing Park and wet *Enterococcus*, total coliform and fecal coliform groups for Ocean Beach. None of the sample data groups had normal distribution.

In this study five analysis were performed: (1) FIB concentrations in dry and wet weather, and between the beaches (section 4.2), (2) precipitation needed for significant raise in FIB concentration (section 4.2), (3) FIB concentrations in relation to watershed land use (section 4.3), (4) spatial and temporal analysis of FIB in beach water (section 4.4) and (5) analysis of relationship between *Enterococcus* concentration in stream water and tributary land use (section 4.5).

Because the FIB concentrations data was not normally distributed, Wilcoxon rank sum test was used to compare dry and wet weather bacterial concentration differences and the concentration differences between the beaches. The same test was used in the procedure of finding the precipitation values at which FIB concentration raise is statistically significant, compared to dry weather. In this procedure data for each sampling site and each of the FIB was grouped in (1) sample containing bacterial concentrations on the days with zero precipitation and (2) sample containing bacterial concentrations for the days with precipitation within defined interval (wet sample). The procedure first runs Wilcoxon rank sum test on the two samples where first sample contains bacterial concentrations from the days with 0 mm precipitation, and the second sample contains bacterial concentrations when daily precipitation was above 0 mm and below or equal to 1mm. If the test returns p-value < 0.05 it means that precipitation above 0 mm and below 1 mm causes significant raise in bacterial concentration. If the test returns p-value ≥ 0.05 the precipitation interval is raised by 1 mm and selection of wet weather sample is rerun. The procedure repeats this step until the test result returns significance (the difference between dry and wet sample is significant). If no significance is found even with comparing the sample with the highest precipitation, the precipitation interval is expanded by 1 mm to ensure more observations within the interval. The procedure is rerun until the test returns significance. The criteria within this procedure is that the sample containing values from the days where precipitation was above 0 mm (wet sample) had at least 8 observations. If the significance is found and the wet sample contains less than 8 observations the precipitation interval is also expanded by 1 mm to ensure additional observation values within the interval and therefore bigger wet sample. The procedure can be seen in Appendix 5.

Plots of FIB concentrations at each distance of sampling location from the closest surface water outlets showed a slight decreasing trend, especially at Ocean Beach alone (Appendix 3). Linear regression test was therefore used to examine relationships between distance from sampling site to the nearest surface water discharge. The test was run for all sample locations together and separately for Ocean Beach sample locations. The calculation of distance was simplified to straight distance between the sample point and the nearest storm water discharge at Tourmaline Surfing Park. At Ocean Beach, the sample location OB1 was defined for the point of discharge. Straight distance was calculated between OB1 and the rest of the sample locations OB2, OB3 and OB4. Straight distance was used to enable simplicity of application. A random beach visitor does not have the means (such as water current direction, tidal movement, turbidity) to do a calculation with all possible variables that can affect the microbial concentration in the water. Simply on the basis of distance one can estimate if swimming could be a health risk at certain location. Linear regression (1) was used to describe the relationship between bacterial concentrations and distance to the closest outlet (Lane et al. 2017):

$$\hat{y} = bx + a \tag{1}$$

where $\hat{y}$ is the predicted variable, x is the explanatory variable, b is the slope (the rate of change in y when change in x) and a is the intercept (the value of y when x = 0). Kruskal Wallis test is a non-parametric alternative to ANOVA and an extension of Wilcoxon rank sum to test more than two groups. Kruskal Wallis test, followed by test for multiple comparisons with Dunn and Sidak's approach were applied to compare *Enterococcus* concentrations between sampling locations for each of the first five days of wet weather and for each of the first five days of dry weather. For presentation purposes the charts depicting concentrations during and after wet weather comprise the geometric mean concentration values on a particular day of all storm events during the study period for each sampling site OB1, OB2, OB3 and OB4. The same method was used to compare sampling site concentrations during dry weather.

Relationship between Lower San Diego River microbial water quality and land use in tributaries was explored with Spearman correlation because of non-normally distributed data (Figure 8).

4 Results

4.1 Watershed land use

Tourmaline watershed covers 270 hectares and Lower San Diego River watershed almost 45,000 hectares. In both Lower San Diego and Tourmaline watershed the highest percentage of land use is residential (Figure 5), though the percentage of residential area in Tourmaline is almost twice as high (61%) as in Lower San Diego (31%). Second highest percentage of land use in Lower San Diego is used for parks and open spaces (29%), followed by transport (13%), undeveloped land (12%), commercial and public services land use (6%), recreation (2%), industry (2%) and other minor uses presented in Table 3. The second highest percentage of total land in Tourmaline watershed is used for transport (23%), followed by parks or open spaces (10%), commercial and public services (4%) and under one percent undeveloped land, recreation, industry and other land use.

Table 3. Land use area and proportions of total area in Lower San Diego River drainage area and Tourmaline drainage area.

	Lower San Diego River		Tourmaline	
Land Use	Area (ha)	Area (%)	Area (ha)	Area (%)
Residential	13809	31	166	61
Park or Open space	13129	29	28	10
Transport	5797	13	63	23
Undeveloped land	5584	12	1	0
Commercial and Public services	2558	6	11	4
Recreation	983	2	<1	<1
Industry	941	2	<1	<1
Military	773	2	0	0
Agriculture	612	1	0	0
Water bodies	300	<1	0	0
Extractive Industry	238	<1	0	0
Other	125	<1	<1	<1
Landfill	80	<1	0	0
Total Area	44929	100	270	100

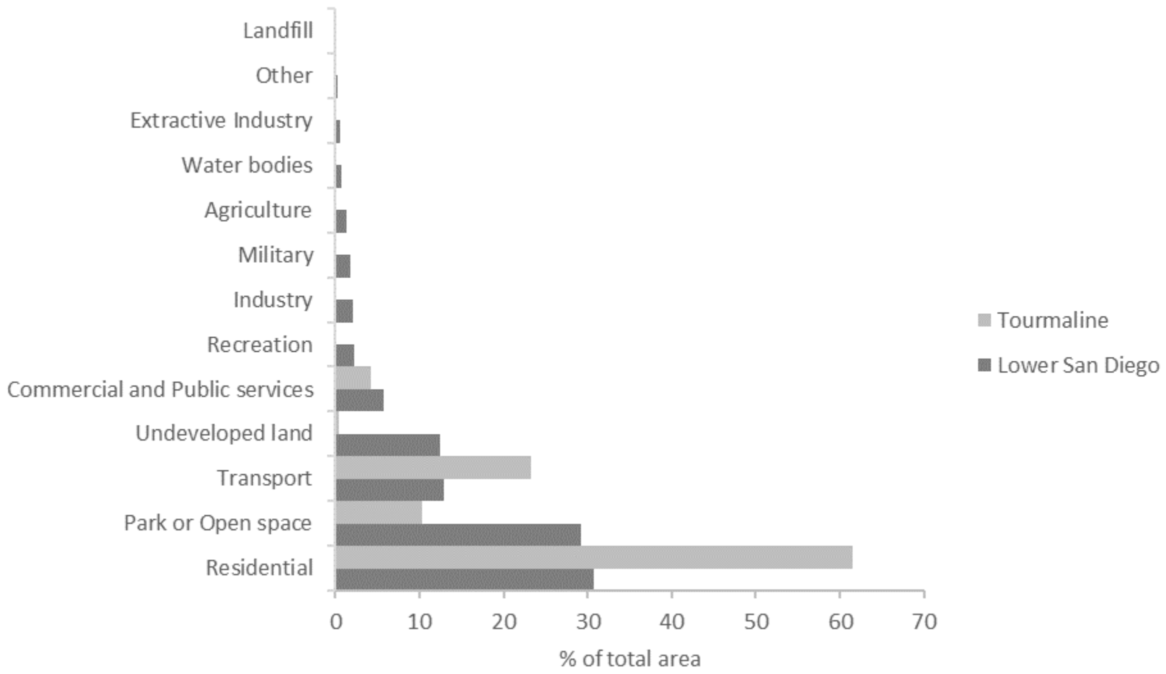

Figure 5. Land use area and proportions of total area in Lower San Diego River drainage area and Tourmaline drainage area.

4.2 Fecal indicator bacteria concentrations

Fecal coliform, total coliform and *Enterococcus* mean concentration levels were higher during wet weather, compared to dry weather (Table 4). Wilcoxon rank sum test returns $p < 0.05$ for all three indicator bacteria at both beaches suggesting the null hypothesis of equal medians for bacterial concentrations can be rejected at 5% significance level and alternative hypothesis that bacterial concentrations are higher in wet weather accepted (Table 5). Wet weather was defined as >2.5 mm (>0.1 inch) of rain in 24 hours which is consistent with the County of San Diego Public Health Department rain advisory (Schiff et al. 2016) .

Table 4. Descriptive statistic for fecal coliform (FC), total coliform (TC) and Enterococcus (ENT) concentrations (CFU / 100 ml) during dry and wet weather at Tourmaline Surfing Park and Ocean Beach. Wet weather is defined as >2.5 mm of rain in 24-hour period. N – number of observations, GM – geometric mean, Q1 – lower quartile, Q3 – upper quartile.

		Dry weather					Wet weather				
		N	GM	Q1	Median	Q3	N	GM	Q1	Median	Q3
Ocean Beach	FC	505	11.9	2.0	8.0	30.5	157	22.1	4.0	20.0	90.5
Ocean Beach	TC	505	37.4	16.0	20.0	80.0	153	126.0	20.0	140.0	400.0
Ocean Beach	ENT	505	18.3	4.0	14.0	60.0	157	31.6	6.0	28.0	120.0
Tourmaline	FC	268	4.6	2.0	2.0	8.0	85	14.4	2.0	10.0	60.0
Tourmaline	TC	268	22.3	8.0	20.0	40.0	83	98.7	20.0	100.0	375.0
Tourmaline	ENT	268	6.8	2.0	4.0	17.0	86	27.4	4.0	22.0	130.0

All dry weather indicator bacterial concentrations were significantly different between the beaches. Wilcoxon rank sum test comparing medians between the beaches returns $p < 0.05$ for all three types of bacterial concentrations, suggesting the null hypothesis of equal medians can be rejected and the alternative hypothesis that the bacterial concentrations are different between the beaches accepted (Table 6). Ocean Beach had higher geometric means for all three indicator bacteria, compared to Tourmaline Surfing Park (Table 4). However, wet weather concentration medians for any of the indicator bacteria did not prove to be significantly different ($p > 0.05$) between the beaches (Table 6).

Table 5. Results for left tailed Wilcoxon rank sum test comparing dry and wet sample of fecal coliform (FC), total coliform (TC) and Enterococcus (ENT) concentrations (CFU / 100 ml) at Tourmaline Surfing Park and Ocean Beach. N – total number of observations.

		N	P-value
Ocean Beach	FC	662	< 0.001
Ocean Beach	TC	658	< 0.001
Ocean Beach	ENT	662	0.001
Tourmaline	FC	353	< 0.001
Tourmaline	TC	351	< 0.001
Tourmaline	ENT	354	< 0.001

Table 6. Results of Wilcoxon rank sum test comparing fecal coliform (FC), total coliform (TC) and Enterococcus (ENT) concentrations (CFU / 100 ml) between Tourmaline Surfing Park and Ocean Beach during dry and wet weather. N – total number of observations.

		N	P-value
Dry weather	FC	773	< 0.001
Dry weather	TC	773	< 0.001
Dry weather	ENT	773	< 0.001
Wet weather	FC	242	0.071
Wet weather	TC	236	0.488
Wet weather	ENT	243	0.459

The wet weather criteria of 2.5 mm of rain was used in the analysis because this is the threshold for San Diego County to issue beach advisories (Schiff et al. 2016). Level of precipitation needed for a significant raise in bacterial concentration at each sampling site was calculated and the size of precipitation interval depended on the available data, so the sample tested had at least 8 observations. Wilcoxon rank sum test results in Table 7 show lower precipitation is needed for a significant raise in bacterial concentration at Ocean Beach sampling site OB1, the closest to San Diego River discharge, compared to sampling sites further away. One can observe a high raise in GM concentrations of 144.6, 373.4 and 296.8 CFU of FC, TC and ENT respectively per 100 ml and GM rainfall of 0.2 mm for FC, 7.3 mm for TC and 5.0 mm for ENT. For all three types of FIB the lower and upper precipitation interval limits are higher at site OB2 and OB3, compared to OB1, which suggests more rainfall is needed for significant raise in concentration at OB2 and OB3. At the furthest sampling site from the river discharge, OB4, the precipitation drops or the precipitation interval is smaller, compared to OB3 and OB2. At T1 sampling site at Tourmaline Surfing Park very low precipitation (from above 0 mm to 4 mm) is needed for significant raise in bacterial concentrations. Only GM of 0.4 mm of rainfall is needed for mean raise of 29.2 CFU of TC per 100 ml. At T2 sampling site FC also raises significantly with very low 0.5 mm of precipitation, however the raise in GM concentrations is only 3.6 CFU per 100 ml. Higher precipitation is needed at T2 for significant raise in TC and ENT with GM 7.3 mm and 4.3 mm of rain respectively.

Table 7. Precipitation levels at which the raise in fecal indicator bacteria concentration is significant. Left tailed Wilcoxon rank sum test comparing concentrations at no precipitation and concentration at precipitation within the defined interval.

		Precipitation interval			Sample size		GM CFU / 100 ml		GM precipitation mm	
Site	FIB	< mm	mm ≤	P-value	Dry	Wet	Dry	Wet	Dry	Wet
OB1	FC	0	1	0.0240	145	11	59.6	204.2	0.0	0.2
OB2	FC	3	7	0.0257	145	8	8.7	31.7	0.0	5.0
OB3	FC	3	13	0.0338	145	12	7.2	12.0	0.0	6.5
OB4	FC	3	11	0.0320	106	8	4.6	9.2	0.0	6.7
T1	FC	1	4	0.0210	144	8	4.7	12.0	0.0	1.9
T2	FC	0	3	0.0308	144	17	4.7	8.3	0.0	0.5
OB1	TC	5	11	0.0325	145	8	167.7	541.1	0.0	7.3
OB2	TC	6	18	0.0200	145	8	34.9	126.7	0.0	9.6
OB3	TC	6	18	0.0491	145	8	27.1	62.1	0.0	9.6
OB4	TC	4	18	0.0250	106	8	20.3	53.9	0.0	8.2
T1	TC	0	2	0.0365	144	15	17.0	46.2	0.0	0.4
T2	TC	5	11	0.0273	144	8	36.1	84.9	0.0	7.3
OB1	ENT	3	7	0.0234	145	8	117.2	414.0	0.0	5.0
OB2	ENT	5	11	0.0277	145	8	13.4	36.9	0.0	7.3
OB3	ENT	5	13	0.0497	145	9	8.8	17.8	0.0	7.8
OB4	ENT	3	11	0.0288	106	8	6.4	14.7	0.0	6.7
T1	ENT	0	1	0.0047	144	11	6.3	15.2	0.0	0.2
T2	ENT	2	7	0.0282	144	10	7.8	19.6	0.0	4.3

4.3 Fecal indicator bacteria concentrations in relation to watershed land use

Comparison of the geometric mean (GM) concentrations between Ocean Beach and Tourmaline Surfing Park and the land use in their adjacent Lower San Diego River watershed and Tourmaline watershed respectively shows that during both, wet and dry weather, the ratio of GM bacterial concentrations is opposite to the ratio of residential and transport area between the watersheds. Higher percentage of residential and transport area does not result in higher concentrations of indicator bacteria. Higher percentage of park or open space, undeveloped land, commercial and public services, recreation, industry and agriculture in Lower San Diego River watershed corresponds to higher FIB GM concentrations at Ocean Beach, compared to Tourmaline watershed with Tourmaline Surfing Park. It has to be emphasized that this is only a visual observation and a correlation cannot be statistically proved due to data limitations.

4.4 Spatial and temporal aspect of fecal indicator bacteria in beach water

4.4.1 Relationship between FIB concentrations and distance to the nearest surface water outfall

Relationship between FIB concentrations and the distance from the sampling site to the nearest surface water outfall (Table 8) was analyzed with a regression test and an ANOVA test was performed to test the regression significance. All but the ANOVA test for TC at Ocean Beach in dry weather resulted in very low significance F value, which indicates that there is a very small percent of chance that the results of the regression analysis occurred by chance (Table 9). The regression analysis showed that small portion of bacterial concentrations can be explained by the distance to the nearest discharge across both beaches. Separate analysis for Ocean Beach was performed which resulted in higher percentage of distance explained bacterial concentrations. In contrast with Tourmaline Surfing Park, bacterial concentrations do show a spatial pattern with values gradually decreasing with distance from the San Diego River outlet. Around 31% of *Enterococcus* and 27% of fecal coliform concentrations can be explained by the distance to the outlet in dry weather at Ocean Beach, while regression for both beaches shows only around 5% of *Enterococcus* and total coliform, and around 4% of fecal coliform concentrations can be explained by the distance from the nearest discharge. During wet weather, around 40% of *Enterococcus*, 27% of total coliform and 42% of fecal coliform concentrations can be explained by the distance to San Diego River outlet. At both beaches together, the percentage of distance to the nearest discharge explained concentrations are much lower, around 14% for *Enterococcus* and around 13% for total coliform and fecal coliform.

Table 8. The shortest distance between the sampling location and the closest surface water discharge.

	T1	T2	OB1	OB2	OB3	OB4
Distance to the closest outlet (m)	33	82	0	401	873	1040

Table 9. Results of Linear regression analysis of fecal indicator bacteria concentrations and distance to the nearest surface water outfall.

	Dry weather						Wet weather					
	ENT	ENT*	TC	TC*	FC	FC*	ENT	ENT*	TC	TC*	FC	FC*
Regression Statistics												
R Square	0.0519	0.3129	0.0474	0.0000	0.0398	0.2723	0.1462	0.4039	0.1374	0.2750	0.1325	0.4281
Adjusted R Square	0.0507	0.3116	0.0463	-0.0020	0.0386	0.2709	0.1427	0.4000	0.1329	0.2702	0.1288	0.4244
Standard Error	0.7620	0.6752	0.6718	0.6461	0.6676	0.6242	0.8466	0.6779	0.7935	0.7263	0.7721	0.6206
N	773	505	814	505	773	505	243	157	195	153	242	157
ANOVA												
F	42.189	229.088	40.435	0.012	31.974	188.263	41.272	105.004	30.738	57.275	36.643	116.029
Sign. F	<0.0001	<0.0001	<0.0001	0.9146	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Coefficients												
Intercept	1.2803	1.8799	1.6583	1.5753	1.0585	1.5913	1.8002	2.2393	2.4123	2.7031	1.5590	2.0572
Distance	-0.0004	-0.0011	-0.0004	0.0000	-0.0003	-0.0009	-0.0009	-0.0014	-0.0008	-0.0011	-0.0008	-0.0013

* *Note that the regression test is for Ocean Beach sample locations only.*

Equation (2) was derived from equation (1) and can be used to predict bacterial concentrations on the basis of distance from San Diego River outlet at Ocean Beach, considering log10 transformation and the coefficients in Table 10:

$$\hat{y} = 10^{a-bx} \qquad (2)$$

Table 10. Coefficients for fecal indicator bacteria concentration (CFU / 100 ml) prediction by the distance x to the outlet at Ocean Beach, where b is the slope and a is the intercept in the equation 2.

	Wet weather		Dry weather	
	b	a	b	a
Enterococcus	0.0014	2.2393	0.0004	1.8799
Fecal coliform	0.0013	2.0572	0.0009	1.5913
Total coliform	0.0011	2.7031		

4.4.2 Fecal indicator bacteria concentrations during first five days of wet weather and first five days after wet weather period

Enterococcus concentrations for each of the first five days of wet and dry weather have been compared between the sampling sites. The results of Kruskal Wallis test show that the null hypothesis that the concentrations from different sampling sites at Ocean Beach come from the same distribution can be rejected at 5% significance level for each of the first five days of the storm (Table 11). The test therefore suggests the concentrations differ between the sites during wet weather. During dry weather the test confirms the concentrations between sites come from different distributions ($p < 0.05$ at 5% significance level) only on the first dry day after a storm, which means the *Enterococcus* concentrations differ only on the first day of dry weather (Table 12). Post hoc test for multiple comparisons shows the concentration differences only occur between sampling site OB1 and the rest of sampling sites at Ocean Beach (Appendix 4). In the Figure 6 as well, one can observe, that this difference is mainly contributed by the sampling site at the San Diego River discharge (OB1). The figure shows FIB geometric mean concentrations variation at each sampling site at Ocean Beach and Tourmaline Surfing Park across first five days of all the storms (wet weather) that occurred during the study period and the variation across five days after storm events. A high increase of all three indicator bacterial concentrations can be observed during the second day of the storm at sampling site OB1 located at the river discharge. There was a small increase in concentrations at the next sampling site to the south (OB2) on the second day for all indicator bacteria. While total coliform concentration still increased on the third day at OB2, *Enterococcus* and fecal coliform has decreased and all three indicator bacterial concentrations returned to the range of concentration during dry weather around day five. At sampling site OB1 the concentrations are noticeably higher during dry weather, compared to sampling locations OB2, OB3 and OB4 further to the south, although Kruskal Wallis test shows concentrations come from different distributions (at 5% significance level) only on the first day of dry weather (Table 12).

The sampling sites at Tourmaline Surfing Park did not significantly differ in median *Enterococcus* concentrations on any day, neither during the storm (Table 11) nor after the storm (Table 12). The mean concentrations of all three indicator bacteria at Tourmaline Surfing Park reached the peak on the first day of the storm and in contrast to the Ocean Beach locations, decreased on the second day of the storm. Fecal indicator bacteria concentrations at Tourmaline Surfing Park returned to approximate range of dry weather concentrations around third and fourth day of the storm (Figure 6). Exact geometric mean concentration values for each sampling site can be seen in Appendix 6.

Table 11. Results for the tests of Enterococcus concentration differences between four sampling sites at Ocean Beach and two sampling sites at Tourmaline Surfing Park on the first five storm days.

	Ocean Beach: Kruskal Wallis				Tourmaline: Wilcoxon Rank Sum
Storm day	P-value	X^2	df	N	P-value
1	0.028	9.1	3	24	0.2667
2	0.001	17.6	3	24	0.6626
3	0.001	16.8	3	24	0.4836
4	0.002	15.2	3	24	0.728
5	0.010	11.3	3	15	0.2381

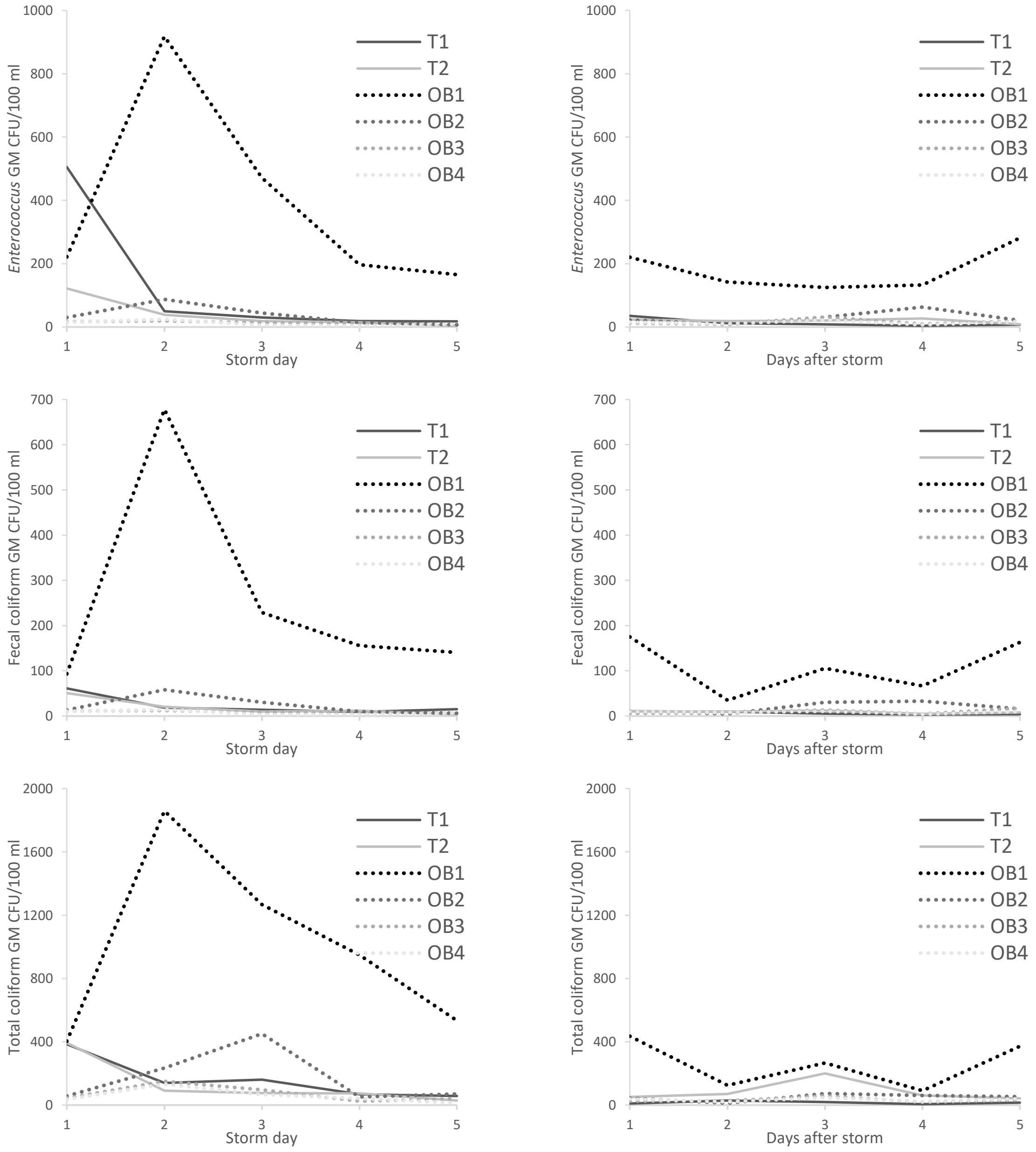

Figure 6. Fecal indicator bacteria geometric mean concentrations for each sampling site at Ocean Beach (OB) and Tourmaline Surfing Park (T) during the first five days of wet weather (left) and five days after wet weather (right). Wet weather is defined as >2.5 mm of rain in 24-hour period.

Table 12. Results for tests of Enterococcus concentration differences between four sampling sites at Ocean Beach and two sampling sites at Tourmaline Surfing Park on the first five days after wet weather.

	Ocean Beach: Kruskal Wallis				Tourmaline: Wilcoxon Rank Sum
Day after storm	P-value	X^2	df	N	P-value
1	0.019	9.9	3	22	0.7354
2	0.074	6.9	3	19	0.6688
3	0.229	4.3	3	16	0.4603
4	0.052	7.7	3	16	0.6825
5	0.102	6.2	3	13	0.7429

Enterococcus concentrations at Ocean Beach trough five days of wet weather are visualized in Figure 7, showing raised concentration at the north end of the beach decreasing south, away from San Diego River outlet. As previously described there is an increase in concentrations on the second day and slowly decreasing towards the fifth day of the storm, though concentrations being higher at the north end of the beach on any day of the storm. *Enterococcus* concentration at the river outlet is around an order of magnitude or more, higher from the concentrations at sampling locations further south.

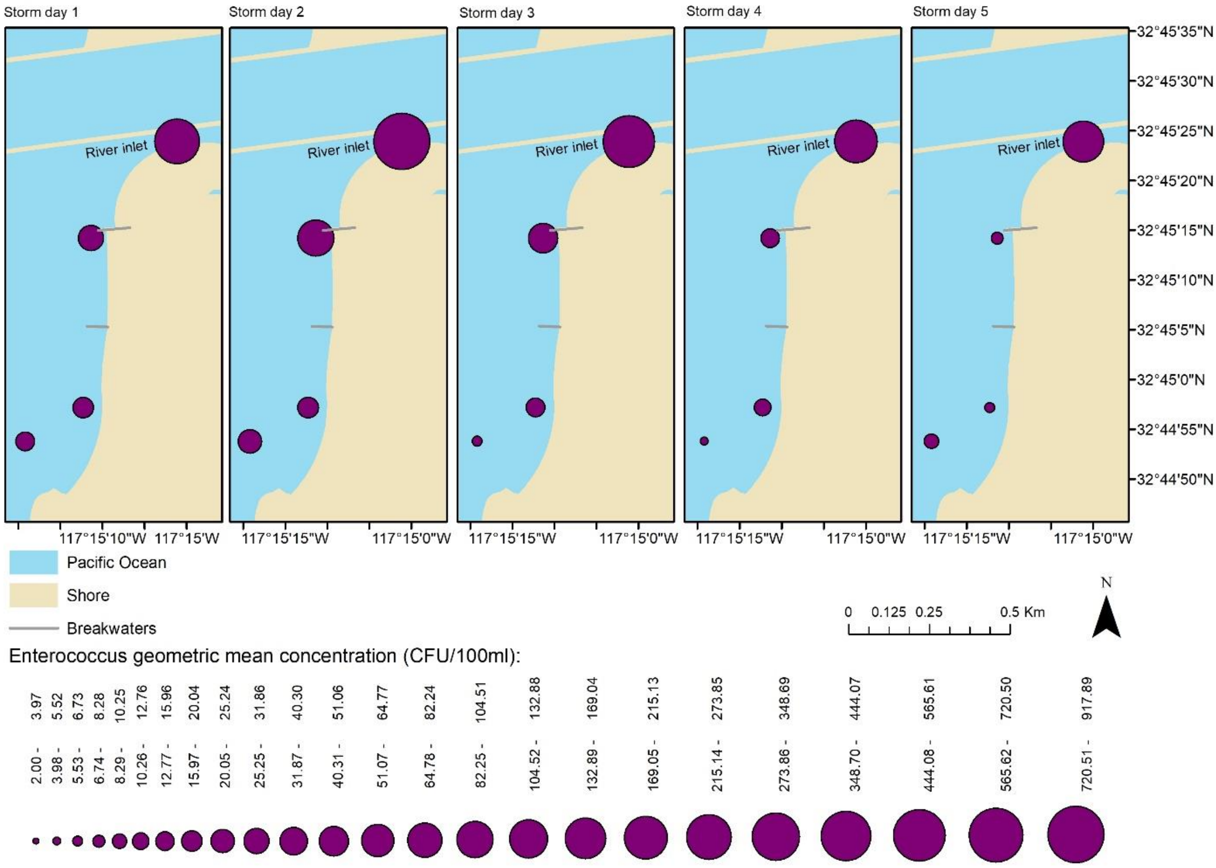

Figure 7. Spatial representation of Enterococcus geometric mean concentrations at Ocean Beach sampling sites across five days of wet weather. Wet weather is defined as >2.5 mm of rain in 24-hour period.

4.5 Lower San Diego River tributary land use and *Enterococcus* concentration in the river

Delineated watershed areas for selected San Diego River tributaries range from just over 11 hectares at Morena Boulevard to just under 5,700 hectares at Forrest Creek. Their land use also vary. All of the tributaries have residential, park or open space, transport and undeveloped land. The proportions of these vary greatly from 56% of residential land at Forrest Creek to as little as 3.8% at Syncamore Canyon Creek. In reverse, parks or open space cover only 5.9% of Forrest Creek while Syncamore Canyon Creek is covered by the highest percentage of 54.1%. Majority of land at the smallest watershed at Morena Boulevard is used by transport (61.4%). Upper Eucalyptus Hills has the smallest percentage of transport (1.7%) and the highest percentage of undeveloped land (40.4%) among all watersheds. Other land use types that cover at least a small percent of most watersheds are used for commercial and public services, recreation and industry. Agriculture is present only in three watersheds, taking 8.4% of the total land in Los Coches Creek and only a fraction (0.1%) in Forrest Creek and Upper Eucalyptus watersheds. Extractive industry is present only in Los Coches tributary and represents less than 0.1% of total tributary land (Table 13).

Table 13. Land use areas and proportions for Lower San Diego River sampling sites' drainage areas.

	Morena Boulevard		Alvarado Creek		Murphy Canyon		Forrest Creek		Sycamore Canyon Creek		Los Coches Creek		Upper Eucalyptus Hills	
Land Use	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%	ha	%
Residential	0.6	5.2	1661.5	48.3	338.4	11.9	3182.3	56.0	166.7	3.8	1752.3	43.0	206.2	45.7
Park or Open space	3.6	32.3	316.7	9.2	1094.6	38.4	333.5	5.9	2403.9	54.1	1092.0	26.8	54.6	12.1
Transport	6.9	61.4	770.2	22.4	428.4	15.0	977.4	17.2	136.3	3.1	332.8	8.2	7.9	1.7
Undeveloped land	0.1	1.1	41.9	1.2	560.8	19.7	337.1	5.9	1154.8	26.0	375.9	9.2	182.2	40.4
Commercial and Public services	-	-	419.3	12.2	213.2	7.5	519.2	9.1	14.3	0.3	106.9	2.6	-	-
Recreation	-	-	142.9	4.2	34.6	1.2	39.9	0.7	41.7	0.9	27.1	0.7	-	-
Industry	-	-	13.5	0.4	112.8	4.0	282.0	5.0	0.7	0.0	28.7	0.7	-	-
Military	-	-	-	-	68.7	2.4	1.9	0.0	495.0	11.1	-	-	-	-
Agriculture	-	-	-	-	-	-	4.8	0.1	-	-	342.7	8.4	0.5	0.1
Water bodies	-	-	73.2	2.1	-	-	-	-	26.7	0.6	2.2	0.1	-	-
Other	-	-	1.0	<0.1	-	-	4.4	0.1	0.6	<0.1	14.4	0.4	-	-
Landfill	-	-	-	-	-	-	0.3	<0.1	0.4	<0.1	-	-	-	-
Extractive Industry	-	-	-	-	-	-	-	-	-	-	1.2	<0.1	-	-
Total Area	11.2	100.0	3440.1	100.0	2851.5	100.0	5683.0	100.0	4441.2	100.0	4076.1	100.0	451.3	100.0

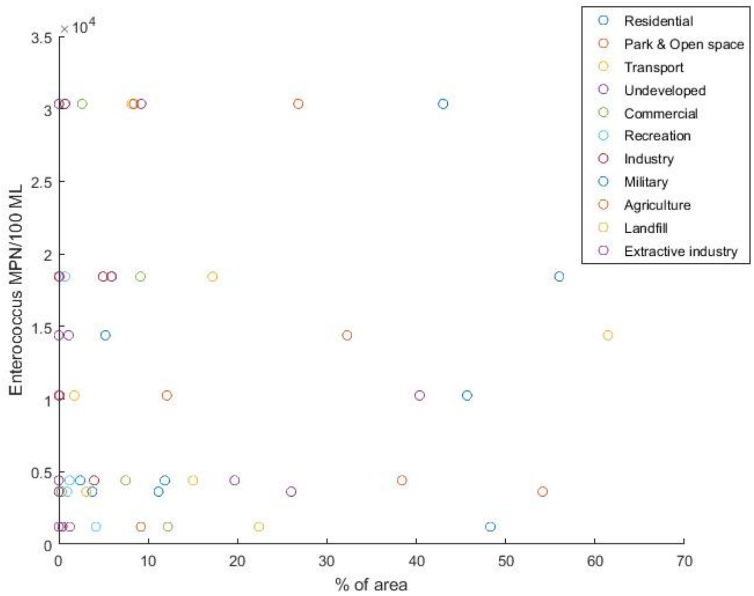

Figure 8. Distribution of Enterococcus concentrations and proportion of different land uses in Lower San Diego River tributaries

Water quality was measured at major tributaries of San Diego River on a single storm event. Spearman correlation test did not confirm relationship between *Enterococcus* concentration and any of the land use groups included in the analysis (Table 14). Despite acceptance of the null hypothesis, that no correlation exists (p-value > 0.05), agriculture and extractive industry resulted in higher Spearman's rho (0.73 and 0.61 respectively) indicating there could be some positive relationship between these two land uses and *Enterococcus* concentration in stream water.

Table 14. Spearman correlation test of Enterococcus concentrations and land use groups at Morena Boulevard, Alvarado Creek, Murphy Canyon, Forrest Creek, Sycamore Canyon Creek, Los Coches Creek and Upper Eucalyptus Creek.

	ρ	P-value
Residential	0.18	0.71
Park or Open space	-0.25	0.59
Transport	0.00	1.00
Undeveloped	-0.14	0.78
Commercial	-0.23	0.61
Recreation	-0.67	0.12
Industry	0.23	0.61
Military	-0.30	0.52
Agriculture	0.73	0.09
Landfill	-0.09	0.90
Extractive industry	0.61	0.29

5 Discussion

This study highlights the importance of considering characteristics of individual watersheds as well as beaches when dealing with coastal water quality issues. The literature reports urban areas, developed land and high density residential areas having significant effect on coastal or stream water impairment (Brownell et al. 2007; Wu and Jackson 2016; Yamahara et al. 2007; Knee and Encalada 2014; Weiskel et al. 1996). The comparison of FIB concentrations between the beaches and the adjacent watersheds' land uses did not suggest that residential and transport land use contribute to increased fecal indicator bacteria in beach water. It showed significantly higher dry weather GM concentrations of all indicator bacteria at Ocean Beach, compared to Tourmaline Surfing Park, of which the adjacent watershed has 61% of residential and 23% of transport land, compared to Lower San Diego River watershed with 31% of residential and 13% of transport land. The result was similar for storm weather, although the difference in the bacterial concentrations was not significant. In relation to San Diego river watershed, Tourmaline watershed has smaller proportion of parks or open space including preserves and natural area, as well as undeveloped land. The outcome of this comparison agrees with Griffith et al. (2010) showing that land from the undeveloped watershed can also contribute to the raised *Enterococcus* concentrations in beach water during rainfall.

Higher fecal indicator bacteria GM concentrations at Ocean Beach have shown to correspond with higher proportion of commercial and public services land use, recreational, industrial and agricultural land in Lower San Diego River watershed during dry and wet weather. Agriculture has been found to be the bacterial contributor to beach water elsewhere (Wu, Jackson 2016). The areas with commercial use, public services and recreation, such as resorts, tourist attractions, stadiums, convention centers and marinas generate crowds and with insufficient environment protection practices can represent a source of microbial pollution.

Likely explanation for generally higher microbial concentrations at Ocean Beach is a constant outflow of San Diego river at this beach while at Tourmaline Surfing Park the surface runoff normally discharges only during wet weather (Schiff et al. 2016). The size of the watershed could be another possible explanation for higher GM bacterial concentrations at Ocean Beach. The literature suggests that bigger catchment surfaces result in more accumulated microbial pollutants being discharged to the sea. For example, Crowther et al. (2003) suggest the size of drainage area is related to the elevated bacterial concentrations. Griffith et al. (2010) reports the watershed size being correlated with the frequency of water quality threshold exceedance for fecal indicator bacteria. In the future, it would be interesting to compare watersheds of similar sizes that differ in proportions of different land uses. This way the watershed size effect (assuming bigger watershed accumulates more pollutants) would be eliminated. Another reason for raised microbial concentration could be the presence of animals in the close proximity. Just above San Diego River discharge there is a dog park and further upstream is a bird sanctuary which are potential sources of FIB.

When comparing to the literature one should bear in mind that the subject of this study were two beaches with their respective watersheds bringing a detailed understanding of this particular environment. While the comparison helps to understand the conditions and bacterial dynamics in these particular areas, the available data restricts us to statistically confirm a correlation between the land use and the bacterial concentrations in beach water. Other studies considered several study sites with several catchment areas and give a generalized knowledge of microbial sources.

Literature as well as this study showed the river entering the ocean contributes to increased microbial concentrations in beach water. Therefore, the study explored the land use upstream of Lower San Diego River tributaries and compared it to the stream water *Enterococcus* concentrations. The results showed diversity in size and land use between and within tributary areas. Most of tributary areas have residential, transport, commercial and public services, industry, recreation, park or open spaces and undeveloped land. The tributary sizes vary from approximately 11 hectares to just under 5,700 hectares.

The test of relationship between the stream water quality and the land use in the tributaries showed no significant correlation between *Enterococcus* concentration in the stream water and any of the land use groups. The measure of correlation was slightly higher for agriculture and extractive industry, which indicates there could be some positive relationship between these two land uses and *Enterococcus* concentration in stream water. Several sources found agriculture to be an imporant bacterial source in stream water (Bradshaw et al. 2016, Crowther et al. 2003; Crowther et al. 2002; Pandey et al. 2012). However, extractive industry represents only a fraction of the land area in a single tributary. A rare source from the literature considering mining land use shows *Enterococcus* mean concentration being lower in stream water passing mining land use areas, compared to agriculture and urban areas (Knee and Encalada 2014). The reviewed literature does not address the problem of microbial pollution in relation to mining, or concludes that mining does not have an impact on water fecal indicator bacteria, therefore the concentration of *Enterococcus* in this study might have an indirect relationship with the presence of extractive industry. Other land use categories, such as residential, transport, commercial and public services, recreation and industry, had either very low or negative correlation indicator value. Interesting outcome of correlation test is stronger negative correlation between *Enterococcus* concentration and recreation land use, considering this group includes tourist attractions, stadiums, race tracks, golf courses, marinas, casinos and other uses, that can represent pressure on the environment (Tiefenthaler et al. 2011).

The spatial analysis of indicator bacteria concentrations in beach water showed the distance to the nearest surface water discharge only partially explains the *Enterococcus* concentration. Between two beaches, at Ocean Beach distance appeared to have higher impact, compared to Tourmaline Surfing Park. The reason could be more intensive mixing with ocean water or different direction of the water current at Tourmaline Surfing Park. Here the storm drain discharges are located between the two sampling locations, while at Ocean Beach all sampling locations are positioned south of San Diego river discharge. Because of a small distance from one end of the beach to the other, the ocean water current is likely to run in one direction along the entire study beach at a time. This means bacterial diststribution will differ if the surface runoff outfals are located between the sampling locations, which could well be the case at Tourmaline Surfing Park.

Examination of the distance between the surface water discharge and bacterial concentration has taken into account the shortest (straight) distance between the locations in question and the actual path of water flow is likely to be slightly longer. The distance from the surface water outfall is not the only factor affecting the microbial concentrations in water. The concentration is also impacted by complex environmental factors, such as beach exposure

(Lee et al. 2006), tidal movement (Shibata et al. 2004), turbidity, water and air temperature (Halliday et al. 2015). The description of distance and bacterial concentrations therefore represents an approximation and the reader should be aware of the complex environment affecting the movement of bacterial concentrations when interpreting results. Detailed data for the water current at the sampling locations at Ocean Beach was not available, however the surface water current mapping on a larger scale (SCCOOS 2017) shows, that the direction of the current can change hourly. Data collected on the Waverider Buoy, positioned around 10 km west of Ocean Beach shows, that the direction, from which the waves were coming from during the study period, around the time of sample collection, between 8 am and 9 am, was exact west in approximately 4% of the time, northwest in 40% of the time and southwest in 56% of the time (National Data Buoy Center 2017a, National Data Buoy Center 2017b). This means that most of the time the breakwater at the north side of San Diego river outflow likely did not give much protection against the waves at Ocean Beach, neither the two smaller breakwaters at the beach. During the sampling time of the day, the beach was also exposed to tidal flushing. Data from NOAA (2017) shows, that during the study period, if high or low tide occurred between 7 am and 10 am, in 73% of the time it was the high tide. This means that once the water from the river entered the ocean it was the subject of intense mixing with the ocean water. This likely explains the quick decline in FIB concentrations between sampling site at San Diego river outflow and the next sampling site to the south.

The bacterial concentration distribution pattern can be well observed at Ocean Beach with *Enterococcus* concentrations decreasing southwards away from the river outlet. The concentrations between sampling sites at Ocean Beach statistically differ on all five days of the storm. The results are consistant with other studies confirming microbial concentration decreasing with the distance from the surface runoff outfals (Riedel et al. 2015; Cloutier et al. 2015). Considering the concentrations are significantly higher at Ocean Beach during dry weather, compared to Tourmaline Surfing Park, and that during dry weather the concentrations within the Ocean Beach mostly don’t significantly differ, it could mean that San Diego River discharge has an effect on the entire beach also when it is not raining and possibly raises the health risk of swimmers at any location on this beach.

It is kown from several studies, that FIB concentrations in beach water drastically increase with the rainfall (Brownell et al. 2007; Liang et al. 2013; Griffith et al. 2010; Schiff et al. 2016; Ackerman and Weisberg 2003; Izbicki et al. 2009; Lee et al. 2006) and this work confirms the outcomes of previous studies. The visualization of data in this study clearly depicts noticeably higher microbial concentrations near the surface water runoff during the wet weather supporting local authority warnings to the bathers to be cautious when in contact with beach water near river or storm water discharges.

There was six locations examined, in total two at Tourmaline Surfing Park and four at Ocean Beach. For better understanding of spatial distribution of bacteria more sampling sites should be available as well as more disperse sampling site distribution. Looking at the results and the overwiew of the Ocean Beach sampling locations one can observe a slight deviation of the southest sampling location OB4 from the observed trend on this beach. OB4 sampling location is positioned at further distance from the shore, compared to other three sampling locations. It is also located by the pier. This raises a question how the distance to the shore, pier and other beach infrastructure impacts the bacterial concentrations in the water and could be the subject of further studies.

Indicator bacterial concentrations were analyzed at each sampling location for each of the first five days of wet weather (defined as > 2.5 mm of rain in 24 hours). The study found, that the peak of GM concentrations across all storm events at Ocean Beach happens on the second day of the storm, compared to Tourmaline Surfing Park, where the highest concentration is reached on the first day of the storm. The reason for this timing difference could be in the size of the watershed. While Lower San Diego River watershed covers more than two orders of a mangnitude bigger surface area, compared to Tourmaline catchments all together, the microbial pollutants have longer path to travel from the source before being discharged into the ocean. Consequently, from this study one could suggest that the pollutants indeed come from further areas and that beach environment is not only affected by the direct surroundings of the beach. The results of spatial and temporal anlysis of bacterial concentration in water are important for the public to be aware of risk swimming in the sea shortly after rainfall. The result shows that the most risky time to contract a disease depends on specific beach and adjacent watershed and that the bacterial concentrations in beach water do not linearly decrease during storm event but can increase days after rain began and only then start to decrease.

The study further investigated how much rainfall is needed for a significant raise in bacterial concentrations. The results showed the rainfall effect on bacterial concentrations change depends on location. Less rain was needed near the river discharge, compared to the sites further away. The study showed as little as 0.2 mm of rainfall is needed for a significant raise in bacterial concentration in beach water. This initial change does not always represent a health threat as only *Enterococcus* concentration at sampling site OB1 at San Diego River discharge, occurring with 3 - 7 mm of rain, exceeds the California's ocean recreational water quality standard of a single sample criteria 104 ENT CFU per 100 ml. In addition, multiple sample criteria for *Enterococcus* (35 ENT CFU per 100 ml) is exceeded with 0 -1 mm of rain at OB2 and criteria for fecal coliform (200 FC CFU per 100 ml) at sampling site OB1 occurring with 5 – 11 mm of rain (State Water Resources Control Board 2013b). The results, however, show how rapidly the change in concetration happens when raining and that public should be therefore careful when swimming near surface water discharges even when very little rain occurs.

6 Conclusions

This study brings a detailed insight into the spatial and temporal variability of fecal indicator bacteria at two popular beaches in San Diego and looks at the possible explanation in the land use of the adjacent watersheds. In any weather conditions, Ocean Beach has higher FIB concentrations, compared to Tourmaline Surfing Park. The study does not confirm higher percentage of residential and transport area result in higher concentrations of indicator bacteria in beach water. It does however suggest, that higher percentage of park or open space, undeveloped land, commercial and public services, recreation, industry and agriculture result in higher indicator bacterial concentrations. No land use was found to be correlated with *Enterococcus* concentration in San Diego river. Negative correlation between the distance to the surface water runoff discharge and FIB concentration in beach water is found at Ocean Beach in dry and wet weather. Fecal indicator bacteria concentrations are significantly higher at San Diego River outflow during wet weather with concentrations decreasing with distance to the south. The beaches differ in timing of the peak concentrations: at Tourmaline Surfing Park, the bacterial concentrations are the highest on the first day of wet weather, while at Ocean Beach, the highest concentrations are observed the second day. The study also shows that even less than 1 mm of rain can cause a significant raise in bacterial concentration in beach water.

Findings in this study contribute valuable information for discussions and decision-making processes related to beach management and ensuring public and coastal environment health. This study shows that each beach is a specific environment on its own as well as being affected by the inland area from where the surface waters are drained.

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Appendices

Appendix 1. SANDAG Land Use four-digit code definition (first column, source: SANDAG 2007) and the reclassification for the purpose of this project (second and third column).

SANDAG CODE AND DESCRIPTION	RECLASSED CODE	RECLASSED DESCRIPTION
1000 SPACED RURAL RESIDENTIAL – Single family homes located in rural areas with lot sizes greater than 1 acre. Rural residential estates may have small orchards, fields or small storage buildings associated with the residential dwelling unit.	10	Residential
1100 SINGLE FAMILY RESIDENTIAL	10	Residential
1110 SINGLE FAMILY DETACHED – Single family **detached housing units**, on lots smaller than 1 acre. Newer developments may include clubhouses, recreation areas, pools, tennis, etc. located within and associated with the residential development, if a separate parcel/lot designation does not exist.	10	Residential
1120 SINGLE FAMILY MULTIPLE-UNITS – Includes single family **attached housing units**, duplexes, townhouses, and lower density condominium developments (in general, less than or equal to12 units per acre). Single family attached units are structures with one or more walls extending from ground to roof separating adjoining structures.	10	Residential
1190 SINGLE FAMILY RESIDENTIAL WITHOUT UNITS – Small parcels of land associated with larger residential parcels. Includes but not limited to strips of land adjacent to developed land, car ports, sloped land, or odd-shaped parcels. May include land where a building straddles parcels and only one parcel has dwelling units.	10	Residential
1200 MULTI-FAMILY RESIDENTIAL – Apartments and higher density condominium developments (in general, more than 12 units per acre). Newer developments may include clubhouses, recreation areas, pools, tennis, etc. located within and associated with the residential development, if a separate parcel/lot designation does not exist.	10	Residential
1280 SINGLE ROOM OCCUPANCY UNITS (SROs) – For Rent SROs provide small, fully furnished rooms with utilities included, and rent on daily weekly and monthly terms.	10	Residential
1290 MULTI-FAMILY RESIDENTIAL WITHOUT UNITS – Small parcels of land associated with larger residential parcels. Includes but not limited to strips of land adjacent to developed land, car ports, sloped land, or odd-shaped parcels. May include land where a building straddles parcels and only one parcel has dwelling units.	10	Residential
1300 MOBILE HOME PARK – Includes mobile home parks with 10 or more spaces that are primarily for residential use. (RV parks are included within the commercial recreation category).	10	Residential
1400 GROUP QUARTERS	10	Residential
1401 JAIL/PRISON/BORDER PATROL HOLDING STATION	10	Residential
1402 DORMITORY	10	Residential
1403 MILITARY BARRACKS	10	Residential
1404 MONASTERY	10	Residential
1409 OTHER GROUP QUARTERS FACILITY– Convalescent or retirement homes not associated with or within a health care facility, rooming houses, half-way houses, California Conservation Corps, Honor Camps and other correctional facilities.	10	Residential
1500 HOTEL/MOTEL/RESORT	10	Residential
1501 HOTEL/MOTEL (LOW-RISE) – Hotels, motels, and other transient accommodations with three or less floors. Commonly found along freeways and prime commercial areas.	10	Residential
1502 HOTEL/MOTEL (HIGH-RISE) – Hotels and motels that have four or more floors. Primarily found in downtown areas and near tourist attractions.	10	Residential
1503 RESORT – Resorts with hotel accommodations that usually contain recreation areas. Examples of resorts would be La Costa Health Spa, Lawrence Welk and the Olympic Resort in Carlsbad near the airport.	70	Recreation
2000 HEAVY INDUSTRY		
2001 HEAVY INDUSTRY – Shipbuilding, airframe, and aircraft manufacturing. Usually located close to transportation facilities and commercial areas. Parcels are typically large, 20-50 acres.	20	Industry
2100 LIGHT INDUSTRY	20	Industry
2101 INDUSTRIAL PARK – Office/industrial uses clustered into a center. The primary uses are industrial but may include high percentages of other uses in service or retail activities.	20	Industry
2103 LIGHT INDUSTRY-GENERAL – All other industrial uses and manufacturing not included in the categories above. These are not located inside of parks, but are usually along major streets or clustered in certain areas. Includes manufacturing uses such as lumber, furniture, paper, rubber, stone, clay, and glass; as well as light industrial uses as auto repair services and recycling centers. Mixed commercial and office uses (if not large enough to be identified separately) are also included. General industrial areas are comprised of 75 percent or more of industrial uses (manufacturing, warehousing, and wholesale trade).	20	Industry
2104 WAREHOUSING – Usually large buildings located near freeways, industrial or strip commercial areas.	20	Industry
2105 PUBLIC STORAGE – Public self-storage buildings are typically long, rectangular and closely spaced. Also includes RV storage areas.	20	Industry

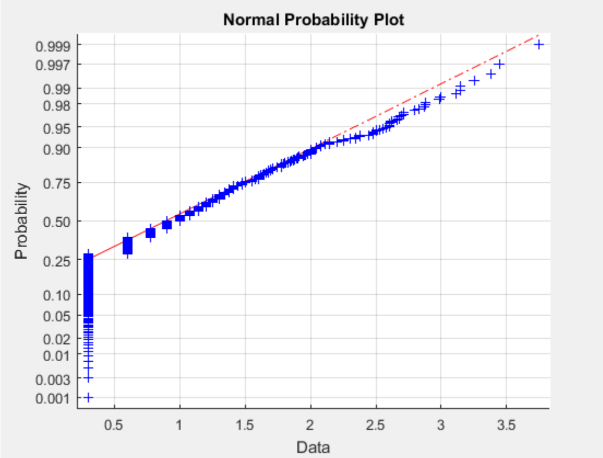
2200 EXTRACTIVE INDUSTRY		
2201 EXTRACTIVE INDUSTRY – Mining, sand and gravel extraction, salt evaporation.	21	Extractive Industry
2300 JUNKYARDS/DUMPS/LANDFILLS		
2301 JUNKYARD/DUMP/LANDFILL – The landscape should show visible signs of the activity. Also include auto wrecking/dismantling and recycling centers.	30	Landfill
4100 AIRPORTS	40	Transport
4101 COMMERCIAL AIRPORT – Lindbergh Field only.	40	Transport
4102 MILITARY AIRPORT – Airports owned and operated by the military. Found on Military bases.	40	Transport
4103 GENERAL AVIATION AIRPORT – All general aviation airports.	40	Transport
4104 AIRSTRIP	40	Transport
4110 OTHER TRANSPORTATION	40	Transport
4111 RAIL STATION/TRANSIT CENTER/SEAPORT – Major transit centers (e.g. Oceanside Transit Center, El Cajon Transit Center), rail stations (e.g. Santa Fe Depot, Solana Beach Station), Coaster stations (Oceanside, Carlsbad Village, Carlsbad Poinsettia, Encinitas, Solana Beach, Sorrento Valley, Old Town, San Diego), major trolley stations, and seaport terminals (Port of SD). Parking areas associated with these uses are included. Transit centers within shopping centers are included within the shopping center category.	40	Transport
4112 FREEWAY – Divided roadways with four or more lanes, restricted access, grade separations, and rights of way greater than 200 ft. wide. Includes all right of way and interchange areas, but not frontage roads.	40	Transport
4113 COMMUNICATIONS AND UTILITIES – TV and radio broadcasting stations, relay towers, electrical power generating plants, water and sewage treatment facilities, and large public water supply storage tanks.	40	Transport
4114 PARKING LOT-SURFACE – All surface parking lots not associated with another land use.	40	Transport
4115 PARKING LOT-STRUCTURE – All large parking structures not associated with another land use.	40	Transport
4116 PARK AND RIDE LOT – Stand-alone parking areas that are not associated with any land use. These are usually located near freeways.	40	Transport
4117 RAILROAD RIGHT-OF-WAY – All railroad ROWs.	40	Transport
4118 SURFACE STREET RIGHT-OF-WAY – All street ROWs.	40	Transport
4119 OTHER TRANSPORTATION – Maintenance yards and their associated activities, transit yards and walking bridges.	40	Transport
4120 MARINE TERMINAL – National City and 10th Street (Centre City) marine terminals.	40	Transport
5000 COMMERCIAL	50	Commercial and public services
5001 WHOLESALE TRADE – Usually located near transportation facilities. Structures are usually large and cover the majority of the parcel. Examples are clothing and supply. Also includes swap meet areas.	50	Commercial and public services
5002 REGIONAL SHOPPING CENTER – Contain one to five major department stores, and usually have more than 50 tenants. Typically, are larger than 40 acres in size.	50	Commercial and public services
5003 COMMUNITY SHOPPING CENTER – Smaller in size than the regional shopping centers. Contain a junior department store or variety store (i.e. a Target Center with other commercial stores) as a major tenant and have 15 to 50 other tenants. Smaller in size, 8 to 20 acres. May also have a variety store (i.e. Target, Home Depot or Price/Costco) by itself.	50	Commercial and public services
5004 NEIGHBORHOOD SHOPPING CENTER – Usually less than 10 acres in size with on-site parking. Includes supermarket and drug store centers not identified as community commercial. May include office uses that are not large enough to code separately. Neighborhood centers with over 100,000 sq. ft. are inventoried by the Chamber of Commerce, and The Union Tribune (Copley) also collects data on neighborhood centers.	50	Commercial and public services
5005 SPECIALTY COMMERCIAL – Tourist or specialty commercial shopping areas such as Seaport Village, Marina Village, Ferry Landing at Coronado, Bazaar del Mundo, Flower Hill, Glasshouse Square, The Lumberyard, Park Plaza at the Village, Promenade, Belmont Park, Del Mar Plaza.	50	Commercial and public services
5006 AUTOMOBILE DEALERSHIP – Includes National City Mile of Cars and Carlsbad's Car Country, among others.	50	Commercial and public services
5007 ARTERIAL COMMERCIAL – Includes commercial activities found along major streets (not in planned centers), with limited on-site parking. May include mixed office uses that are not large enough to be identified as a separate area. Also, may include mixed residential uses, i.e. residential on top of commercial or residential units adjacent to commercial establishments.	50	Commercial and public services
5008 SERVICE STATION – Includes gasoline service stations and associated convenience store on stand-alone parcels where it is the primary use.	50	Commercial and public services
5009 OTHER RETAIL TRADE AND STRIP COMMERCIAL – Other retail land uses not classified above.	50	Commercial and public services
6000 OFFICE	50	Commercial and public services
6001 OFFICE (HIGH-RISE) – High rise buildings with **more than four stories** containing banking, offices for	50	Commercial and

business and professional services (finance, insurance, real estate), some retail activities and restaurants.		public services
6002 OFFICE (LOW-RISE) – Low rise buildings with **less than five stories** containing banking, offices for business and professional services (finance, insurance, real estate), some retail activities and restaurants.	50	Commercial and public services
6003 GOVERNMENT OFFICE/CIVIC CENTER – Large government office buildings or centers (outside of military reservations) and civic centers, or city halls of local governments. Also includes the Chamber of Commerce buildings and DMV Offices.	50	Commercial and public services
6100 PUBLIC SERVICES	50	Commercial and public services
6101 CEMETERY	50	Commercial and public services
6102 RELIGIOUS FACILITY	50	Commercial and public services
6103 LIBRARY	50	Commercial and public services
6104 POST OFFICE	50	Commercial and public services
6105 FIRE/POLICE/RANGER STATION	50	Commercial and public services
6108 MISSION	50	Commercial and public services
6109 OTHER PUBLIC SERVICES – cultural facilities, museums, art galleries, social service agencies, humane societies, historic sites and observatories.	50	Commercial and public services
6500 HOSPITALS	50	Commercial and public services
6501 UCSD/VA HOSPITAL/BALBOA NAVAL HOSPITAL	50	Commercial and public services
6502 HOSPITAL-GENERAL – Hospitals not included above.	50	Commercial and public services
6509 OTHER HEALTH CARE – Medical centers and buildings or offices, health care services and other health care facilities. Smaller medical offices and facilities may be included within office, strip commercial or other surrounding uses.	50	Commercial and public services
6700 MILITARY USE	60	Military
6701 MILITARY USE – Defense installations; operational facilities; maintenance facilities (non-weapons); research and development; supply and storage (non-weapons); community support facilities and any other military use that does not fall in other categories.	60	Military
6702 MILITARY TRAINING – Academic, operational and combat training facilities; training ranges; and special purpose training ranges.	60	Military
6703 WEAPONS FACILITY – Weapons assembly, maintenance and storage facilities.	60	Military
6800 SCHOOLS	50	Commercial and public services
6801 SDSU/CSU SAN MARCOS/UCSD	50	Commercial and public services
6802 OTHER UNIVERSITY OR COLLEGE	50	Commercial and public services
6803 JUNIOR COLLEGE – Includes trade or vocational schools.	50	Commercial and public services
6804 SENIOR HIGH SCHOOL	50	Commercial and public services
6805 JUNIOR HIGH SCHOOL OR MIDDLE SCHOOL	50	Commercial and public services
6806 ELEMENTARY SCHOOL	50	Commercial and public services
6807 SCHOOL DISTRICT OFFICE	50	Commercial and public services
6809 OTHER SCHOOL – Includes adult schools, non-residential day care and nursery schools.	50	Commercial and public services
7200 COMMERCIAL RECREATION	70	Recreation
7201 TOURIST ATTRACTION – Sea World, Zoo, and Wild Animal Park, Legoland.	70	Recreation
7202 STADIUM/ARENA – Sports Arena, San Diego Stadium, and Petco Park.	70	Recreation
7203 RACETRACK – Del Mar, San Luis Rey Downs.	70	Recreation

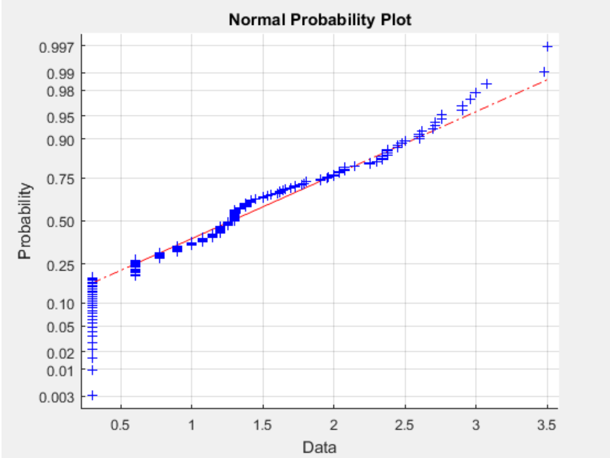
7204 GOLF COURSE – Public and private golf courses.	70	Recreation
7205 GOLF COURSE CLUBHOUSE – Clubhouses, swimming and tennis facilities and parking lots associated with the golf course.	70	Recreation
7206 CONVENTION CENTER – Centre City, Embarcadero.	70	Recreation
7207 MARINA – Includes marinas such as Oceanside Harbor, Quivira Basin, Shelter Island, Harbor Island, Embarcadero and Chula Vista marina.	70	Recreation
7208 OLYMPIC TRAINING CENTER – Olympic Training Center in Chula Vista	70	Recreation
7209 CASINO – Gambling establishments, typically located on Indian Reservations.	70	Recreation
7210 OTHER RECREATION-HIGH – High intensity uses primarily in urban areas. Drive-in theaters, fitness clubs, boys/girls clubs, YMCA's, swim clubs, and stand-alone movie theaters. Also includes tennis clubs without golf, rodeo grounds and senior recreation centers.	70	Recreation
7211 OTHER RECREATION-LOW – Campgrounds and other low intensity recreation. Includes public and private primitive and developed camping areas for tents and RVs. Also includes camps and retreat centers owned or used by religious organizations, scouting, or YMCA. Other low intensity uses such as rifle ranges are included.	70	Recreation
7600 PARKS	71	Park or Open space
7601 PARK-ACTIVE – Recreation areas and centers containing one or more of the following activities: tennis or basketball courts, baseball diamonds, soccer fields, or swings. Examples are Robb Field, Morley Field, Diamond Street Recreation Center, Presidio Park. Smaller neighborhood parks with a high level of use are also included as active parks.	70	Recreation
7603 OPEN SPACE PARK OR PRESERVE – Wildlife and nature preserves, lands set aside for open space, and parks with limited development and access. Examples are Torrey Pines State Reserve, Penasquitos Canyon Reserve, San Elijo Ecological Preserve, Nature Conservancy properties.	71	Park or Open space
7604 BEACH-ACTIVE – Accessible sandy areas along the coast or major water bodies (San Diego and Mission Bay) allowing swimming, picnicking, and other beach related recreational activities. Usually has parking associated with it.	70	Recreation
7605 BEACH-PASSIVE – Other sandy areas along the coastline with limited parking and access (beaches along cliffs, or near preserves).	71	Park or Open space
7606 LANDSCAPE OPEN SPACE – Actively landscaped areas within residential neighborhoods such as greenbelt areas, hillsides with planted vegetation (trees/shrubs), among others.	71	Park or Open space
7607 RESIDENTIAL RECREATION – Active neighborhood parks that are for the use of residents only such as fenced in areas that may contain pools, tennis and basketball courts, barbecues and a community meeting room.	70	Recreation
7609 UNDEVELOPABLE NATURAL AREA * **(Planned land-use only)** – Undevelopable natural areas that are not part of an established open space park or preserve. Examples are Cleveland National Forest and open space easements around developments.	71	Park or Open space
8000 AGRICULTURE	80	Agriculture
8001 ORCHARD OR VINEYARD	80	Agriculture
8002 INTENSIVE AGRICULTURE – Nurseries, greenhouses, flower fields, dairies, livestock, poultry, equine ranches, row crops and grains.	80	Agriculture
8003 FIELD CROPS – Pasture, fallow.	80	Agriculture
9100 VACANT AND UNDEVELOPED LAND * (Historical and Existing only)		
9101 VACANT	90	Undeveloped land
9200 WATER	91	Water bodies
9201 BAY OR LAGOON	91	Water bodies
9202 INLAND WATER – Lakes, reservoirs and large ponds.	91	Water bodies
9300 INDIAN RESERVATION * (Planned land-use only)	92	Other
9400 PUBLIC/SEMI-PUBLIC * (Planned land-use only)	92	Other
9500 UNDER CONSTRUCTION * (Historical and Existing only)	92	Other
9501 RESIDENTIAL UNDER CONSTRUCTION – Usually located near existing residential developments.	92	Other
9502 COMMERCIAL UNDER CONSTRUCTION – Usually located near existing commercial or residential areas.	92	Other
9503 INDUSTRIAL UNDER CONSTRUCTION – Usually located near existing industrial or commercial developments.	92	Other
9504 OFFICE UNDER CONSTRUCTION – Usually located near existing industrial or commercial developments.	92	Other
9505 SCHOOL UNDER CONSTRUCTION	92	Other
9506 -ROAD UNDER CONSTRUCTION	92	Other
9507 - FREEWAY UNDER CONSTRUCTION	92	Other

9600 SPECIFIC PLAN AREA * (Planned land-use only)	92	Other
9700 MIXED USE * (Planned land-use only)	92	Other

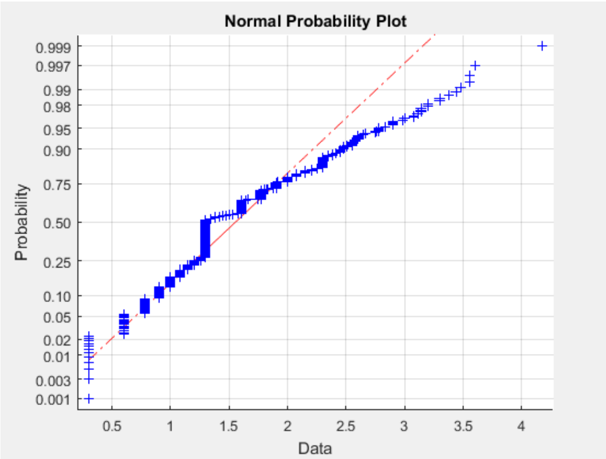
Appendix 2. Normal probability plots for each fecal indicator bacteria group in dry and wet weather at Tourmaline Surfing Park and Ocean Beach. Normally distributed sample data appears along the reference line. Distributions other than normal can introduce curvature in the plot.



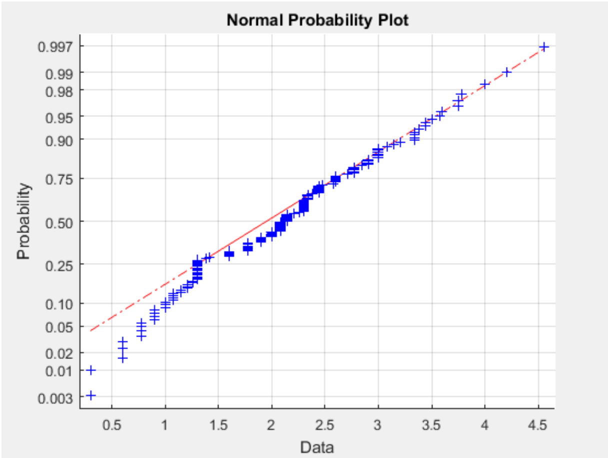
Normal probability plot for Ocean Beach dry weather fecal coliform log10 transformed concentration values.



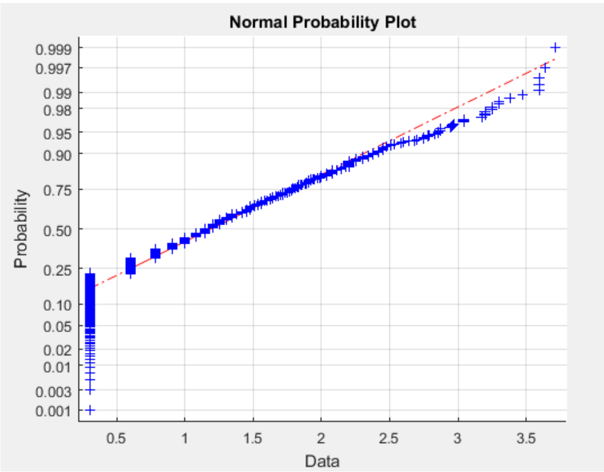
Normal probability plot for Ocean Beach wet weather fecal coliform log10 transformed concentration values



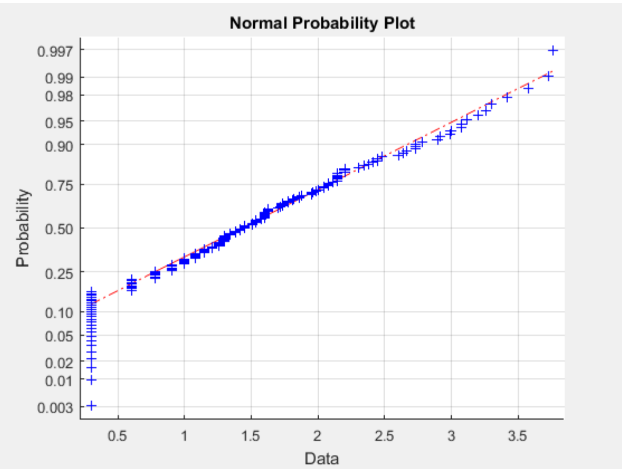
Normal probability plot for Ocean Beach dry weather total coliform log10 transformed concentration values.



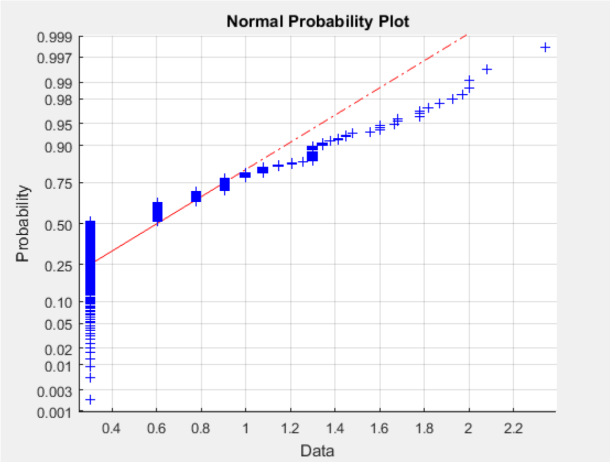
Normal probability plot for Ocean Beach wet weather total coliform log10 transformed concentration values.



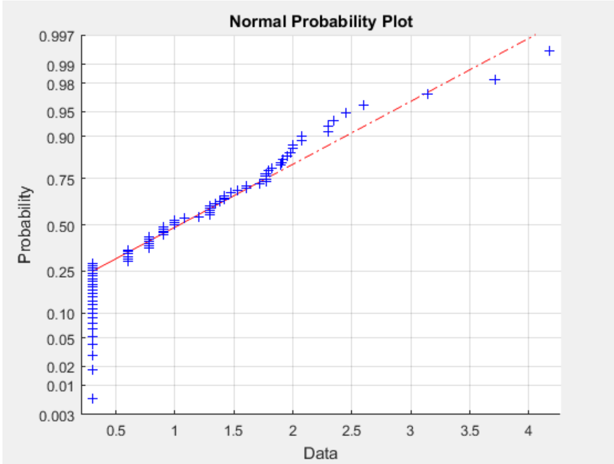
Normal probability plot for Ocean Beach dry weather Enterococcus log10 transformed concentration values.



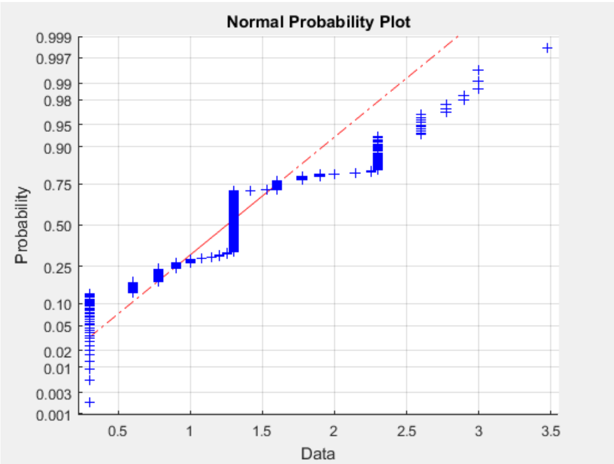
Normal probability plot for Ocean Beach wet weather Enterococcus log10 transformed concentration values.



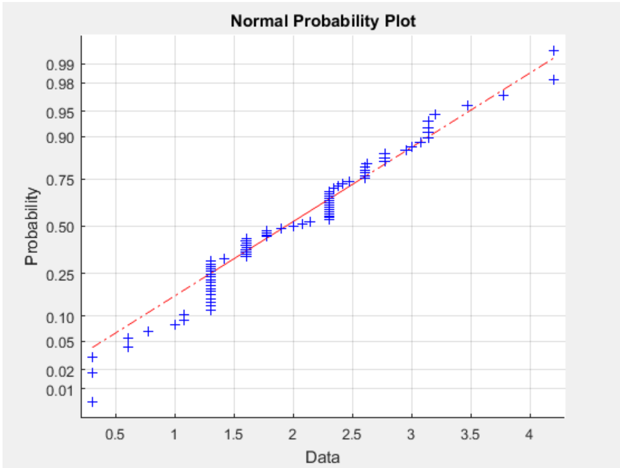
Normal probability plot for Tourmaline Surfing Park dry weather fecal coliform log10 transformed concentration values.



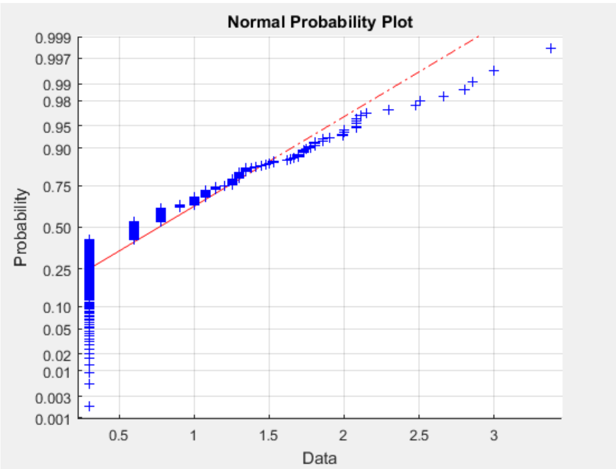
Normal probability plot for Tourmaline Surfing Park wet weather fecal coliform log10 transformed concentration values.



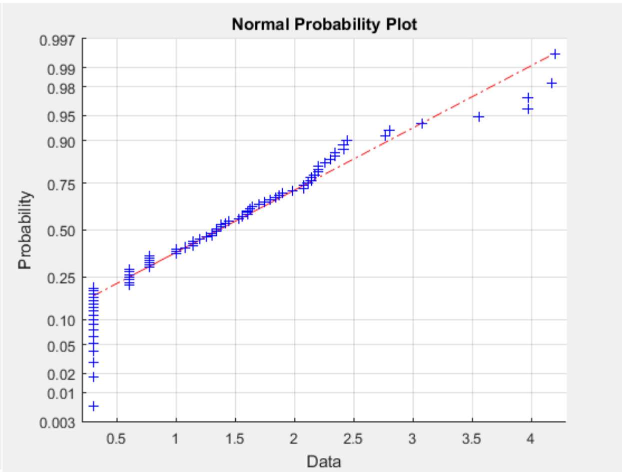
Normal probability plot for Tourmaline Surfing Park dry weather total coliform log10 transformed concentration values.



Normal probability plot for Tourmaline Surfing Park wet weather total coliform log10 transformed concentration values.

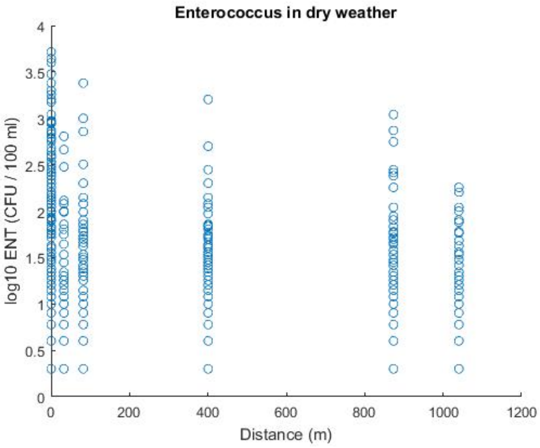


Normal probability plot for Tourmaline Surfing Park dry weather Enterococcus log10 transformed concentration values.

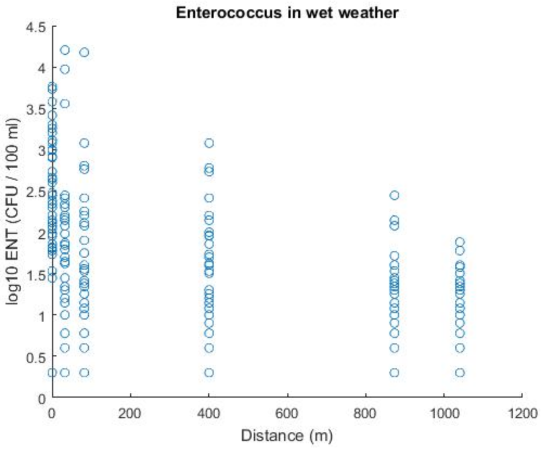


Normal probability plot for Tourmaline Surfing Park wet weather Enterococcus log10 transformed concentration values.

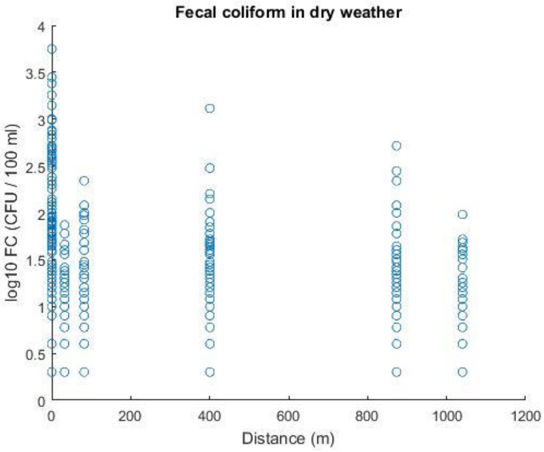
Appendix 3. Logarithm transformed fecal indicator bacteria concentration values at the distance to the closest surface water outfall at Ocean Beach and Tourmaline Surfing Park in dry and wet weather.



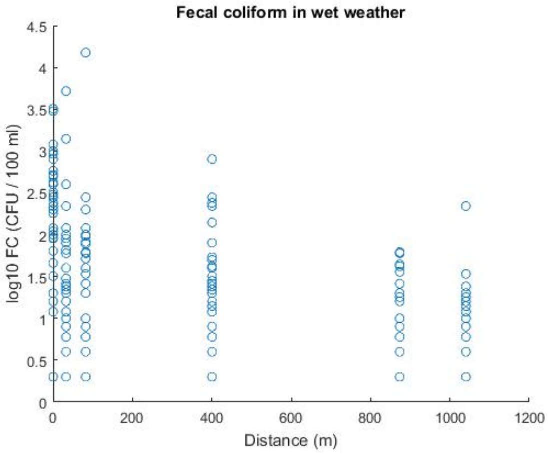
Enterococcus concentration values show decreasing trend with the distance to the closest surface water outfall in dry weather.



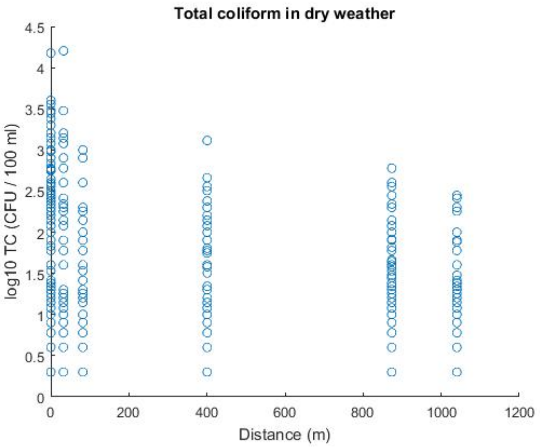
Enterococcus concentration values show decreasing trend with the distance to the closest surface water outfall in wet weather.



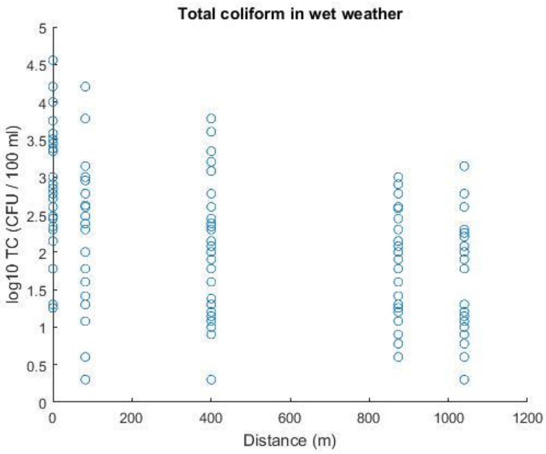
Fecal coliform concentration values show decreasing trend with the distance to the closest surface water outfall in dry weather.



Fecal coliform concentration values show decreasing trend with the distance to the closest surface water outfall in wet weather.

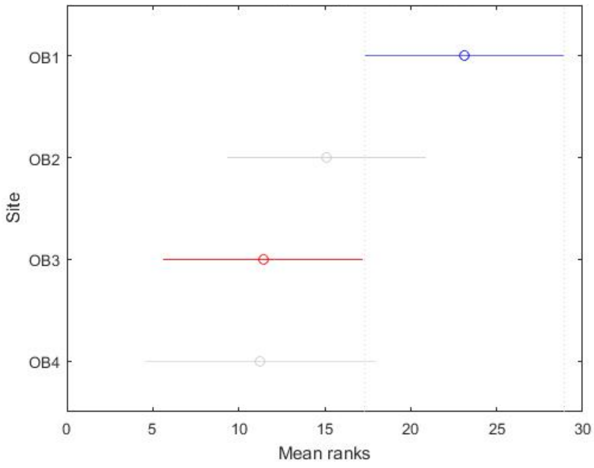


Total coliform concentration values show decreasing trend with the distance to the closest surface water outfall in dry weather.

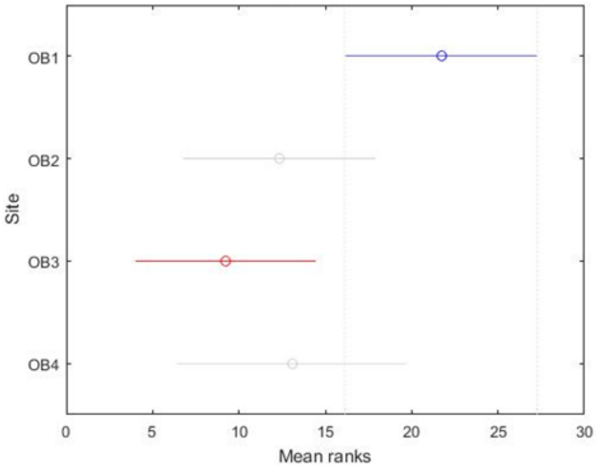


Total coliform concentration values show decreasing trend with the distance to the closest surface water outfall in wet weather.

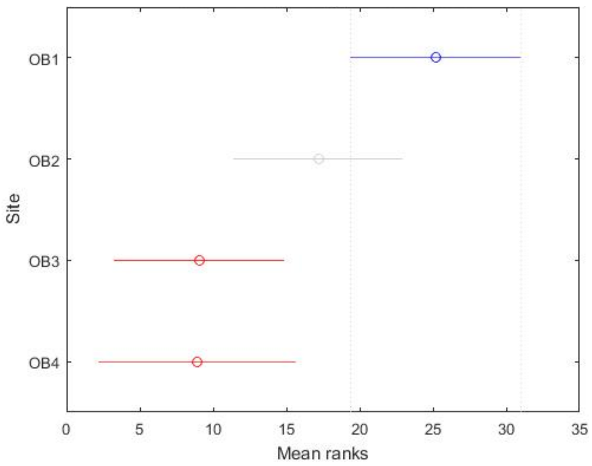
Appendix 4. Dunn – Sidák multiple comparisons test of Enterococcus concentrations between sampling sites OB1, OB2, OB3 and OB4 at Ocean Beach.



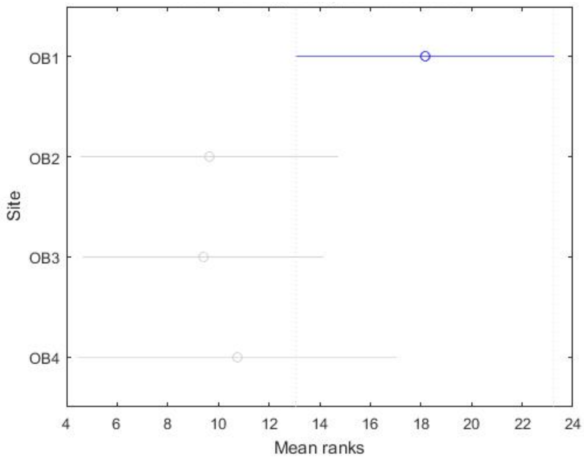
Enterococcus concentrations comparison between sampling sites on day 1 of wet weather. The mean ranks of OB1 and OB3 are significantly different.



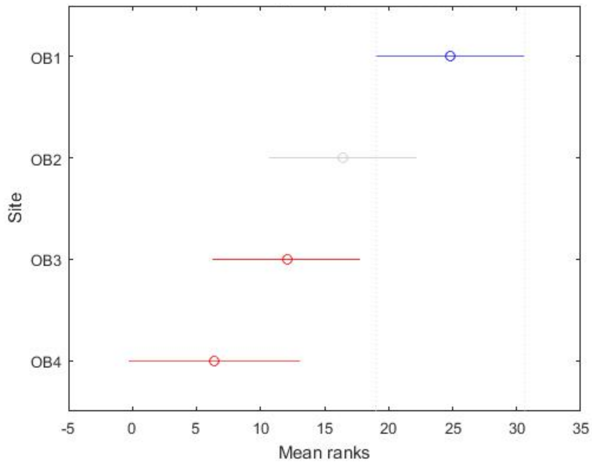
Enterococcus concentrations comparison between sampling sites on day 1 after wet weather. The mean ranks of OB1 and OB3 are significantly different.

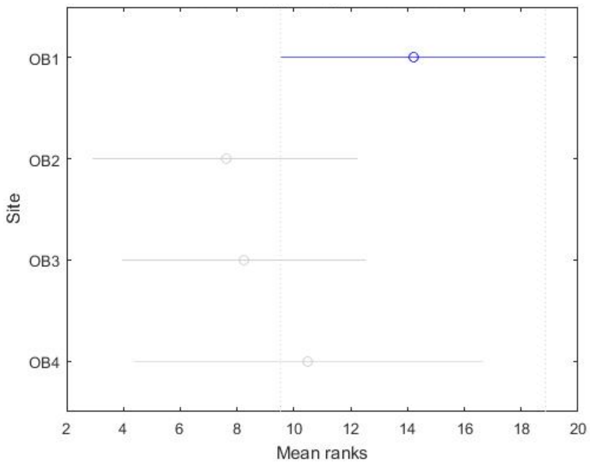


Enterococcus concentrations comparison between sampling sites on day 2 of wet weather. The mean ranks of OB1 are significantly different from the mean ranks of OB3 and OB4.



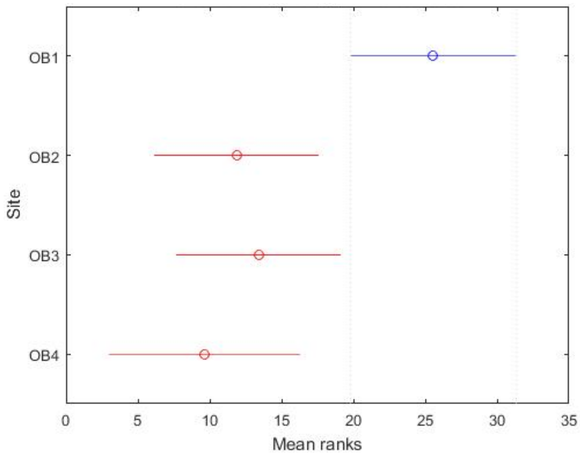
Enterococcus concentrations comparison between sampling sites on day 2 after wet weather. The mean ranks do not significantly differ between sampling sites.

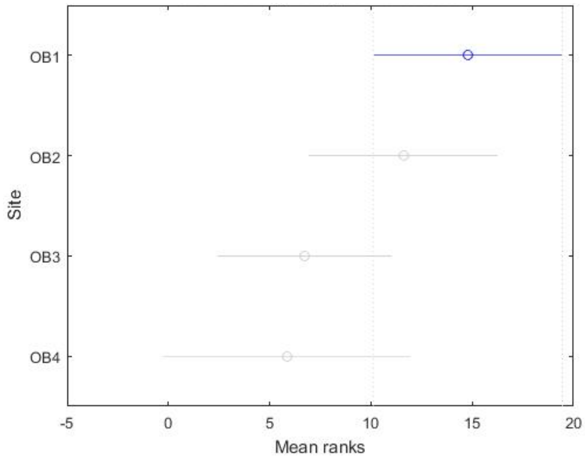




Enterococcus concentrations comparison between sampling sites on day 3 of wet weather. The mean ranks of OB1 are significantly different from the mean ranks of OB3 and OB4.

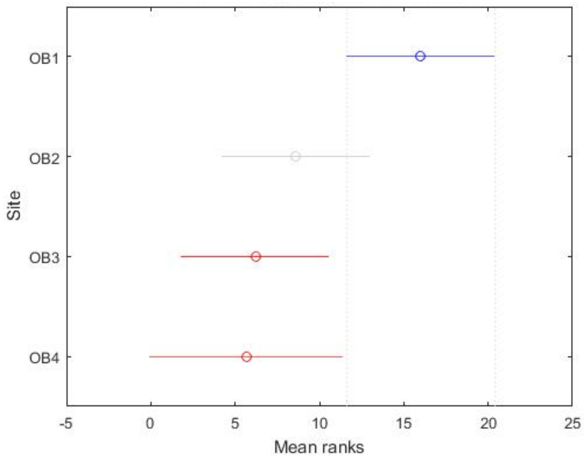
Enterococcus concentrations comparison between sampling sites on day 3 after wet weather. The mean ranks do not significantly differ between sampling sites.

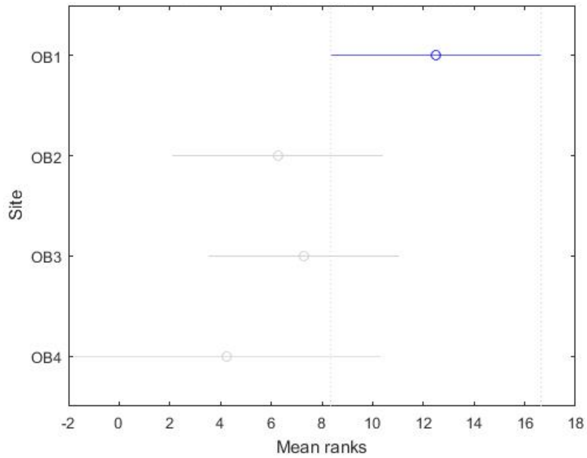




Enterococcus concentrations comparison between sampling sites on day 4 of wet weather. The mean ranks of OB1 are significantly different from the mean ranks of OB2, OB3 and OB4.

Enterococcus concentrations comparison between sampling sites on day 4 after wet weather. The mean ranks do not significantly differ between sampling sites.





Enterococcus concentrations comparison between sampling sites on day 5 of wet weather. The mean ranks of OB1 are significantly different from the mean ranks of OB3 and OB4.

Enterococcus concentrations comparison between sampling sites on day 5 after wet weather. The mean ranks do not significantly differ between sampling sites.

Appendix 5. Matlab procedure for calculation of precipitation that causes significant raise in fecal indicator bacteria concentrations at each sampling site (OB1, OB2, OB3, OB4, T1, T2) for fecal coliform (FC), total coliform (TC) and Enterococcus (ENT).

```
fileID = fopen('PrecResultPresent.csv','w');
fprintf(fileID,'site,fib,lower,upper,h,p,z,d size,w size,mean con d,mean conc w,mean prec d,mean
prec w\n');

fib = {'FC','TC','ENT'};
site = {'OB1','OB2','OB3','OB4','T1','T2'};
for y=1:length(fib)
   for x = 1:length(site)
      fileread = sprintf('preclog10Result%s_%s.csv',fib{1,y},site{x});

% fileread contains column one with bacterial concentration values and column two with matched
% precipitation value for particular site and bacteria on a particular day in each row. Concentrations
% are log10 transformed.

      data = load(fileread);
      conc = data(:,1);
      mm = data(:,2);

      int = 1;
      tr = 0;
      while tr <= 46
         lower = tr;
         d=[];
         w=[];
         for r = 1:length(data)
            if mm(r) == 0
               d = cat(1,d,data(r,[1 2]));
            elseif mm(r) > tr && mm(r) <= tr + int
               w = cat(1,w,data(r,[1 2]));
            end
         end
         dsize = length(d);
         wsize = length(w);
         if isempty(w)
            tr = tr + 1;
            continue
         end
         [p,h,stats] = ranksum(d(:,1),w(:,1),'Tail','left');
         zval=stats.zval;
         if tr == 46
           if h == 0
              if int == 47
                 upper = tr+1;
                 break;
              end
```

```
            int = int + 1;
            tr = 0;
            continue
          end
          upper = tr+1;
          break;
        elseif h == 1
           if wsize < 8
              int = int + 1;
              tr = 0;
              continue
           end
           upper = tr + int;
           break;
        end
        tr = tr + 1;
     end
     mcd = mean(d(:,1));
     mcd = 10^mcd;
     mpd = geomean(d(:,2));
     mcw = mean(w(:,1));
     mcw = 10^mcw;
     mpw = geomean(w(:,2));


fprintf(fileID,'%s,%s,%d,%d,%d,%d,%d,%d,%d,%d,%d,%d,%d\n',site{x},fib{1,y},lower,upper,h,p,zval,ds
ize,wsize,mcd,mcw,mpd,mpw);
   end
end
fclose(fileID);
```

Appendix 6. Enterococcus geometric mean (GM) concentrations for sampling sites at Tourmaline Surfing Park (T1, T2) and Ocean Beach (OB1, OB2, OB3, OB4) for each of the first five days of wet weather (storm), and the first five days of dry weather following wet weather (after storm).

Storm	*Enterococcus* GM CFU / 100 ML						After Storm	*Enterococcus* GM CFU / 100 ML					
Day	T1	T2	OB1	OB2	OB3	OB4	Day	T1	T2	OB1	OB2	OB3	OB4
1	35.15	23.66	220.77	22.08	11.82	15.36	1	35.15	23.66	220.77	22.08	11.82	15.36
2	12.00	18.39	141.92	7.96	8.58	9.85	2	12.00	18.39	141.92	7.96	8.58	9.85
3	8.22	20.74	124.91	31.42	31.20	21.91	3	8.22	20.74	124.91	31.42	31.20	21.91
4	3.89	26.80	132.69	62.98	9.75	6.93	4	3.89	26.80	132.69	62.98	9.75	6.93
5	7.33	8.71	281.43	20.27	18.65	16.39	5	7.33	8.71	281.43	20.27	18.65	16.39
Storm	Fecal coliform GM CFU / 100 ML						After Storm	Fecal coliform GM CFU / 100 ML					
Day	T1	T2	OB1	OB2	OB3	OB4	Day	T1	T2	OB1	OB2	OB3	OB4
1	10.41	10.60	175.06	10.47	5.65	10.05	1	10.41	10.60	175.06	10.47	5.65	10.05
2	9.62	9.72	35.02	4.56	6.99	7.80	2	9.62	9.72	35.02	4.56	6.99	7.80
3	5.21	12.10	105.32	30.22	13.29	10.53	3	5.21	12.10	105.32	30.22	13.29	10.53
4	3.48	4.96	66.96	32.97	4.70	4.23	4	3.48	4.96	66.96	32.97	4.70	4.23
5	3.80	8.24	162.98	15.65	17.22	9.86	5	3.80	8.24	162.98	15.65	17.22	9.86
Storm	Total coliform GM CFU / 100 ML						After Storm	Total coliform GM CFU / 100 ML					
Day	T1	T2	OB1	OB2	OB3	OB4	Day	T1	T2	OB1	OB2	OB3	OB4
1	384.39	393.14	402.86	57.43	43.85	36.99	1	158.00	52.06	435.29	42.84	25.43	37.46
2	139.99	91.22	1858.33	234.33	150.13	132.36	2	28.84	71.09	125.30	11.70	26.65	20.74
3	160.03	75.67	1266.94	450.72	96.26	66.04	3	20.00	200.00	266.49	72.82	57.71	46.81
4	68.62	74.68	948.67	51.33	24.89	41.13	4	5.77	59.85	90.72	60.82	18.23	23.17
5	57.42	28.62	533.26	70.39	39.17	13.39	5	14.80	42.29	371.31	52.64	32.06	40.66

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