MULTIVARIATE STUDY OF FECAL INDICATOR BACTERIA
CONCENTRATION IN THE MALIBU LAGOON AND
NEARBY BEACHES IN MALIBU, CA

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to the Faculty of
California State University, Chico

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in
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Professional Science Master Option

by
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Summer 2011
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# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Publication Rights ................................................................. iii</td>
</tr>
<tr>
<td>List of Tables .................................................................................. vi</td>
</tr>
<tr>
<td>List of Figures ............................................................................... vii</td>
</tr>
<tr>
<td>List of Abbreviations and Definitions ...................... ix</td>
</tr>
<tr>
<td>Abstract ......................................................................................... xii</td>
</tr>
</tbody>
</table>

**CHAPTER**

I. Introduction ..................................................................................... 1

II. Site and Data Description ............................................................ 12

III. Results .......................................................................................... 20

IV. Discussion ...................................................................................... 42

V. Conclusion ....................................................................................... 53

Lagoon Processes ................................................................................... 53
Lagoon/Beach Interaction ...................................................................... 54
Surfrider Storm Processes .................................................................. 54
Model Critique ................................................................................... 55
Dry Season Spikes ............................................................................... 55
1999-2010 Data .................................................................................. 57
Future Study ....................................................................................... 57

References Cited ................................................................................ 59
Appendices

A. Non-Transformed Fecal Coliform Data at Surfrider Beach (2006-2010) Plotted Against Q(Fi) Values to Determine if Data is Normally Distributed Using a Rank Analysis ........................................ 67

B. Log Base 10 Transformed Data at Surfrider Beach (2006-2010) Plotted Against Q(Fi) Values to Determine if the Data is Normally Distributed Using a Rank Analysis ........................................ 69

C. Statistical Test of Differences Between Fecal Indicator Bacteria Concentrations Between the Years of 2006-2010 at Surfrider Beach (DHS 003) ........................................................................ 71

D. Statistical Differences Using Log-Transformed FIB Levels at Surfrider Beach (2006-2010) Between DHS 002, 003, and 004 ........................................ 73

E. Statistical Differences Using Log-Transformed 2006-2010 Fecal Indicator Bacteria Concentrations Between Malibu Pier (DHS 002) and Surfrider Beach (003) .................................................. 75

F. Statistical Differences Using Log-Transformed FIB Levels Between Puerco Beach (DHS 004) and Surfrider Beach (DHS 003) ........................................ 77

G. Statistical Differences Using Log-Transformed FIB Levels Between Puerco Beach (DHS 004) and Malibu Pier Beach (DHS 002) .................................................. 79

H. Statistical Differences Between Enterococci Concentrations at Surfrider (DHS 003), Malibu Pier (DHS 002) and Puerco Beach (DHS 004) for Each Year (2006-2010) ........................................ 81

I. Excerpts from the Correlation Data Matrix for 2008-2009 Surfrider Beach Bacterial Data .................................................. 83

J. Excerpts from the Correlation Data Matrix for 2008-2009 Data from Malibu Lagoon .................................................. 85
<table>
<thead>
<tr>
<th>TABLE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Data Source Organization Table</td>
<td>17</td>
</tr>
<tr>
<td>2. Enterococci Distributions over Year and Site</td>
<td>22</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>FIGURE</th>
<th>PAGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Los Angeles Area Map</td>
<td>2</td>
</tr>
<tr>
<td>2. Map of Sampling Locations at Malibu Lagoon and Surrounding Beaches</td>
<td>13</td>
</tr>
<tr>
<td>3. Enterococci Concentrations at Surfrider Beach in Relation to EPA Regulations</td>
<td>23</td>
</tr>
<tr>
<td>4. Discrepancy Between Fecal Coliform Data Collected by Different Agencies at Surfrider Beach</td>
<td>24</td>
</tr>
<tr>
<td>5. Measured Versus Modeled Fecal Coliform Levels in Relation to Creek Streamflow at Malibu Lagoon</td>
<td>26</td>
</tr>
<tr>
<td>6. Measured Versus Modeled Fecal Coliform Levels Compared to Previous Day’s Precipitation at Malibu Lagoon</td>
<td>27</td>
</tr>
<tr>
<td>7. Measured Versus Modeled Enterococci Levels Compared to Wave Power Density at Surfrider Beach</td>
<td>29</td>
</tr>
<tr>
<td>8. Measured Versus Modeled Enterococci Concentrations Compared to Last 72 Hours of Precipitation at Surfrider Beach</td>
<td>30</td>
</tr>
<tr>
<td>10. Single-Mass Curve of Enterococci at Malibu Pier Beach</td>
<td>32</td>
</tr>
<tr>
<td>11. Single-Mass Curve of Enterococci at Puerco Beach</td>
<td>33</td>
</tr>
<tr>
<td>13. Tidal Fluctuations in the Santa Monical Bay During 2008</td>
<td>35</td>
</tr>
<tr>
<td>FIGURE</td>
<td>DESCRIPTION</td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
</tr>
<tr>
<td>14.</td>
<td>Malibu Lagoon Depth During 2008</td>
</tr>
<tr>
<td>15.</td>
<td>Malibu Lagoon Temperature During 2008</td>
</tr>
<tr>
<td>16.</td>
<td>Precipitation at Malibu Canyon During 2008</td>
</tr>
<tr>
<td>17.</td>
<td>Malibu Creek Discharge Rate During 2008</td>
</tr>
<tr>
<td>18.</td>
<td>Fecal Indicator Bacteria Concentrations at Surfrider Beach During 2008</td>
</tr>
<tr>
<td>19.</td>
<td>Fecal Indicator Bacteria Concentrations at Malibu Lagoon During 2008</td>
</tr>
</tbody>
</table>
LIST OF ABBREVIATIONS AND DEFINITIONS

CDEC: California Data Exchange Center

CFU·100 mL⁻¹: Colony forming units per 100 milliliters of sample. A water sample is plated on an agar substrate and left to incubate for at least 12 h; individual colony growth is counted and represents singular bacteria in the original water sample.

Detection limit: The lowest number of bacteria that an individual test can measure.

DHS 002: Los Angeles County Department of Public Health site abbreviation for Malibu Pier.

DHS 003: Los Angeles County Department of Public Health site abbreviation for Surfrider Beach in front of the Malibu Lagoon.

DHS 004: Los Angeles County Department of Public Health site abbreviation for Puerco Beach.

DOC: Dissolved organic carbon

EC: Escherichia coli. A Gram negative rod-shaped bacterium that is commonly found in the lower intestine of warm-blooded organisms, including sea birds. They are able to survive outside their host for a limited time, which makes them a good fecal indicator.

ENT: Enterococcus faecalis, enterococci. Group of Gram-positive bacterium that lives in the guts of warm-blooded organisms. Can live for a time outside of the host, but does not replicate in the environment.
EPA: Environmental Protection Agency

FC: Fecal coliform bacteria

FIB: Fecal indicator bacteria. Non-pathogenic bacteria that make good markers of fecal contamination, because they can be easily and cheaply tested in the lab, whereas pathogens are difficult to detect.

LACDPH: Los Angeles County Department of Public Health

LACPW: Los Angeles County Public Works

LVMWD: Las Virgenes Municipal Water District

MCW-1: Los Angeles County Public Works site abbreviation for Malibu Lagoon at the Pacific Coast Highway.

MPN·$100 \text{ mL}^{-1}$: Most probable number of bacteria per 100 milliliters of sample. The value is based on bacterial counts from dilutions of the original sample.

Neap tides: Occur when the sun and moon’s gravitational pulls work in opposition, which results in smaller tide fluctuations.

NOAA NDBC: National Oceanic and Atmospheric Administration’s National Data Buoy Center

qPCR: Quantitative Polymerase Chain Reaction

SMBBB TMDL CSMP: Santa Monica Bay Beaches Bacterial Total Maximum Daily Load Coordinated Shoreline Monitoring Plan

Spring tides: Occur when the sun and the moon’s gravitational pull add up so that the high and low tides are maximized and minimized, respectively. Spring tides result in the greatest amount of wave action affecting the beach area.
**TC**: Total coliform

**Tertiary treatment**: Advanced wastewater treatment that removes fine suspended solids and nutrients such as nitrates and phosphates. Uses chlorination to kill pathogens in secondary treated effluent

**TMDL**: Total maximum daily load

**T-RFLP**: Terminal-Restriction Fragment Length Polymorphism

**USGS**: United States Geological Survey

**UVB**: Ultra Violet B
ABSTRACT

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The present study investigates the influences of the natural environment on detected concentrations of fecal indicator bacteria (total and fecal coliform, and *Enterococcus faecalis*) in the Malibu lagoon (Malibu, CA), Surfrider Beach and surrounding beaches. Focused study is needed to identify the underlying factors that influence pollution transport. Data on the following environmental factors that influence bacterial levels were gathered from various water quality agencies: wave height and period, precipitation, tide height, lagoon temperature and depth, sand berm condition, and Malibu creek discharge rate. Surfrider Beach and adjacent Puerco Beach were found to have significantly lower average fecal indicator bacteria than Malibu Pier, also adjacent to Surfrider Beach. High precipitation and elevated wave power density, associated with a storm
event, increased bacterial concentrations at Surfrider Beach. The combination of precipita-
tion and Malibu Creek streamflow caused an increase in fecal indicator bacteria concentra-
tions in Malibu Lagoon. During the winter, high concentrations of bacteria are caused by
urban runoff from high precipitation and to a smaller degree from waves that churn up
bacteria. During the summer, high levels of bacteria occurred during low tides, where
lagoon water contaminated with bacteria flowed into the nearby ocean with the falling tide.
CHAPTER I

INTRODUCTION

Water quality of beaches is a large concern for Southern California. Twenty one different organizations sample 576 sites for an estimated 87,000 tests annually, making up one of the largest beach monitoring systems in the nation. The tests cost Southern California around $3 million annually, which is more than any other part of the nation (Schiff and Weisberg, 2001). Southern California spends such large amounts of money for beach monitoring because it is a popular tourist destination. In 2010, around 25.7 million people visited Los Angeles and spent approximately $13.1 billion dollars. Tourism is the city’s largest and most lucrative industry (Business Wire, 2011). People come from all over the country to visit LA’s white sandy beaches. Clean water along the beaches is important to ensure visitor safety and increase tourist visits, which result in revenue to the region (see Figure 1 for area map).

Malibu is home to the rich and famous and is known for its picturesque cliffs overlooking the ocean. The Malibu Lagoon, located in Los Angeles County, has had recurring problems of fecal contamination for decades (Heal the Bay, 2010). Surfrider Beach is located in front of the Malibu Lagoon, shown in Figure A, and is one of the most notorious contaminated beaches in Los Angeles County (Heal the Bay, 2010). One of the main concerns for beachgoers is the effect on human health associated with swimming in contaminated waters. Fecal material poses a significant health threat to
swimmers in marine waters. Diseases such as ear, nose, throat and gastro-intestinal infections; salmonella poisoning; and even hepatitis can be contracted by contact with contaminated water (US EPA, 2009; Schoen and Ashbolt, 2010). Surfers are particularly at risk, since they are in full contact with the water and often ignore beach closure signs (Stone et al., 2008).

Extensive research has been performed on the subject of fecal contamination in recreational waters as it relates to human health. A comprehensive study performed by the US EPA categorizes the risks of sewage contamination in recreational waters (US EPA, 2009). The work includes a compilation of literature that pertains to illness resulting from exposure to contaminated water. Fecal indicator bacteria are non-pathogenic bacteria naturally found in the intestinal tracts of warm-blooded animals. If a beach is downstream from a known source of human sewage, such as a wastewater
treatment plant, then FIB can be an accurate measurement of potential human illness. However, using current water quality tests such as bacterial cultures, indicator bacteria from wild bird or mammal feces are counted the same as indicator bacteria from human waste. Human sewage may contain human-specific pathogens, which are a greater threat to human health than animal waste. If a recreational beach is not located downstream from a point source of human contamination, such as a wastewater plant, cultured FIB data can be less effective indicators of water-borne pathogens. Animal waste increases the FIB count, yet minimally increases the risk of illness. Pathogens from human sources can survive for extended times in the environment, which makes causes of illness harder to track and increases the threat to human health. A study of Southern California beaches indicates that the greatest risk of illness from recreational water occurs during the summer when beach usage is high (Brinks et al., 2008). According to Heaney et al. (Heaney et al., 2009), contact with or digging in wet sand is positively correlated with gastrointestinal illness and diarrhea. Pathogens are more protected from sunlight inactivation, predation, and harsh marine environments when surrounded by wet sand. Beachgoers playing in the sand can come into contact with harmful bacteria and other pathogens that can lead to gastrointestinal, ear, eye, and throat infections (Heaney et al., 2009).

In an attempt to prevent water-borne illnesses, the EPA has set specific FIB limits for fresh and saline recreational waters. The most commonly tested FIB include total coliform, fecal coliform, *Escherichia coli*, and *Enterococcus faecalis*. Malibu city is within the Los Angeles Regional Board 4 water regulation district. Regulations cover both single sample limits and geometric mean limits (US EPA, 2003). The geometric
means of the FIB densities are based on a statistically sufficient number of samples (usually not less than 5 samples equally spaced over a month). The geometric mean of freshwater samples may not exceed 126 \textit{E. coli}, or 200 fecal coliform. The geometric mean of ocean water samples may not exceed 35 enterococci, 200 fecal coliform or 1,000 total coliform. Single sample levels collected from recreational freshwater may not exceed 235 \textit{E. coli} and 400 fecal coliform per 100 mL. Single sample marine levels may not exceed 104 ENT, 400 FC, or 10,000 TC per 100 mL (US EPA, 2003).

Fecal indicator bacteria die-off rates are strongly influenced by the surrounding environment. Fecal indicator bacteria exhibit lower die-off rates in wet beach sand and ocean sediment, where they are protected from sunlight, harsh marine conditions, and predation (Lee et al., 2006; Mika et al., 2009; Haller et al., 2009; Ferguson et al., 2005). Water chemistry also plays a role in bacterial survivability. One study found a correlation between nutrients delivered by runoff and the survivability of indicator bacteria in aquatic sediments (Toothman et al., 2009). In a man-made concrete channel, they found that FIB levels are strongly correlated with dissolved organic carbon (DOC) concentration in runoff. In particular \textit{Escherichia coli} and \textit{Enterococcus faecalis} bacteria populations exhibited exponential decay when DOC levels were under 7 mg L$^{-1}$ and phosphorus was under 0.07 mg L$^{-1}$ (Surbeck et al., 2010).

Since the study area is located at the mouth of a coastal lagoon, it is important to understand how enteric bacteria used as FIB react in both fresh and saltwater environments. FIB survivability in freshwater and ocean water has been studied widely over the years, because it is a key factor in interpreting water quality data (Carlucci and Pramer, 1959; Kay et al., 2005). Predation by ameba, low nutrient availability, sunlight,
and salinity all decrease FIB survival. Increasing salinity decreases the survival rate of FIB coliform and enterococci. Within 72 to 120 h of transfer from freshwater to temperate seawater FIB counts decrease exponentially to 90% of the initial concentration (Carlucci and Pramer, 1959). Fecal indicator bacteria survival was also shown to decrease linearly in tropical estuarine waters (Bordalo et al., 2002). Sunlight linearly increases the death rate of FIB in saline water. Coliform bacteria have a lower resistance than enterococci to salinity and other environmental factors (Bordalo et al., 2002). High turbidity and suspended solids levels decrease sunlight penetration and increase FIB survival (Kay et al., 2005). The rate of enterococci mortality depends on the UVB intensity and days of exposure. Boehm has measured the die-off rate at $7 \text{ CFU} \cdot d^{-1} \cdot (W \text{ UVB})^{-1} \cdot m^{-2}$ (Boehm et al., 2009).

Enterococci and other FIB are useful indicators of sewage contamination, but FIB measurements do not differentiate between human and animal feces (Kinzelman et al., 2008). FIB only represent endothermic animal feces, such as mammals and birds. For example, a statistical correlation between ENT counts and the genetic markers for human-specific enteric organisms was not observed in the beaches surrounding the Mississippi Delta. Levels of enterococci were thought to be due to natural biological sources rather than sewage contamination (Flood et al., 2011). Thus, the accuracy of ENT and other FIB in predicting human pathogens in the natural environment may be suspect. Faster, more accurate and more effective techniques than bacterial cultures may be more protective of public health. Most water quality agencies use bacterial cultures, that take anywhere from 24-48 h for results. Bacterial levels in recreational waters most likely will have changed during the testing period. To protect the health of people swimming in
recreational waters, faster and more cost-effective ways need to be found for identifying virulent versus harmless microbes (Stewart et al., 2009). However, until new technologies are implemented, enterococci measurements are recommended by the World Health Organization (WHO) as a primary human health parameter for marine recreational water compliance (Kay et al., 2005).

A new technology that is currently used in water quality analysis is quantitative polymerase chain reaction (qPCR). Using qPCR analysis allows scientists to test for certain genes that are specific to human enteric organisms, such as FIB or pathogens (Kephart and Bushon, 2009; Kon et al., 2009; Francy, 2009; Layton et al., 2009). Quantitative PCR differentiates between non-human and human feces but is currently too expensive to use on a regular basis. In a comparison between qPCR and membrane filter culture analyses for enterococci, both methods were found to be reliable, but the qPCR assay was able to measure a higher concentration of bacteria, while the culture method was able to detect bacteria at lower levels (Haugland et al., 2005). Similar results were found in a parallel study (Ferretti et al., 2008). The sensitivity of qPCR is now routinely improved by adding a culture step before the qPCR.

A post-survey of bathers at a contaminated beach used qPCR to link beach microbes to human illnesses (Wade et al., 2010). A similar cohort study found a positive correlation between gastrointestinal illness and fecal indicator organism counts measured by qPCR in marine recreational water (Wade et al., 2010). Unlike FIB, qPCR analysis is a direct indicator of human sewage contamination.

Today, predictive bacterial models are so widely used that the U.S. Geological Survey and the Department of the Interior published a procedure guideline of how to
create an effective predictive indicator bacteria model for recreational waters (Francy and Darner, 2006). Use of the predictive models allows rapidly measured variables to be used to predict beach water quality, rather than slower methods, such as bacterial cultures. Every model is created differently according to the specific environment of the site it describes. The influence of environmental conditions on bacteria, pathogens or human health must be included to create a satisfactory predictive model. In one case, multivariate statistical analysis is performed to identify links between different variables. For example, linkages among natural system parameters and FIB concentrations can be investigated. Descriptive variables, such as precipitation, can be entered into predictive equations.

Serrano et al. (1998) developed a multiple regression model to predict microbial, viral, and Salmonella indicator density according to environmental factors. Environmental variables found significant were time of day (early morning), overcast skies, high and low tides, waves, and flotsam in the water. Highly significant equations could describe the current data, but their predictive capabilities were limited (Serrano et al., 1998).

An artificial neural-network model utilizing water temperature, conductivity, turbidity, rainfall, and time lapse from last rainfall was used to predict the dispersion and concentration of FIB at two San Diego beaches (Li-Ming and Zhen-Li, 2008). Another study in a freshwater environment used precipitation and time since last rain event as predictive variables (Heberger et al., 2008). A similar study found river turbidity, gage height, rainfall and E. coli concentrations all to be statistically and linearly correlated
(Brady 2009). A study performed by Jian and Yuan (2009) used a Bayesian model to numerically predict the TMDL of fecal coliform in an estuary with limited samples.

The Malibu Lagoon has been a topic of study and monitoring due to its continuing water quality issues (Ambrose and Orme, 2000; Heal the Bay, 2010; County of Los Angeles Department of Public Works, 2004, 2008). The hydro-geomorphology of the Malibu Lagoon leads to a large variance in seasonal water volume and a change in depositional environment during the wet and dry seasons. The lagoon is very dynamic and responds quickly to changes in precipitation (Ambrose and Orme, 2000; Schwartz, 1999). Therefore, it is important to study Malibu Lagoon as a unique system to create models specifically for the lagoon.

The management of the Malibu lagoon and nearby beaches has been a topic of controversy. In late 2010, the State Water Regional Control Board approved a ban of onsite wastewater treatment systems in certain parts of the City of Malibu to attempt to improve the microbial quality of the lagoon and nearby beaches (City of Malibu, 2010). In response to the ban, the City of Malibu contacted the US Geological Survey to identify whether the septic tanks surrounding the lagoon were contributing to the fecal contamination at the beaches. In addition to onsite wastewater treatment systems, other possible contamination sources include urban runoff, marine life such as seabirds, and naturally occurring bacteria. Onsite wastewater treatment systems discharge treated effluent, containing bacteria, into the groundwater. For the discharge to affect coastal waters, there must be an interaction between the groundwater and ocean water. The USGS study on the Malibu lagoon conducted between July 21-27, 2009 and during April, 2010, studied whether onsite wastewater treatment system discharge travels
through the groundwater and impacts the local beaches. The study used $^{222}$Radon as a tracer in the groundwater to estimate groundwater discharge to Malibu Lagoon and the near-shore ocean. Fecal indicator bacteria concentrations in groundwater, Malibu Lagoon, and near-shore ocean water were also measured. The study also used bacterial source tracking Terminal-Restriction Fragment Length Polymorphism (T-RFLP) and measured numerous chemicals, such as caffeine, fecal sterols, and detergents, which are wastewater indicators (Izbicki and Martin, 2009; Izbicki, 2010; Izbicki et al., 2011).

Izbicki et al. (2011) reported that the ground water and lagoon water flows into the ocean during low tide periods as the ocean level decreases. He found very high FIB in onsite wastewater treatment systems, but very low FIB in groundwater well samples. In combination with genetic and chemical analyses, Izbicki’s study found that ground water transport from onsite wastewater treatment systems is not a large contributor to FIB in the lagoon (Izbicki et al., 2011).

In addition to studying the influence of wastewater treatment systems, Izbicki studied the oceanic and other natural influences on fecal indicator bacteria concentration in Malibu lagoon and Surfrider beach. The lagoon water and sediment is thought to contain and accumulate large amounts of bacteria and could be a significant source of FIB for Surfrider Beach. During a rising high tide, FIB concentrations were diluted by the influx of saline water over and through the sand berm (Izbicki and Martin, 2009). High tide increased lagoon depth, increased specific conductance of the lagoon water, and diluted lagoon FIB. When the tide was at its highest level, and there was no influx of ocean water into the lagoon, lagoon FIB were shown to slowly increase. Colder, saline ocean water sank to the bottom of the lagoon and contained more FIB than the upper
layer of water (Izbicki and Martin, 2009), which was unexpected. Higher levels of FIB in the ocean water at the bottom of the lagoon indicates that FIB could be released from the lagoon sediment into the water column. Enterococci concentrations dropped during the day, but then rebounded during the night as a result of inactivation by sunlight during the latter part of the day. Izbicki’s study found that the near-shore conductivity was lowest an hour after low tide, which means that the less saline lagoon water flows over or percolates through the sand berm into the ocean due to the decrease of hydrostatic pressure. At the same time, enterococci were at their highest levels in the beach samples, which indicate that the enterococci moved with the lagoon water into the ocean (Izbicki and Martin, 2009: Izbicki, 2010; Izbicki et al., 2011).

The purpose of the present project was to investigate the possible impacts of the oceanic, weather, and physical processes on bacterial concentration over time in and around the Malibu Lagoon. Possible natural influences include the following: tidal fluctuation, solar radiation, precipitation, stream discharge, an open channel between the lagoon and the beach, and wave intensity. The project was initiated so that long-term lagoon and beach and lagoon data could be analyzed and compared to ongoing studies (Izbicki and Martin, 2009: Izbicki, 2010; Izbicki et al., 2011) that involve intensive water quality testing during the summer and spring. In contrast, the present project examines long-term data and multivariate interactions. Ultimately, a better understanding of the natural influences will help predict conditions that could lead to health hazards and non-compliance to regulations.

By examining four and a half years of data, possible trends of FIB concentration could be determined. A combination of long-term trend analysis coupled
with short-term multivariate study was used to identify the natural processes that influence FIB concentrations on a local scale. Most water quality agencies provide sampling data and some agencies provide an interpretation of those data by giving a beach a letter grade (Heal the Bay, 2010). However, a statistical model of the physical processes that influence bacterial concentrations in and around the Malibu Lagoon can identify specific natural processes that effect FIB concentrations.

There were several limitations to the study resulting from the use of data collected for regulatory purposes. Bacterial monitoring can regularly span over years when funding is readily available, such as for the LA County Department of Public Health beach water quality testing. However, much of the time an organization will only have funding for a short-term water quality study. In addition, different organizations collect data at different times of the day and week. Especially for the lagoon data, there were incomplete data records, different collection site names, and different methodologies that limit the usefulness of the long-term record. Another limitation was the inability of FIB to differentiate between human and warm-blooded animal feces. However, since the project was a study of factors that influence bacterial concentration, consistent levels of natural animal contamination was assumed constant and discounted. Natural streams in Southern California do not usually exceed EPA limits (Tiefenthaler et al., 2009). Quantitative PCR analyses may distinguish between animal and human sewage, but the data are not consistently available on a long-term basis. Because of data gaps associated with the lagoon data, focus was shifted to the consistent, long-term beach fecal indicator bacteria.
CHAPTER II

SITE AND DATA DESCRIPTION

The Malibu Valley Sub-basin covers 2.5 km² east of Los Angeles, California and is surrounded by extremely steep canyons and its proximity to the ocean. The study area has a Mediterranean climate, characterized by dry summers and wet winters with an average yearly precipitation of 305-356 mm. Malibu is characterized primarily by residential buildings with some businesses and has less hard-surface urbanization than most of nearby Los Angeles. The basin has many small, intermittent streams that flow into the Malibu Creek. The Malibu Creek ultimately drains into the Malibu Lagoon, that discharges into the Pacific Ocean. During the dry summer season, Malibu Lagoon is separated from the ocean by a natural sand berm that often has an opening to the ocean. Winter flow in Malibu Creek maintains an opening in the berm and allows tidal circulation into the lagoon. Surfrider Beach, located in front of Malibu Lagoon, is the primary focus for studying the interactions between the lagoon and the ocean. Malibu Pier and Puerco Beach were included in the study to compare their bacterial concentrations with those of Surfrider Beach to establish a baseline for the area (see Figure 2).

Surfrider Beach has had a history of bacterial contamination issues (Ambrose and Orme, 2000). Ambrose and Orme (2000) suggested that urban runoff, onsite wastewater treatment systems, and the upstream Tapia wastewater treatment facility
Figure 2. Map of sampling locations at Malibu Lagoon and surrounding beaches. Map of Malibu Lagoon (MCW-1), Malibu Pier (DHS 002), Surfrider Beach (DHS 003), and Puerco Beach (DHS 004) sites. Puerco Beach is located approximately 4.8 km west of the Malibu Lagoon and is not shown on this map (US Geological Survey, The National Map Viewer).

Could be possible contributors to FIB in Malibu near-shore waters. Urban runoff is known to be a large contributor to bacterial contamination at beaches (US EPA, 2003, 2009). Onsite wastewater treatment systems are shown to convey insignificant levels of FIB through the groundwater into the lagoon or the ocean (Izbicki et al., 2011). The Tapia water treatment plant is located upstream of the Malibu Lagoon in the Las Virgenes Municipal water district. The plant has the capacity to discharge up to 60.57 million liters of tertiary-treated wastewater into Malibu Creek per day, but usually only releases an average of 30.95 million L·d⁻¹. As part of their wastewater treatment permit, the Tapia plant disinfects prior to discharge and is able to show no FIB at its discharge point (Las Virgenes Municipal Water District, 2011). Cryptosporidium have been detected right below the discharge point at the Tapia plant and increased levels of Giardia were found below the plant, in the lagoon, and in the surf zone (Ambrose and Orme, 2000). Vibrio
*cholerae*, at a concentration of 60.9 CFU · L⁻¹ have been found at the mouth of the lagoon (Jiang, 2001). However, the Tapia wastewater treatment facility has won multiple awards from the EPA and other agencies, such as the Association of California Water Agencies Environmental Achievement Award for 1989, 1995, and 2003 (Las Virgenes Municipal Water District, 2011). Detected pathogens are not necessarily due to the upstream wastewater facility, as pathogens could result from recreational water users.

The present study explores long-term FIB trends and environmental influences on bacterial concentrations in the Malibu Lagoon and the adjacent ocean. The study presents a review of existing literature related to the lagoon and a statistical available data collected for regulatory purposes. Agencies and departments that performed studies in the Malibu lagoon were identified (Malibu Creek Watershed Council, 2007). Data were obtained from these agencies through personal contacts or through online web searches. Data collected were sorted and organized using Microsoft Excel, and a matrix was made to keep track of data and information needs. Requesting and receiving data is often a lengthy process, as large amounts of data are stored in databases and can take time to retrieve.

Beach and lagoon bacterial data were processed using the most probable number test with 100 mL of sample (MPN·100 mL⁻¹). Table 1 lists agencies and data. Lagoon data were provided by the LVMWD. The data was then prepared as described in the historical data section above. The beach sites (DHS 002, 003, and 004) were sampled weekly by the Los Angeles County Department of Public Health (LACDPH) on a long-term basis (Los Angeles County Department of Public Health, 2010). The Malibu Lagoon (MCW-1) is not sampled on a consistent basis and data were primarily received from
individual studies, such as total maximum daily load (TMDL) reports (CDM, 2007; County of Los Angeles Department of Public Works, 2004, 2008). It must be noted that the beach and lagoon sampling times are offset by one day. LACDIPH Beach sampling is done every Tuesday, whereas the lagoon samples were collected every Wednesday.

The condition of the sand berm (open or closed) in front of the Malibu lagoon was collected by LA county lifeguards and processed by the Las Virgenes Municipal Water District (LVMWD).

Malibu creek discharge rates were received from the U.S. Geological Survey in Excel format. The majority of discharge rates were found on the USGS Instantaneous Data Archive (USGS, 2008).

Wave height and period were retrieved directly from the National Oceanic and Atmospheric Administration’s (NOAA) National Data Buoy Center (NDBC) - Santa Monica Buoy (National Data Buoy Center, 2010). Precipitation data were obtained from the Department of Water Resources California Data Exchange Center (CDEC) (Department of Water Resources, 2010).

Since different agencies may collect water samples at different times and have different analytical protocols, it was important to correctly match the sampling location numbers with the agency that collects at each site. Lagoon data was collected primarily for short-term total maximum daily load (TMDL) studies (Brantley et al., 2005; CDM, 2007; County of Los Angeles Department of Public Works, 2004, 2008). The TMDL studies were available to the public online, so obscure site abbreviations and their corresponding locations were found in the studies. It is important to choose agencies that sample from a consistent location. Data also needed to match up temporally, as well as
spatially. Lagoon bacterial data were collected for short-term projects, and for some years there were no corresponding hydrologic lagoon data. In contrast, Malibu beach sites are consistently sampled weekly and extensive oceanic data, such as tide and wave height, is available for public use. Because more data was available at the Malibu beach sites, the focus of the project was shifted from the lagoon to the beach bacterial data.

After difficulty locating long-term, public-use climatic data at Malibu Lagoon, the California Data Exchange Center (CDEC) was used to find a precipitation measurement center that was close enough to the lagoon to adequately describe its climatic conditions. The closest sampling location to the Malibu lagoon is Malibu Canyon (MCY), located at 185.9 m (610 feet) elevation and approximately 4.8 km (3 miles) upstream (118.7033 lat, 34.0839 long) (Department of Water Resources, 2010). By inputting the site code, type of data needed, and the time reference into the historical data selector, data were retrieved from the database. The data were then copied into Microsoft Notebook and uploaded into Excel.

To characterize wet or dry years, the NOAA State of the Climate Report on drought conditions in California were used (National Environmental Satellite, Data, and Information Service, 2010). Wet months were designated as November through April and dry months were designated as May through October. The seasons are characteristic of the Southern Californian Mediterranean climate. Table 1 summarizes the compiled data used.

Once all the available data had been gathered, the data were formatted for analyses. Difficultly matching data entries with date and time occurred when data were collected on very small time scales. Some data were manually copied and pasted into
<table>
<thead>
<tr>
<th>Site Name or Location</th>
<th>Agency</th>
<th>Type of Samples</th>
<th>Number/Frequency of Samples</th>
<th>Time span</th>
</tr>
</thead>
<tbody>
<tr>
<td>Malibu Lagoon (MCW-1)</td>
<td>LACPW</td>
<td>TC, ENT</td>
<td>89/Weekly</td>
<td>3/11/08-6/8/10</td>
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<tr>
<td>Malibu Lagoon at PCH</td>
<td>LVMWD</td>
<td>Lagoon depth, T, salinity</td>
<td>23,701/15 min</td>
<td>4/19/07-12/16/09</td>
</tr>
<tr>
<td>Surfrider Beach</td>
<td>Heal the Bay-Stream Team</td>
<td>E coli, TC</td>
<td>71/Sporadic weekly</td>
<td>11/10/98-10/6/04</td>
</tr>
<tr>
<td>Surfrider Beach (SMB-MC-2)</td>
<td>SMBBB TMDL CSMP</td>
<td>E coli, TC, ENT</td>
<td>287/Daily</td>
<td>11/1/04-10/29/05</td>
</tr>
<tr>
<td>Surfrider Beach (DHS 003)</td>
<td>LACDPH</td>
<td>FC, TC, ENT</td>
<td>241/Weekly</td>
<td>1/3/06-7/19/10</td>
</tr>
<tr>
<td>Malibu Pier (DHS 002)</td>
<td>LACDPH</td>
<td>FC, TC, ENT</td>
<td>241/Weekly</td>
<td>1/3/06-7/19/10</td>
</tr>
<tr>
<td>Puerco Beach (DHS 004)</td>
<td>LACDPH</td>
<td>FC, TC, ENT</td>
<td>199/Sporadic weekly</td>
<td>1/3/06-7/19/10</td>
</tr>
<tr>
<td>Surfrider Beach</td>
<td>LVMWD</td>
<td>Lagoon sand berm condition</td>
<td>Daily data</td>
<td>3/10/08-11/23/09</td>
</tr>
<tr>
<td>Malibu Creek</td>
<td>USGS</td>
<td>Creek discharge</td>
<td>Hourly data</td>
<td>10/1/07-4/20/09</td>
</tr>
<tr>
<td>Santa Monica Buoy</td>
<td>NOAA NDBC</td>
<td>Wave height and wave period</td>
<td>Data every 15 min</td>
<td>1/1/06-12/31/10</td>
</tr>
<tr>
<td>Malibu Canyon (MCY)</td>
<td>CDEC</td>
<td>Precipitation</td>
<td>Hourly data</td>
<td>1/1/06-12/31/10</td>
</tr>
</tbody>
</table>

*Note:* Includes a list of the location name and site abbreviation, the agency that was primarily in charge of collecting data at each site, the number or frequency of samples collected for each data type and the time span of collection.
Excel, as was the case with FIB data from the LACDPH. To correlate each datum point with the correct time and date, an Excel formula was created that entered Julian dates that increased by 15 min per cell. The same procedure was used for tide and wave data.

Wave power density \( (W \cdot m^{-2}) \) was calculated using the equation,

\[
P_{\text{density}} = \rho_{\text{water}} g H^2 (8T)^{-1},
\]

where \( P_{\text{density}} \) is the wave power density, \( \rho \) is the density of seawater \( [1000 \text{ kg} \cdot \text{m}^{-3}] \), \( H \) is the wave height in m, and \( T \) is the wave period (Vining, 2005). Both the wave height and period were taken from the National Oceanic and Atmospheric Association’s (NOAA) National Data Buoy Center (NDBC) Santa Monica location (National Data Buoy Center, 2010).

An organizational data matrix was generated (see Appendices I and J) to correlate the bacterial data to other data. The data include tide, waves, precipitation, lagoon temperature and depth, creek flow, and sand berm condition. Each temporally corresponding datum entry was searched and copied into the matrix. The estimated beach bacterial data collection time was provided by the Los Angeles County Department of Public Health. It was estimated that most of the samples were collected around 10:00 AM (LACDPH, 2010).

Variables included in this study that were thought to influence bacterial concentrations include wave height and period, precipitation, tide height, lagoon condition, lagoon temperature and depth, and Malibu creek discharge rate. Minitab 16 was used to create a multiple regression model using its general regression tool on the log\(_{10}\) transformed bacterial data (Minitab, 2011). Multiple regression deals with the relative effectiveness of the independent variables as predictors of the dependent variable.
The independent variables were precipitation, wave power density, etc., and the dependent variable was bacterial concentration. A polynomial equation of the form $y_i = \beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i}^2 \ldots + \beta_m x_{m_i}^m + \varepsilon_i$ is created in a multiple regression. ANOVA, F-tests, and T-tests are then used to determine the significance of each independent variable in relation to the dependent variable (Davis, 2002). Minitab 16 outputs included the best-fit polynomial equation and the statistical significance of each variable. A general regression with all of the variables was created and then variables were added or taken away to get the highest descriptive correlation possible with the fewest number of variables.
CHAPTER III

RESULTS

Before performing any statistical analyses, a normal quantile plot was created to determine normality of the data collected at Surfrider Beach. It was determined that a base ten logarithmic transformation was needed to make the data normally distributed (see Appendices A and B, plots of non-transformed and base ten transformed data). Other bacterial data at adjacent beach sites are normally distributed after a log base ten transformation, as well. A single factor, one-way ANOVA was used to statistically test the bacterial concentration differences at Surfrider Beach between the years. Data were combined for all years (2006-2010) at Surfrider Beach, but each bacteria type was tested separately. The single-factor ANOVA showed significant differences for enterococci and fecal coliform concentrations at Surfrider Beach between 2006 and 2010. However, there was no significant difference between total coliform levels between the years. Appendix C contains the F-values of the ANOVA analysis.

Besides testing if there was a concentration difference over time at Surfrider Beach (DHS 003), bacterial levels at Surfrider were also compared with the two adjacent sampled beaches Malibu Pier (DHS 002) and Puerco Beach (DHS 004). Since all three sets of beach data were collected on the same days with the same time span of years, the data should account for wet and dry year differences between the years and allow for a comparison of the differences between the sites. There was a significant difference
between all bacterial category concentrations at the three beach sites (Appendix D). Figure 2 shows actual values that can be compared to statistical results. Surfrider and Puerco Beaches were not found to be statistically different for any fecal indicator bacteria type (Appendix F). However, a statistical difference was found between Surfrider and Malibu Pier beaches’ bacterial concentrations (Appendix E). There were also statistical differences between bacterial concentrations at Puerco and Malibu Pier beaches (Appendix G). Puerco and Surfrider Beach have similar average bacterial concentrations, whereas Malibu Pier Beach has significantly higher average bacterial concentrations (Table 2).

ANOVA analyses were performed to test differences between enterococci levels during specific years at Surfrider, Puerco, and Malibu Pier Beaches. Results of ANOVA analysis showed no significant differences found within 2006 or 2008 enterococci data at any of the beaches. However, a significant difference was found between ENT concentrations during the years 2007, 2009, and 2010 at these beaches (Appendix H). Possible reasons for the differences between these years will be discussed in later sections.

Enterococci concentrations over time listing the maximum, 25th percentile, mean, 75th percentile, and the percentage of sampling days that exceeded regulations (104 enterococci per single sample) are shown in Table 2. The table shows the distribution of enterococci values over time at each site. Numerical analysis showed statistical differences between the beaches, but Table 2 compares the actual values. Malibu Pier ENT concentrations had consistently higher means, 75th percentiles, and exceedances than Surfrider or Puerco Beach.
<table>
<thead>
<tr>
<th>Year</th>
<th>Site</th>
<th>Maximum</th>
<th>First Quartile (25&lt;sup&gt;th&lt;/sup&gt; percentile)</th>
<th>Third Quartile (75&lt;sup&gt;th&lt;/sup&gt; percentile)</th>
<th>Median</th>
<th>Mean</th>
<th>Fraction of Exceedances</th>
</tr>
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<tbody>
<tr>
<td>2006</td>
<td>DHS 002</td>
<td>2,187</td>
<td>10</td>
<td>55</td>
<td>30</td>
<td>142</td>
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<td>2,143</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>96</td>
<td>7/52</td>
</tr>
<tr>
<td></td>
<td>DHS 004</td>
<td>24,192</td>
<td>10</td>
<td>41</td>
<td>10</td>
<td>10</td>
<td>5/52</td>
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<tr>
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<td>3,255</td>
<td>10</td>
<td>63</td>
<td>10</td>
<td>121</td>
<td>7/49</td>
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<tr>
<td></td>
<td>DHS 003</td>
<td>132</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>22</td>
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<td>10</td>
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<td>11,199</td>
<td>10</td>
<td>51</td>
<td>10</td>
<td>449</td>
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<td>264</td>
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<td>10</td>
<td>10</td>
<td>27</td>
<td>1</td>
<td>1/29</td>
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<td>487</td>
<td>10</td>
<td>52</td>
<td>20</td>
<td>70</td>
<td>10/53</td>
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<tr>
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<td>DHS 003</td>
<td>4,611</td>
<td>10</td>
<td>10</td>
<td>10</td>
<td>149</td>
<td>5/53</td>
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<td></td>
<td>DHS 004</td>
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<td>10</td>
<td>10</td>
<td>24</td>
<td>2</td>
<td>2/53</td>
</tr>
<tr>
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<td>10</td>
<td>84</td>
<td>20</td>
<td>225</td>
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<td>10</td>
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<td>0/28</td>
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<td>146</td>
<td>10</td>
<td>10</td>
<td>23</td>
<td>1</td>
<td>1/24</td>
</tr>
</tbody>
</table>

Note: Enterococci concentrations at each site; maximum concentration tested, mean concentration, geometric mean concentration, and number of weeks that exceeded EPA single sample standards over total weeks (104 ENT 100 mL<sup>-1</sup>). Sites include Malibu Pier Beach (DHS 002), Surfrider Beach (DHS 003), and Puerco Beach (DHS 004).
Figure 3 shows the enterococci exceedances of EPA regulations at Surfrider Beach. 10 MPN·100 mL⁻¹ is the detection limit for enterococci. Enterococci exceedances tended to occur sporadically during a season; one week samples were at the detection limit (10 MPN·100 mL⁻¹ enterococci) and then the next week concentrations were at 10,000 MPN·100 mL⁻¹. Enterococci exceedances occurred more often during the wet, winter months than during the summer, which is expected due to higher winter precipitation. However, exceedances also occurred during the dry season, which will be explained in the discussion section.

The total coliform concentrations at Surfrider Beach reported between 1999 and 2010 were a combination of three different datasets from different agencies (Figure
4). Total coliform were used because it was the only bacteria sampled consistently throughout the data sets. The 25th percentile of the data fell near the detection limit of 10

![Figure 4. Discrepancy between fecal coliform data collected by different agencies at Surfrider Beach. Total coliform distribution at Surfrider Beach (DHS 003). The data set between 1999 and 2003 (●) were collected by the Heal the Bay’s Stream Team on a monthly basis, or 13-15 samples a year. The data from 2004-2005 (■) was collected by the Santa Monica Bay Beaches Bacterial TMDL Coordinated Shoreline Monitoring Program on a daily basis. Fifty-two samples were collected in 2004 and 233 in 2005. The data from 2006-2010 (▲) was collected exclusively by the Los Angeles County Department of Public Health and was collected weekly. Shapes represent the mean, or 50th percentile, the upper error bar goes to the highest concentration measured that year and the lower error bar represents the 25th quartile.

MPN·100 mL⁻¹ and the 75th percentile at 84 MPN·100 mL⁻¹ (Figure 4). The mean (50th percentile) of 1999-2005 TC measurements (●, ■) averaged at 3,000 MPN·100 mL⁻¹ enterococci, while the mean of 2006-2010 TC concentrations (▲) averaged 50 MPN·100 mL⁻¹. Further numerical and graphical analyses were not performed on 1999-2005
Surfrider Beach bacterial data sets collected by Heal the Bay and the SMBBB. The Heal the Bay and SMBBB samples were not used because they were collected by different agencies and therefore had different procedures, sampling times, and duration. The only obvious similarities between the 1999-2010 data sets are consistent maximum values. The mean of the data sets are visually different between 1999-2005 and 2006-2010.

Two general regression models were generated, the first using 2006-2010 LACDPH beach data as the dependent variable, and the second using LACPW bacterial lagoon data as the basis of the model. The independent variables that were tested for significance included wave power density (W·m⁻²), precipitation (mm), tide height (m), lagoon temperature (°F) and depth (m), sand berm condition (open or closed), and Malibu creek discharge rate (m³·s⁻¹). The software Minitab 16 was used to produce the multivariate general regression equations. One model addresses fecal coliform concentrations in the Malibu Lagoon and the other describes enterococci levels at Surfrider Beach. ENT and TC were not modeled in Malibu Lagoon due to lack of data. The equation that best describes the fecal coliform trends in the Malibu Lagoon with the available measurements follows:

\[
\text{Lagoon FC} = 2 - (0.06 \times \text{Previous Day’s Precip mm}) + (0.19 \times \text{Daily Streamflow m}^3\text{·s}^{-1}) + (0.13 \times \text{Previous Day’s Precip mm} \times \text{Daily Streamflow m}^3\text{·s}^{-1}).
\] (1)

The previous equation describes the data with an \( R^2 \) value of 0.21, or 21% accuracy.

Figures 5 and 6 show the interaction between the measured fecal coliform data and predicted fecal coliform in Malibu Lagoon, estimated from equation 1, as a function of creek streamflow and previous day’s precipitation data. Figures 5 and 6 illustrate the accuracy of the model equation to predict bacterial concentration values. Measured fecal
coliform levels in Malibu Lagoon were plotted on a graph with bacterial levels predicted by equation 1. Figure 5 plots the interaction between Malibu creek discharge rate against total coliform concentrations. Measured FC concentrations cluster from 20-3,000 MPN·100 mL⁻¹ at a streamflow rate of 0-0.3 (m³·s⁻¹). The descriptive model created values at around 100 MPN·100 mL⁻¹ for discharge rates of 0-1 m³·s⁻¹. Model bacterial levels reached 2,000 MPN·100 mL⁻¹ at discharge rates of 1.3 m³·s⁻¹. Modeled concentrations reflect the average concentrations of measured fecal coliform from streamflow rates of 0-1 m³·s⁻¹. Equation 1 seems to produce more accurate modeled bacteria concentrations at higher streamflow and precipitation levels. A fecal coliform outlier at 6.7 m³·s⁻¹ had a bacterial level of 5,000 MPN·100 mL⁻¹ and is not shown on the
Figure 6. Measured versus modeled fecal coliform levels compared to previous day’s precipitation at Malibu Lagoon. Figure 6 plots previous day’s precipitation mm against estimated (○) and measured (♦) fecal coliform concentrations MPN·100 mL⁻¹. The Y-axis is in logarithmic scale.

Figure 6 shows fecal coliform levels in Malibu Lagoon and modeled fecal coliform concentrations plotted against previous day’s precipitation data. Lagoon FC concentrations clustered from 20-5,000 MPN·100 mL⁻¹ at precipitation levels of 0-1 mm. Predicted bacterial concentrations were estimated at an average of 100-200 MPN·100 mL⁻¹ at 0 mm precipitation. Measured outliers occured at 80 MPN·100 mL⁻¹ and 9.5 mm, and at 3,000 MPN·100 mL⁻¹ and 11.5 mm. Predictive bacterial outliers fell at 65 MPN·100 mL⁻¹ and 9.5 mm, and at 2,300 MPN·100 mL⁻¹ and 11.5 mm. Measured and model data are somewhat sporadic and do not show a clear trend with increasing
precipitation. Modeled bacterial concentrations (from equation 1) become more accurate as precipitation and streamflow increase.

The equation that best describes enterococci levels at Surfrider beach is:

\[
\text{Beach ENT} = 1.2 - (0.05 \times \text{last 72 hour precip mm}) - (0.00008 \times \text{Wave power density W·m}^{-2}) + (0.0001 \times \text{last 72 hour precip mm} \times \text{Wave power density W·m}^{-2}). \tag{2}
\]

The variables of the last 72 h of precipitation mm and wave power density W·m^{-2} were used to describe enterococci concentrations at Surfrider Beach. The previous equation describes enterococci levels with \(R^2 = 0.26\) or 26\% accuracy.

Figure 7 visualizes measured and modeled enterococci levels (created from equation 2) at Surfrider Beach plotted against wave power density (W·m^{-2}) data. Surfrider ENT concentrations clustered from 10-1,000 MPN·100 mL^{-1} at wave power densities of 50-400 W·m^{-2}. Measured data also clustered at 10-30 MPN·100 mL^{-1} with wave power densities of 600-800 W·m^{-2}. One measured data outlier lay at 9,000 MPN·100 mL^{-1} and 700 W·m^{-2}. Predictive bacterial concentrations remained fairly constant at 15 MPN·100 mL^{-1} with increasing wave power (50-900 MPN·100 mL^{-1}). At 100 W·m^{-2}, a modeled enterococci concentration outlier reached 3,500 MPN·100 mL^{-1}, and was not shown on the graph. Predicted ENT concentrations fit average measured ENT concentrations fairly well, but failed to describe high ENT data events.

Figure 8 shows measured enterococci concentrations in Surfrider Beach and modeled ENT concentrations (created using equation 2) plotted against last 72 h precipitation. Surfrider Beach ENT concentrations clustered at 10-2,000 MPN·100 mL^{-1} at precipitation levels of 0-5 mm. Measured and modeled data outliers occurred at 50 MPN·100 mL^{-1} and 35 mm, and at 8,000 MPN·100 mL^{-1} and 40 mm. Modeled
bacterial concentrations (from equation 2) increased from concentrations of 15 MPN·100 mL⁻¹ at 0-2 mm, 30 - 40 MPN·100 mL⁻¹ from 5 - 35 mm, and 4,000 MPN·100 mL⁻¹ at 40 mm of precipitation. Predicted ENT values at precipitation levels above 1 mm were good matches to measured ENT concentrations. Model concentrations clustered around 20 MPN·100 mL⁻¹ at 0 mm.

A single-mass curve graph (Figure 9) was created to compare the enterococci concentrations at Surfrider Beach (DHS 003) over the years 2006 to 2010. 2008 had the highest single-mass curve while 2007 has the lowest. 2007 was a dry precipitation year. The year 2006 had a relatively low curve that increased sharply by about 1,000 MPN·100
Figure 8. Measured versus modeled enterococci concentrations compared to last 72 hours of precipitation at Surfrider Beach. Last 72 hours of precipitation mm against estimated (○) and measured (♦) enterococci concentrations MPN·100 mL⁻¹ at Surfrider Beach. The Y-axis is in logarithmic scale.

mL⁻¹ during August 2006 and then slowly climbed to 5,000 MPN·100 mL⁻¹. The 2007 levels increased very gradually to about 1,000 MPN·100 mL⁻¹ by the end of December 2007. The year 2008 had the largest jump in enterococci levels measured during 2006-2010. In late January 2008, the enterococci concentration increased from around 1,000 MPN·100 mL⁻¹ to 12,000 MPN·100 mL⁻¹, and then remained fairly level throughout the year. The 2009 curve increased by 5,000 MPN·100 mL⁻¹ in February 2009, and then by about 2,000 MPN·100 mL⁻¹ during August 2009. Bacterial data were not collected after late May 2010. Enterococci levels from January to May of 2010 increased very gradually to around 200 MPN·100 mL⁻¹. No data were collected after July 20th 2010.
Figure 9. Single-mass curve of enterococci at Surfrider Beach from 2006-2010. Single-mass curve of enterococci concentration at Surfrider Beach (DHS 003). Each line represents the cumulative enterococci levels throughout the corresponding year. 2006 is denoted as a dashed and dotted line, 2007 is shown as a dotted line, 2008 is illustrated as a dashed line, 2009 is denoted as a solid gray line, and 2010 is shown as a gray dashed line.

Figure 10 shows the enterococci levels at Malibu Pier Beach from 2006-2010. The 2008 single-mass curve is noticeably higher than the rest of the years due to two large increases in ENT concentration in January 2008. The 2008 single-mass curve increased to 10,000 MPN·100 mL⁻¹ on January 1st, then increased to 22,000 MPN·100 mL⁻¹ in the middle of January. Enterococci concentrations slowly increased by 5,000 MPN·100 mL⁻¹ from the middle of January to the end of the year. During 2006, ENT levels increased to 2,500 MPN·100 mL⁻¹ on January 1st, remained constant until May 10th, then increased to 6,000 MPN·100 mL⁻¹. 2007 followed a similar trend except that from January 1st to April 11th, ENT concentrations steadily increased from 0 MPN·100 mL⁻¹ to 2,000 MPN·100 mL⁻¹. 2009 showed a gradual increase over the year of 4,000
Figure 10. Single-mass curve of enterococci at Malibu Pier Beach. Single-mass curve of enterococci concentrations at Malibu Pier Beach (DHS 002) collected by the Los Angeles Department of Public Works. Each line represents the cumulative enterococci levels throughout the corresponding year. 2006 is denoted as a dashed and dotted line, 2007 is shown as a dotted line, 2008 is illustrated as a dashed line, 2009 is denoted as a solid gray line, and 2010 is shown as a gray dashed line.

MPN·100 mL⁻¹. The single-mass curve for 2010 increased by 2,000 MPN·100 mL⁻¹ during the end of January, increased by 3,000 MPN·100 mL⁻¹ on April 11th, and then increased on May 20th by 1,000 MPN·100 mL⁻¹. No data was collected after July 20th.

Figure 11 shows the enterococci concentrations at Puerco Beach (DHS 004) for the years 2006-2010. Data was not collected for the present analysis after June 20th 2010. Data is missing for certain months at this location. The single-mass curves for all years were below 500 MPN·100 mL⁻¹, except for 2006 that exhibited a huge increase of ENT on May 22nd. The enterococci values for the years 2007 to 2010 gradually increased.
Figure 11. Single-mass curve of enterococci at Puerco Beach. Single-mass curve of enterococci concentrations at Puerco Beach (DHS 004) collected by the Los Angeles Department of Public Works. Each line represents the cumulative enterococci levels throughout the corresponding year. Data is missing for some months at DHS 004. 2006 is denoted as a dashed and dotted line, 2007 is shown as a dotted line, 2008 is illustrated as a dashed line, 2009 is denoted as a gray solid line, and 2010 is shown as a gray dashed line.

over the year to end at approximately 1,000 MPN·100 mL$^{-1}$ at the end of December.

However, 2006 exhibited a drastic difference in enterococci levels. From January to early May, there was an increase of 3,000 MPN·100 mL$^{-1}$. Then on May 22$^{nd}$ 2006, there was an increase of 24,000 MPN·100 mL$^{-1}$. Enterococci levels then remained stable from May through December.

The enterococci and fecal coliform concentrations at Malibu Lagoon during 2008 and 2009 are shown in Figure 12. Fecal coliform were included because there are
Figure 12. Single-mass curve of enterococci and fecal coliform in Malibu Lagoon from 2008-2009. Single-mass curve of enterococci levels in the Malibu Lagoon were sampled at the Pacific Coast Highway from 2008-2009. Enterococci concentrations during 2008 are represented by a solid gray line. Enterococci levels during 2009 are symbolized by a solid black line. 2008 fecal coliform concentrations are shown as a dashed black line. Fecal coliform levels during 2009 are represented by a dotted black line.

missing enterococci data entries during 2008. Enterococci and fecal coliform concentrations tended to be positively correlated, even though fecal coliform counts are usually higher than enterococci. Therefore, trends can be seen from total coliform levels even though enterococci data are missing. FC levels increased gradually from February to July 2008 to a level of 5,000 MPN·100 mL⁻¹. Levels were stable until late October, when both FC and ENT levels increase by around 4,000 MPN·100 mL⁻¹. ENT and FC levels increased by about 7,000 MPN·100 mL⁻¹ during February 2009, and then slowly
increased from February to July by 5,000 MPN·100 mL\(^{-1}\). In July 2009, ENT concentrations increased by about 3,000 MPN·100 mL\(^{-1}\) and then stayed constant.

Figures 13-19 depict the natural conditions in the Malibu Lagoon area from March 2008 to December 2008. The graphs were originally created with longer time spans but were considered too lengthy to include. A shorter time span allows for more precise comparison between graphs. The fluctuating black line in Figure 13 represents the tide height (m) in the Santa Monica Bay. Larger fluctuations indicate spring tides, where tide levels vary significantly throughout the day. Smaller oscillations signify neap tides, when tide heights change less.

Figure 14 shows the changes in depth in Malibu Lagoon, denoted by the black line. Large fluctuations in daily lagoon depth indicate that there is water transfer over the
Figure 14. Malibu Lagoon depth during 2008. Malibu Lagoon depth (m) from 3/11/2008 to 6/30/2008, measured by the Las Virgenes Municipal Water District at the Pacific Coast Highway.
sand berm that separates the lagoon and the ocean. Rising and falling tides move water in and out of the lagoon, increasing and lowering the lagoon depth, respectively. The sand berm was open from late March to the middle of April, from late April to early May, and throughout June 2008. An open sand berm resulted in lagoon depths that fluctuated about 1 m with the changing tides. The sand berm was closed during the middle of April (resulting in a lagoon depth around 1.2 m) and throughout May (resulting in a lagoon depth of 1.1 to 1.2 m), as is shown by the lack of depth oscillations. There were some rain events during May (Figure 16), which increased the lagoon depth by increasing runoff into Malibu Creek.

Figure 15, shows the temperature (°F) of Malibu Lagoon. Large fluctuations in lagoon temperature show that ocean water, moved by the tides, is moving into the

![Figure 15. Malibu Lagoon temperature during 2008. Malibu Lagoon temperature (°F) from 3/11/2008 to 6/30/2008, measured by the Las Virgenes Municipal Water District at the Pacific Coast Highway.](image)
lagoon. Colder ocean water mixes with and cools the relatively warm lagoon water. As was the case with lagoon depth, oscillating temperature signifies tidal influence, which occurred when the sand berm was open. The sand berm was closed during the middle of April and throughout May 2008 according to higher and more constant water temperatures (65-80°) during those times.

Figure 16 shows daily precipitation (mm) at Malibu Canyon. The Malibu Canyon weather station was chosen because it was the closest station to the lagoon. Malibu Canyon is approximately 4.8 km upstream of Malibu Lagoon. Small rain events occurred during late March (1 mm), in the beginning of May (0.5 mm) and around the 25th of May (1.5 mm).

Figure 16. Precipitation at Malibu Canyon during 2008. Precipitation (mm) measured by the California Data Exchange Center at the Malibu Canyon climate station approximately 4.8 km upstream from the Malibu Lagoon from 3/11/2008 to 6/30/2008.
Figure 17 depicts the Malibu Creek discharge rate (m$^3$·s$^{-1}$). Discharge rates were high during March 11 (1.1 m$^3$·s$^{-1}$), but dropped to 0.42 m$^3$·s$^{-1}$ during March 26$^{th}$. Discharge rates fluctuated during early April (0.45 – 0.79 m$^3$·s$^{-1}$), which coincided with rain events during that time. Discharge peaked at 0.82 m$^3$·s$^{-1}$ during late April and then decreased to 0.17 m$^3$·s$^{-1}$ on May 1$^{st}$ 2008. Discharge rates increased again during the middle of May (0.37 m$^3$·s$^{-1}$), which matched with precipitation events during the same time. From late May to July, discharge rates slowly decreased from 0.14 to 0.057 m$^3$·s$^{-1}$.

Figure 18 shows the fecal indicator bacteria concentrations at Surfrider Beach from March 11$^{th}$ 2008 to June 30$^{th}$ 2008. Most FIB concentrations hovered around 10-100 MPN·100 ml$^{-1}$, which were below EPA single sample marine recreational water (US EPA
Figure 18. Fecal indicator bacteria concentrations at Surfrider Beach during 2008. Enterococci (▲), fecal coliform (♦) and total coliform (□) concentrations (MPN·100 ml⁻¹) at Surfrider Beach (DHS 003) from 3/11/2008 to 6/30/2008, measured by the Los Angeles Department of Public Health.

2003). However, TC concentrations reached 5,000 MPN·100 ml⁻¹ on May 10th. FC and ENT also increased during May 5th (80 and 20 MPN·100 ml⁻¹, respectively). There was a small rain event on May 7th of 0.5 mm. The lowest bacterial level shown on this graph is at detection limit (10 MPN·100 ml⁻¹). Zero values cannot be shown because the Y-axis is in a logarithmic scale. Enterococci are usually found at the lowest concentrations, followed by fecal coliform, where total coliform are measured at the highest concentrations.

Figure 19 describes the fecal indicator bacteria concentrations at Malibu Lagoon from March 11th 2008 to June 30th 2008. Enterococci concentrations were at or
Figure 19. Fecal indicator bacteria concentrations at Malibu Lagoon during 2008. Enterococci (▲), fecal coliform (♦) and total coliform (□) concentrations at Malibu Lagoon from 3/11/2008 to 6/30/2008, measured by the Los Angeles County Public Works.

below detection limit (10 MPN·100 ml⁻¹) from March 11th to May 25th, and then fluctuated from 0 – 100 MPN·100 ml⁻¹ until June 20th. Total coliform levels fluctuated from 200 – 10,000 MPN·100 ml⁻¹. Fecal coliform concentrations usually fell below total coliform, but above enterococci levels. Fecal coliform concentrations tended to be higher in the lagoon than at Surfrider Beach.
CHAPTER IV

DISCUSSION

During the wet season, fecal indicator bacteria concentrations in Malibu Lagoon are influenced by the previous day’s precipitation and streamflow in Malibu Creek. It is thought that the previous day’s precipitation affected bacterial levels more than daily precipitation because precipitation takes time to flow over the watershed and into the lagoon. However, little or no direct trends could be found between lagoon fecal coliform concentration and previous day’s precipitation in the present study besides a very slight decrease in FC concentrations (Figure 6). Precipitation data is missing for large portions of the model graphs, so it is difficult to interpret direct trends. As daily streamflow from Malibu Creek increases, FC in the lagoon slightly increases as well, which suggests that urban runoff collects in Malibu Creek and flows into the lagoon (Figure 5). Precipitation and elevated creek discharge associated with a storm event, indicated by the interactive term in equation 1, caused an increase in modeled bacteria concentrations. Storm events increase the amount of measured bacteria in the lagoon (Figure 5 and 6). A large rain event would supply enough water to wash pollutants into Malibu Creek. Modeled fecal coliform values reflected only the average of the measured concentrations at low precipitation and streamflow rates, but were able to closely match concentrations at higher precipitation and streamflow levels (Figures 5 and 6). It is expected to see more accurate model descriptions at higher precipitation and streamflow
levels because the higher the descriptive variables, the more influence the variables have on FC concentrations.

Predictive, qualitative models were used to identify processes that affect FIB in Malibu Lagoon and Surfrider Beach. The predictive models’ descriptive variables included precipitation and creek flow, which are negligible during the summer. The regression model for Malibu Lagoon assumes that precipitation and creek streamflow are the only factors influencing bacterial levels at the beach since those were the only two variables used in calculating lagoon FIB. High bacteria levels at Malibu Lagoon, without corresponding rainfall or large waves, cannot be predicted with the current regression models. It is presently impossible to create a model that describes bacterial concentrations in the environment 100% of the time. Natural systems are very complex and many other variables could be contributing factors to bacterial levels.

The models presented here were developed to understand how processes in the Malibu Lagoon and Surfrider Beach interact with FIB concentrations. Regulatory data is not designed to be used for predictive models. The low descriptive capabilities of the models in this study (equations 1 and 2) showed that regulatory data is not sufficient. It is important to test the flexibility and reliability of models, if they are going to be used predicatively. Low predictive capability was most likely caused by high seasonal variability of precipitation levels and lack of more significantly predictive variables. Significant equations for current data, but low predictive capabilities were found in a similar study (Serrano et al., 1998). Models in the present project were mainly influenced by precipitation and were only based on data during 2008 and 2009. The years of 2007, 2008, 2009 were categorized as dry years, while 2006 and 2010 were considered normal.
precipitation years (National Environmental Satellite, Data, and Information Service, 2010). It is possible that during wet to normal precipitation years bacterial levels at Surfrider Beach and Malibu Lagoon are influenced more by precipitation and wave power, whereas dry years are dominated by alternate processes such as tides and sand berm condition. Dry weather dynamics will be discussed in a later section.

Malibu Lagoon influences FIB concentrations at Surfrider Beach. Malibu Lagoon receives a large amount of urban runoff because it is the drainage point for the Malibu sub basin. According to regulatory data, FIB concentrations in the lagoon seemed to be higher and more consistent than beach FIB levels (Figures 9, 12, 18 and 19). However, Malibu Lagoon exhibits variations in FIB levels due to tidal influences (Izbicki and Martin, 2009). Regulatory data used in this project were sampled regularly on a weekly basis, which is too large a time frame to measure hourly and daily fluctuations in the lagoon. When the sand berm is closed the lagoon is protected from the action of the tides and waves, except during high tides, and is primarily influenced by precipitation and creek flow. When the sand berm is open, ocean water flows in and out of the lagoon with the rising and falling tides. Malibu Lagoon is a source of fecal indicator bacteria at Surfrider Beach when lagoon water flows into the ocean. An example of an interaction between Malibu Lagoon and Surfrider Beach occurred May 5th and on May 25th 2008. On May 5th 2008, there were high tidal fluctuations, no precipitation, and the sand berm was open to the ocean (Figures 13-19). The conditions resulted in total coliform concentrations as high as 3,900 MPN·100 mL⁻¹ at Surfrider beach. In contrast, on May 25th 2008 when the sand berm was closed, beach FIB levels were very low even though there was precipitation of 3.3 mm in the previous 72 hours (Figures 13 and 16). The
difference between the two days was the condition of the sand berm and mixing between the ocean and the lagoon (Figures 14 and 15). Bacterial concentrations on Surfrider Beach in the absence of precipitation are influenced by tidal flow in and out of the lagoon (Izbicki et al., 2011).

During the winter, bacterial concentrations on Surfrider Beach are influenced by wave power density and the last 72 h of precipitation. Precipitation above 40 mm increased bacterial concentrations, while levels below 40 mm tended to reflect the average of the measured data (equation 2, Figure 8). It can be concluded that precipitation levels above 40 mm would result in an increase in FIB at Surfrider Beach due to urban runoff from the watershed. It was expected that previous 72 h of precipitation would be more significant than daily precipitation in raising bacterial levels, because surface runoff takes time to collect in the watershed and travel to the ocean. Additionally, it was expected that precipitation would increase the amount of bacteria along the beach by washing urban pollution into the waterways, but small rain events below 40 mm decreased the concentration of bacteria in near-shore waters (Figure 5). Apparently, lighter rain events were unable to wash large amounts of bacteria into the ocean, but resulted in diluted bacterial concentration at the beach.

During the wet season, the action of waves mixes near-shore bacteria at Surfrider Beach with non-contaminated ocean water and therefore lowers the concentration of bacteria along the beach (Figure 7). However, at a wave power density of 700 W·m⁻², a high concentration of 6,000 MPN·100 mL⁻¹ occurred (Figures 7 and 9). Seaweed and marine debris along the high tide line often contains seabird waste, and larger waves can disperse the FIB on the debris into the water (Boehm, 2009). Natural
and anthropogenic bacteria, as well as pathogens, live in beach sands and lagoon sediment (Lee et al., 2006; Mika et al., 2009; Haller et al., 2009; Ferguson et al., 2005). In general, waves mix and dilute the FIB concentrations along the beach, but tides could also have an influence on bacterial concentrations.

In regards to the predictive model, precipitation and wave power interaction at Surfrider Beach was interpreted as a storm event. Precipitation increases and ocean waves usually increase during coastal storms. The combined factors of precipitation and wave power increased concentrations of bacteria in equations 2 (Figures 7 and 8). High amounts of precipitation wash fecal contamination out of the watershed and into the ocean. It is well documented that bacterial concentrations increase as a result of precipitation and subsequent runoff (Li-Ming and Zhen-Li, 2008; Brady and Plona, 2009; Jian and Yuan, 2009). An example of precipitation and wave action contributing to high fecal indicator bacteria occurred on February 17th, 2009 (Appendices I and J). There were no significant rain storms during 2009 until the week prior (February 9th) when it rained 9.4 mm, and the week of February 17 when it rained 11.2 mm. Fecal bacteria accumulated in the watershed over the summer and was washed into the stream during this first large rain storm of the winter rainy season.

The largest increases in enterococci levels in the Surfrider single-mass curve were studied to identify hydrological and oceanographic processes that influence bacteria concentrations (Figure 11). Regression models were based only on data collected during 2008 to 2009, so the models may not account for all of the variables that could influence bacterial concentrations in the lagoon and beach. Single-mass curves were created to analyze the data further. Selections from the data matrix used to correlate the different
variables to bacterial concentration are displayed in Appendix I. The high spike in enterococci levels during January 28, 2008 was caused by a large storm event with powerful waves. The average wave height was 2.52 m, which resulted in a very high wave power density of 1,410 W·m⁻². There was also a high tide (1.126 m) and daily precipitation of 10.7 mm. During January 28th there were no data on whether the sand berm was open or closed, but the sand berm is generally open during the rainy season and would have opened to accommodate increased flow from Malibu Creek.

During February 17th 2009 there were similar storm conditions as in January 28th 2008, which resulted in a similar spike of FIB concentrations. There was a high tide of 1.35 m, high wave power density (737 W·m⁻²), and high daily precipitation (11.2 mm). The storm event was the first of 2009, so pollutants that were deposited in the watershed over the summer were washed into Malibu Creek. Precipitation and wave power density levels were high enough that they most likely contributed to increases of FIB concentrations. The sand berm was reported as being closed at the time, but a high tide and increased precipitation most likely opened it. However, regardless of storm conditions, if there were a large storm event late in the season after most of the watershed contamination had been flushed out by previous storms, one would expect there to be less bacterial pollution in the near-shore waters.

During the summer, increases in enterococci levels were seen during August of 2006 and early September of 2009 (Figure 11). On September 8th, 2009 there was no precipitation, an open sand berm, a low monthly falling tide (0.846 m), and a low wave power density (178 W·m⁻²). Dry weather conditions are not usually associated with high fecal indicator bacteria concentrations at most beaches. However, the low tide enabled
water from the lagoon to flow into the ocean. A similar spike at Surfrider Beach on August 21, 2006, occurred under similar conditions—a low tide (-0.188 m) and normal wave power (396 W·m⁻²), during a dry period with no precipitation (Appendix I). An increase in recreational swimming, and possible fecal shedding, may occur during the hottest months of summer; July through September. Such contamination could be a result of babies or young children with diapers swimming in the water, and may negatively affect water quality (Elmir et al., 2009). Human activity is an inconsistent and unpredictable contributor to beach pollution and could explain several dry weather bacterial spikes.

Statistical analyses were done to show if beach concentrations varied across year or location. Surfrider and Puerco Beach were not found to be statistically different, which was surprising because Surfrider is subject to discharges from Malibu Lagoon. It was expected that Surfrider Beach would have higher overall FIB concentrations (Appendix F). Both Surfrider and Puerco Beach had similar average enterococci concentrations (Table 2) that were usually below EPA regulations (Figure 3). Bacterial data at the two beaches were characterized by low concentrations with infrequent high peaks in concentration.

It was not expected that Malibu Pier would have consistently higher enterococci levels than Surfrider Beach (Appendix E). Malibu Pier had the highest number of EPA water quality exceedances of the three beaches and a 75th quartile ranging from 40-80 during 2006-2010 (Table 2, Figure 3). In contrast, Surfrider and Puerco Beaches only had a 75th quartile ranging from 10-41 MPN·100 mL⁻¹. It is possible that ocean currents could transport bacterial contamination from Malibu Pier to Surfrider
Beach or vice versa since the sites are only 0.48 km apart. The currents in the Santa Monica Bay near Malibu usually flow west to east, but tend to shift direction frequently (Southern California Coastal Ocean Observing System, 2010). Fecal indicator bacteria have a low survival rate in ocean water (Kay et al., 2005; Calucci and Pramer, 1959), so for bacterial transport to be plausible, ocean currents near the shore would have to flow steadily from Surfrider to Malibu Pier Beach.

A statistical difference was also found between ENT concentrations at Puerco and Malibu Pier Beach, where Malibu Pier Beach had higher average concentrations. Several studies have found large variations between marine beaches due to differences in hydro-geomorphology, pollution transport, and contamination sources upstream (Li-Ming and Zhen-Li, 2008; Brady and Plona, 2009; Ambrose and Orme, 2000; Schwartz, 1999). The three beaches in this study are downstream from different sub basins and could be influenced by different pollution sources. Factors that could influence hydro-geomorphology and pollution transport at the three beaches studied include the following: sub basin area and slope, soil and rock type, drainage from natural creeks or storm drains, and differences in land use.

The following section compares bacterial levels during individual years among the three beach sites. No significant differences were found among Surfrider, Puerco, and Malibu Pier Beaches during 2006 (Appendix H). Cumulative enterococci concentrations at both Surfrider and Malibu Pier Beaches rose to around 7,000 MPN·100 mL⁻¹ by the end of December (Figures 11-13). Puerco Beach, however, exhibited a very large spike in enterococci concentration during May 22nd (25,000 MPN·100 mL⁻¹). The rain event of 50 mm during May 22nd 2006, likely contributed to the high level at Puerco
Beach, but Malibu Pier and Surfrider Beach showed no increase in bacterial concentration. Since this rain event was so late in the season, urban runoff was most likely not a large contributor to bacterial contamination during this event. Puerco Beach must have been influenced by a concentrated source of fecal contamination that drained from the nearby Marie Canyon storm drain. The lack of significant differences among the beaches was likely due to the very low bacterial concentrations at all three beaches, except for a few very high enterococci levels.

A significant difference was found between 2007 beach concentrations. Puerco and Surfrider Beach had very low levels of enterococci that were probably caused by extremely low precipitation levels during 2007 (National Environmental Satellite, Data, and Information Service, 2010). However, Malibu Pier had higher enterococci levels during the spring and early summer and finally reached 6,000 MPN·100 mL⁻¹ by December.

It was unexpected that no significant differences were found among enterococci concentrations at Malibu Pier and Surfrider Beaches during 2008. Malibu Pier concentrations were twice as high as Surfrider Beach concentrations. Cumulative increases in ENT concentrations at the two beaches were primarily influenced by one very high concentration during January 28th, 2008 (Figures 11 and 12). Factors that contributed to the ENT spike at Surfrider Beach during January 28th were discussed in a previous section and include high tide, large waves, and a large rain event. Possible reasons that there could be no significant difference among the three beaches could be due to missing data from Puerco Beach (January to August 2008) and the single high concentration on January 28th at Malibu Pier and Surfrider Beach. If the January 28th
samples were removed from the data set, all the beaches would have very low cumulative enterococci values. Although there were clearly significant differences on individual days, on average there was no significant difference among the beaches.

During 2009, a significant difference was found between beach bacterial concentrations. Malibu Pier and Puerco Beach had very low cumulative enterococci levels throughout 2009. At Surfrider Beach however, enterococci spikes were seen in February and August 2009. A large storm event contributed to the spike during February 2009, with high tides and waves mixing lagoon and ocean water during August 2009. High ENT levels were only seen at Surfrider Beach, most likely because Malibu Lagoon was a source of FIB contamination at Surfrider.

Enterococci concentrations were significantly different at all three beaches during 2010. Puerco and Surfrider Beach ENT concentrations were very low, whereas the Malibu Pier single-mass curve increased to 6,000 MPN·100 mL⁻¹ by mid July. Early 2010 had very high precipitation, there were many rain events ranging from 1-22 mm from January to March 2010. Frequent, large rain events washed most of the urban pollution out of the watershed in Malibu. Puerco and Surfrider Beaches are most likely influenced by FIB contamination from smaller areas upstream and ENT concentrations did not increase at these locations. Malibu Pier, however, could be influenced by a different contamination source.

Data collected earlier than 2006 at Surfrider Beach by Heal the Bay (Heal the Bay Stream Team, 2008) and the Santa Monica Bay Beaches Bacterial Total Maximum Daily Load Coordinated Shoreline Monitoring Plan was compared on a year-by-year basis (Figure 4). Heal the Bay only sampled monthly due to budget constraints, so there
are fewer sampling dates from 1999-2003 (Figure 4). The Coordinated Shoreline Monitoring Plan (CSMP) sampled during weekdays from September, 2004, through October, 2005. CSMP measured water coming out of the lagoon exactly at the point where the lagoon water mixed with the surf zone (County of Los Angeles Department of Public Works, 2004). 2006-2010 LACDPH samples could have been taken farther into the surf zone where the lagoon water mixes with ocean water. After comparing average CSMP total coliform levels with average Surfrider Beach and Malibu Lagoon samples, CSMP samples more closely resemble Malibu Lagoon concentrations (ranging from 170-16,000 MPN·100 mL⁻¹). Both CSMP and Malibu Lagoon bacterial concentrations were typically higher than Surfrider samples. The sampling locations for LACDPH and CSMP were described as the same location, but differences in actual sampling location had very large influences on the data. It is important to look very closely at sampling methods, and if at all possible use water quality data from a single agency. It would be more useful if agencies utilized standard analytical methods, but intra-laboratory and inter-laboratory differences would still need to be considered.
CHAPTER V

CONCLUSION

The present study investigates the oceanic, climatic, and physical properties in and around the Malibu Lagoon that drive bacterial concentration over time. Environmental data, such as wave height and period, precipitation, tide height, lagoon temperature and depth, lagoon condition, and Malibu creek discharge, all of which are thought to influence bacterial levels, were gathered from various water quality agencies.

Lagoon Processes

2008-2009 data were used to examine interactions among the various parameters by creating regression models. Factors that affected fecal coliform concentrations in Malibu Lagoon were last 72 hours of precipitation and creek streamflow. Precipitation alone did not seem to have a direct impact on FC concentrations in the lagoon, but overall precipitation slightly decreased fecal coliform concentrations. Increasing creek streamflow rates resulted in increasing bacterial concentrations. A combination of high precipitation and a high creek discharge, namely a storm event, increased bacterial concentrations. Urban runoff fueled by precipitation is thought to be the largest contributor to fecal contamination in the lagoon during the winter.
Lagoon/Beach Interaction

Malibu Lagoon had higher and more constant levels of fecal indicator bacteria throughout the year than Surfrider Beach. Nutrient-rich lagoon water and sediment allows fecal bacteria to survive longer than in the ocean. Lagoon distribution curves gradually increased over time as opposed to suddenly increasing like beach samples. The gradual increase is most likely because the sand berm shelters the lagoon from waves that would normally dilute the bacterial concentrations. When closed, the sand berm separates the lagoon from the ocean and decreases the influx of turbulent, saline ocean waves into Malibu Lagoon. When the sand berm is open and the tide is low, high bacterial concentrations are able to flow out of the lagoon and saline water can enter the lagoon.

Surfrider Storm Processes

Variables that affected FIB levels at Surfrider Beach included precipitation and wave power density. Precipitation over 40 mm increased the concentration of bacteria in near-shore waters. Smaller amounts of precipitation slightly diluted the concentration of bacteria in the near-shore waters, but precipitation data is incomplete so trends are difficult to interpret. Measured bacterial concentrations decreased with increasing wave power densities. Smaller ocean waves mix and dilute contaminated near-shore water with cleaner ocean water and more quiescent waves could allow for tidal influences to have more effect. Storm events with rain above 40 mm and waves higher than 700 W·m$^{-2}$ resulted in an increase of bacteria concentration. Powerful storm waves stir up the sand on the beach and release FIB into the water column. High precipitation associated with storm events wash fecal pollution from the watershed into the lagoon.
Model Critique

The utility or predictive nature of the relationships established from the general regression models was poor. Many estimated values were merely an average of the measured values and were not able to accurately describe overall FIB variation. The general regression model was created only from weekly data collected during 2008 and 2009. The models could have been influenced by unusual precipitation, creek discharge, or wave power levels and may not apply to all years. However, a lack of strong predictive capabilities is not uncommon in multivariable models performed on natural systems. The models may however be useful for indicating conditions when high FIB concentrations could occur.

Dry Season Spikes

Analyses of spikes in bacterial concentrations demonstrated two distinctly different climatic and oceanic scenarios. During the winter, high precipitation, high tides, and large waves resulted in high concentrations of bacteria, which are expected due to increased urban runoff and re-suspension of sediment and FIB into the water column. However, high summer FIB levels were also found during low tides with low wave power, low creek flow, and little to no precipitation. The dry weather events were caused by tidal influences that mixed lagoon and ocean water when the berm was open, thereby increasing FIB levels at Surfrider Beach. Low tide pulls contaminated lagoon water onto Surfrider Beach.

There was no statistical difference in bacterial concentrations at Surfrider and Puerco Beaches between 2006 and 2010. Seventy-five percent of the data were at or near
detection limit at the two beaches. However, Malibu Pier was found to have statistically higher levels of FIB than Surfrider Beach. Malibu Pier also had a higher number of EPA water quality exceedances and a 75th quartile ranging from 40-80 MPN·100 mL⁻¹. Quantitative PCR should be performed at Malibu Pier to identify the source of bacterial contamination.

During 2006 specifically, no significant differences were found among the concentrations of enterococci at Surfrider, Malibu Pier, or Puerco Beach. Surfrider and Malibu Pier had similar cumulative distribution curves, but Puerco had very low values, except for one very high enterococci level. The increase in concentration could be attributed to a pollutant along the beach or from a nearby storm drain. Significant differences were found among FIB concentrations at all three beaches during 2007. Puerco and Malibu Pier Beach cumulative enterococci levels were very low, whereas Surfrider Beach had a high cumulative curve that was most likely caused by contaminated lagoon water flowing onto the beach. 2008 FIB concentrations were not significantly different even though Puerco Beach had very low concentrations, and Surfrider and Malibu Pier beaches had low levels of enterococci throughout the year, except for one extremely high sample. The lack of significant difference was attributed to missing samples at Puerco Beach and the singular high enterococci concentrations at Surfrider and Malibu Pier.

During 2009 there was a significant difference in bacteria at the three beaches. Malibu Pier and Puerco beaches had very low cumulative distribution curves, whereas Surfrider exhibited two large spikes in enterococci. One peak was caused by a storm event and the other could have been caused by either contaminated lagoon water or
recreational swimmers at Surfrider Beach. A significant difference was found between beach concentrations during 2010. Puerco and Surfrider Beach had extremely low enterococci values, whereas the Malibu Pier Beach cumulative distribution curve was much higher. 2010 was a very wet year; urban pollution was most likely flushed out of the watershed, which is why Puerco and Surfrider Beach had low enterococci levels. Puerco and Surfrider Beach are influenced primarily by urban runoff, whereas Malibu Pier contamination is thought to be caused by sea birds or mammals attracted to fishing at the pier, which is independent of the watershed condition.

1999-2010 Data

Data collected by the Santa Monica Bay Beaches Bacterial TMDL during 2004-2005 was distinctly higher than data collected by LACDPH due to differences in sampling. The Santa Monica Bay Bacterial TMDL study data more closely resembled Malibu Lagoon concentrations than Surfrider Beach levels. The SMBB collected samples right at the point where lagoon discharge mixes with the surf zone, whereas the LACDPH must have collected samples farther into the surf zone. The large difference between data was caused by differences in sampling procedures.

Future Study

Further research should be performed to create more accurate predictive models for bacterial levels at Surfrider Beach and Malibu Lagoon. General regression models at the locations examined should differentiate between physical parameters, instead of between years. For instance, future models could test the hypothesis that small levels of precipitation and smaller waves dilute bacterial concentrations, while high levels
of precipitation and larger waves increase bacterial levels at Surfrider Beach. Bacterial data should be segregated and tested individually, for example, between samples collected in dry conditions versus wet conditions, or summer versus winter, or high tide versus low tide. Regulatory data are not specific or frequent enough to create a predictive model. The sediment of Malibu Lagoon should also be tested for FIB enumeration to see if it is a repository of bacteria. Single-mass curve graphs should be created that rank-order bacterial data. Bacterial data could be rank ordered and divided by the total number of samples to get a percentage that could be compared between beach sites. Non-parametric statistical tests should also be considered to use on regulatory bacteria data. Consistent bacterial and hydrological sampling is needed in the Malibu Lagoon for additional long-term analysis. Based on the findings of the study, the following simple recommendations for data collection are made. Firstly, water quality agencies should record and standardize sample collection times. Secondly, data that distinguish between human and other sources of bacteria should be collected. Lastly, sample analyses must follow recommended techniques that ensure inter-laboratory reliability. Collection of samples based on precipitation events, tides, and wave power, instead of the day of week, will greatly increase the probability of understanding how oceanic, weather, and physical processes affect bacterial concentrations in the Malibu Lagoon area.
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Non-transformed fecal coliform data at Surfrider Beach (2006-2010) plotted against q(fi) values to determine if data is normally distributed using a rank analysis.
Log base 10 transformed data at Surfrider Beach (2006-2010) plotted against q(fi) values to determine if the data is normally distributed using a rank analysis.
Statistical test of differences between fecal indicator bacteria concentrations between the years of 2006-2010 at Surfrider Beach (DHS 003).

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<td>2.4101</td>
</tr>
<tr>
<td>Total Coliform</td>
<td>1.6531</td>
<td>2.4101</td>
</tr>
<tr>
<td>Enterococci</td>
<td>2.6145</td>
<td>2.4101</td>
</tr>
</tbody>
</table>
APPENDIX D
Statistical differences using Log-transformed FIB Levels at Surfrider Beach (2006-2010) between DHS 002, 003, and 004.

<table>
<thead>
<tr>
<th>Fecal Indicator Bacteria type</th>
<th>F - value</th>
<th>F – critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Coliform</td>
<td>23.7414</td>
<td>3.0091</td>
</tr>
<tr>
<td>Total Coliform</td>
<td>30.9831</td>
<td>3.0091</td>
</tr>
<tr>
<td>Enterococci</td>
<td>14.4069</td>
<td>3.0091</td>
</tr>
</tbody>
</table>
APPENDIX E
Statistical differences using Log-transformed 2006-2010 fecal indicator bacteria concentrations between Malibu Pier (DHS 002) and Surfrider Beach (003).

<table>
<thead>
<tr>
<th>Fecal Indicator Bacteria type</th>
<th>F - value</th>
<th>F – critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Coliform</td>
<td>25.4234</td>
<td>3.8610</td>
</tr>
<tr>
<td>Total Coliform</td>
<td>42.4771</td>
<td>3.8610</td>
</tr>
<tr>
<td>Enterococci</td>
<td>18.1339</td>
<td>3.8610</td>
</tr>
</tbody>
</table>
Statistical differences using Log-transformed FIB levels between Puerco Beach (DHS 004) and Surfrider Beach (DHS 003).

<table>
<thead>
<tr>
<th>Fecal Indicator Bacteria type</th>
<th>F - value</th>
<th>F – critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Coliform</td>
<td>0.77670</td>
<td>3.8629</td>
</tr>
<tr>
<td>Total Coliform</td>
<td>0.02359</td>
<td>3.8629</td>
</tr>
<tr>
<td>Enterococci</td>
<td>0.22071</td>
<td>3.8629</td>
</tr>
</tbody>
</table>
Statistical differences using Log-transformed FIB levels between Puerco Beach (DHS 004) and Malibu Pier Beach (DHS 002).

<table>
<thead>
<tr>
<th>Fecal Indicator Bacteria type</th>
<th>F - value</th>
<th>F – critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fecal Coliform</td>
<td>39.0681</td>
<td>3.86292</td>
</tr>
<tr>
<td>Total Coliform</td>
<td>42.1595</td>
<td>3.86292</td>
</tr>
<tr>
<td>Enterococci</td>
<td>20.8113</td>
<td>3.86292</td>
</tr>
</tbody>
</table>
Statistical differences between enterococci concentrations at Surfrider (DHS 003), Malibu Pier (DHS 002) and Puerco Beach (DHS 004) for each year (2006-2010).

<table>
<thead>
<tr>
<th>Year</th>
<th>F - value</th>
<th>F – critical value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2006</td>
<td>0.78534</td>
<td>3.0552</td>
</tr>
<tr>
<td>2007</td>
<td>7.6561</td>
<td>3.0617</td>
</tr>
<tr>
<td>2008</td>
<td>2.0364</td>
<td>3.0603</td>
</tr>
<tr>
<td>2009</td>
<td>5.6302</td>
<td>3.0540</td>
</tr>
<tr>
<td>2010</td>
<td>9.5635</td>
<td>3.1303</td>
</tr>
</tbody>
</table>
APPENDIX I
Excerpts from the correlation data matrix for 2008-2009 Surfrider Beach bacterial data

<table>
<thead>
<tr>
<th>Date/Time</th>
<th>TC/100 mL</th>
<th>FC/100 mL</th>
<th>ENT/100 mL</th>
<th>Precip. Inches</th>
<th>Sand Berm Condition</th>
<th>Verified Tide (m)</th>
<th>Tide Category</th>
<th>Wave Height (m)</th>
<th>Wave Period (sec)</th>
<th>Wave power density (W/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/5/08</td>
<td>3,878</td>
<td>52</td>
<td>20</td>
<td>0.00</td>
<td>ND</td>
<td>-0.277</td>
<td>rising</td>
<td>1.11</td>
<td>6.39</td>
<td>236.442</td>
</tr>
<tr>
<td>12/22/08</td>
<td>3,441</td>
<td>134</td>
<td>573</td>
<td>0.00</td>
<td>ND</td>
<td>1.112</td>
<td>falling</td>
<td>0.8</td>
<td>5.34</td>
<td>146.966</td>
</tr>
<tr>
<td>2/17/09</td>
<td>24,196</td>
<td>617</td>
<td>4,611</td>
<td>0.44</td>
<td>closed</td>
<td>1.353</td>
<td>rising</td>
<td>2.01</td>
<td>6.72</td>
<td>737.228</td>
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<tr>
<td>8/10/09</td>
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<td>0.00</td>
<td>open</td>
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<td>falling</td>
<td>0.75</td>
<td>7.03</td>
<td>98.1174</td>
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<tr>
<td>9/8/09</td>
<td>364</td>
<td>345</td>
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<td>open</td>
<td>0.846</td>
<td>falling</td>
<td>0.93</td>
<td>5.95</td>
<td>178.249</td>
</tr>
</tbody>
</table>
Excerpts from the correlation data matrix for 2008-2009 data from Malibu Lagoon

<table>
<thead>
<tr>
<th>Date</th>
<th>TC/100 mL</th>
<th>FC/100 mL</th>
<th>ENT/100 mL</th>
<th>Precip. Inches</th>
<th>Sand berm condition</th>
<th>Verified Tide (m)</th>
<th>Tide Category</th>
<th>Wave Height (m)</th>
<th>Wave Period (sec)</th>
<th>Average Wave Period (sec)</th>
<th>Wave power density (W/m^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5/6/08</td>
<td>800</td>
<td>340</td>
<td>10</td>
<td>0.00</td>
<td>ND</td>
<td>-0.277</td>
<td>rising</td>
<td>1.11</td>
<td>6.39</td>
<td>236.4417</td>
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</tr>
<tr>
<td>12/23/08</td>
<td>2400</td>
<td>230</td>
<td>1350</td>
<td>0.00</td>
<td>ND</td>
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<td>falling</td>
<td>0.8</td>
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<td>146.9663</td>
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</tr>
<tr>
<td>2/17/09</td>
<td>16000</td>
<td>5000</td>
<td>6131</td>
<td>0.44</td>
<td>closed</td>
<td>1.353</td>
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<tr>
<td>8/11/09</td>
<td>130</td>
<td>20</td>
<td>2909</td>
<td>0.00</td>
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<td>0.829</td>
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<tr>
<td>9/8/09</td>
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<td>300</td>
<td>10</td>
<td>0.00</td>
<td>open</td>
<td>0.846</td>
<td>falling</td>
<td>0.93</td>
<td>5.95</td>
<td>178.2493</td>
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</tbody>
</table>