RUNOFF, EROSION, FECAL INDICATOR BACTERIA, AND EFFECTS OF FERAL PIG (*Sus scrofa*) EXCLUSION IN MANOA WATERSHED

A THESIS SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI‘I IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF SCIENCE

IN

NATURAL RESOURCES AND ENVIRONMENTAL MANAGEMENT (ECOLOGY, EVOLUTION, AND CONSERVATION BIOLOGY)

DECEMBER 2009

By

Dashiel O. Dunkell

Thesis Committee:

Gregory L. Bruland, Co-Chairperson

Carl I. Evensen, Co-Chairperson

Creighton M. Litton

Mark Walker
We certify that we have read this thesis and that, in our opinion, it is satisfactory in scope and quality as a thesis for the degree of Master of Science in Natural Resources and Environmental Management.

_____________________________
Co-Chairperson

_____________________________
Co-Chairperson
ACKNOWLEDGEMENTS

I greatly appreciate my advisors Dr. Greg Bruland and Dr. Carl Evensen, for the guidance and assistance they have provided throughout my time at UH Manoa. I thank my thesis committee members, Dr. Creighton Litton and Dr. Mark Walker for their expertise and help with this project. I would like to thank Chad Browning, Ben Cooke, Mark Chynoweth, Sarah Henly-Shepard, Safeeq Khan, Dereck Marciel, Leena Muller, Emily Phares, Anne Quidez, Sarah Stebbing, and Adam Williams for assistance with field and lab work. Thank you to Dr. Christopher Lepczyk for help with statistical analyses. Thank you to Dr. Ali Fares for guidance and use of equipment.

Finally I would like to thank my family for all their love and support. I could never have gotten this far without them.
Abstract

While feral pigs (*Sus scrofa*) have impacted many ecosystems in Hawaii, their effect on soil loss, water quality, and microbial contamination is not well known. This study investigated the processes of runoff and soil erosion in upper forested areas of a Hawaiian watershed and assessed the effects of feral pigs on erosion, runoff, water quality, and pathogen transport. Runoff was collected monthly after storm events from June 2008 to April 2009 at seven sites throughout Manoa watershed on the island of Oahu. Each site consisted of paired runoff plots (5.04 m²) with one plot located inside a fenced pig exclosure and the other located in the adjacent area subject to feral pig activity. Forest composition and structure was measured at each site, including inventory of all tree species, seedling and sapling counts, stand basal area, and stand density. Soil moisture, throughfall, and runoff amount were recorded for each storm event. Runoff volume was quantified and samples were tested for total suspended solids (TSS) and *Enterococcus spp.* bacteria. Ground cover, infiltration, and Enterococci levels in soil were also assessed. Runoff volumes varied from <1 to >128 L over the study period.

Repeated measures ANOVA indicated site by month and site by treatment (fenced versus unfenced plots) interactions for runoff volume. Total SS levels in runoff ranged from <0.01 to 7.05 g L⁻¹. Repeated measures ANOVA indicated a site by month interaction for TSS in runoff. While TSS levels were generally higher in wet season months, this was not consistent across all sites. Enterococci in runoff ranged from <1 to 72,700 CFU 100 mL⁻¹, and while the repeated measures ANOVA indicated a month by site interaction, there were also significantly higher (α = 0.1) levels of from unfenced plots than fenced plots. Enterococci in soil ranged from 24-476 CFU g⁻¹, and differed significantly among
sites though not between fenced and unfenced treatments. According to multiple stepwise regression, TSS in runoff was significantly related to throughfall, soil moisture, and percent coarse woody debris cover, while Enterococci levels in runoff were significantly related to runoff volume.
Table of Contents

Acknowledgements...........................................................................................................III
Abstract.................................................................................................................................IV
List of Tables.......................................................................................................................VIII
List of Figures......................................................................................................................X
List of Abbreviations.........................................................................................................XII

Chapter 1: Introduction and Background..........................................................................1
1.1 Introduction .....................................................................................................................1
1.2 Hawaiian Watersheds, Runoff, and Sediment Transport .............................................2
1.3 Infiltration, Permeability and Throughfall .................................................................4
1.4 Fecal Indicator Bacteria .............................................................................................5
1.5 Feral Pigs and Invasive Species ....................................................................................7
1.6 Study Area: Manoa Watershed ....................................................................................11
1.7 Research Objectives ..................................................................................................16

Chapter 2: Sediment in Runoff .........................................................................................19
2.1 Introduction ...................................................................................................................19
2.2 Site Selection ................................................................................................................20
2.3 Site Layout ...................................................................................................................22
2.4 Runoff Plot Design .......................................................................................................23
2.5 Activation Periods and Runoff Sampling ....................................................................26
2.6 Estimation of Other Environmental Variables ..........................................................27
2.7 Runoff Collection and Analysis ..................................................................................32
2.8 Statistical Analysis .......................................................................................................34
2.9 Soils .............................................................................................................................34
2.10 Throughfall ................................................................................................................37
2.11 Infiltration ...................................................................................................................38
2.12 Species, Stem Density, and Basal Areas of the Study Sites .......................................39
2.13 Ground Cover .............................................................................................................43
2.14 Runoff Volume ............................................................................................................49
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.15 Total Suspended Solids in Runoff</td>
<td>54</td>
</tr>
<tr>
<td>2.16 Correlation of TSS with Environmental Variables</td>
<td>57</td>
</tr>
<tr>
<td>2.17 Discussion</td>
<td>60</td>
</tr>
<tr>
<td>2.18 Conclusions</td>
<td>69</td>
</tr>
<tr>
<td>Chapter 3: Enterococci in Runoff and Soils</td>
<td>72</td>
</tr>
<tr>
<td>3.1 Introduction</td>
<td>72</td>
</tr>
<tr>
<td>3.2 Site Selection</td>
<td>73</td>
</tr>
<tr>
<td>3.3 Site Layout</td>
<td>76</td>
</tr>
<tr>
<td>3.4 Runoff Plot Design</td>
<td>77</td>
</tr>
<tr>
<td>3.5 Activation Periods and Runoff Sampling</td>
<td>78</td>
</tr>
<tr>
<td>3.6 Estimation of Other Environmental Variables</td>
<td>79</td>
</tr>
<tr>
<td>3.7 Runoff Collection and Analysis</td>
<td>84</td>
</tr>
<tr>
<td>3.8 Enterococci in Soils</td>
<td>87</td>
</tr>
<tr>
<td>3.9 Statistical Analyses</td>
<td>87</td>
</tr>
<tr>
<td>3.10 Enterococci in Runoff</td>
<td>88</td>
</tr>
<tr>
<td>3.11 Enterococci in Soils</td>
<td>92</td>
</tr>
<tr>
<td>3.12 Correlation of Enterococci with Environmental Variables</td>
<td>94</td>
</tr>
<tr>
<td>3.13 Discussion</td>
<td>97</td>
</tr>
<tr>
<td>3.14 Conclusions</td>
<td>103</td>
</tr>
<tr>
<td>Chapter 4: Conclusions</td>
<td>107</td>
</tr>
<tr>
<td>4.1 Further Research</td>
<td>109</td>
</tr>
<tr>
<td>4.2 Recommendations for Improvement</td>
<td>110</td>
</tr>
<tr>
<td>Appendix A</td>
<td>112</td>
</tr>
<tr>
<td>Appendix B</td>
<td>114</td>
</tr>
<tr>
<td>Appendix C</td>
<td>117</td>
</tr>
<tr>
<td>Literature Cited</td>
<td>121</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1. Characteristics of seven sites in Manoa watershed</td>
<td>22</td>
</tr>
<tr>
<td>2.2. ANOVA for mean soil moisture</td>
<td>35</td>
</tr>
<tr>
<td>2.3. ANOVA for throughfall means</td>
<td>38</td>
</tr>
<tr>
<td>2.4. Saturated hydraulic conductivity (Ksat) across plots</td>
<td>39</td>
</tr>
<tr>
<td>2.5. Stem density and basal area for the seven sites</td>
<td>40</td>
</tr>
<tr>
<td>2.6. List of canopy tree species observed at the seven sites</td>
<td>41</td>
</tr>
<tr>
<td>2.7. List of mid-story woody plant species observed at the seven sites</td>
<td>41</td>
</tr>
<tr>
<td>2.8. ANOVA for ground cover fenced versus unfenced means among sites</td>
<td>45</td>
</tr>
<tr>
<td>2.9. ANOVA for bare soil fenced versus unfenced means among sites</td>
<td>48</td>
</tr>
<tr>
<td>2.10. ANOVA for runoff amount means</td>
<td>51</td>
</tr>
<tr>
<td>2.11. ANOVA for TSS means</td>
<td>55</td>
</tr>
<tr>
<td>2.12. Spearman correlation matrix for the environmental variables and TSS</td>
<td>60</td>
</tr>
<tr>
<td>3.1. Characteristics of seven sites in Manoa watershed</td>
<td>76</td>
</tr>
<tr>
<td>3.2. ANOVA overall model for Enterococci levels in runoff</td>
<td>88</td>
</tr>
<tr>
<td>3.3. ANOVA for site effects on Enterococci levels in soil</td>
<td>91</td>
</tr>
<tr>
<td>3.4. ANOVA for treatment effects on Enterococci levels in soil</td>
<td>91</td>
</tr>
<tr>
<td>3.5. Spearman correlation values for Enterococci and environmental variables</td>
<td>95</td>
</tr>
<tr>
<td>4. List of canopy tree species at Lyon Arboretum</td>
<td>111</td>
</tr>
<tr>
<td>5. List of canopy tree species at Manoa Cliffs</td>
<td>111</td>
</tr>
<tr>
<td>6. List of canopy tree species at Manoa Falls</td>
<td>111</td>
</tr>
<tr>
<td>7. List of canopy tree species at Pauoa Flats</td>
<td>112</td>
</tr>
<tr>
<td>8. List of canopy tree species at Puu Pia</td>
<td>112</td>
</tr>
<tr>
<td>9. List of canopy tree species at Roundtop</td>
<td>112</td>
</tr>
<tr>
<td>10. List of canopy tree species at Roundtop</td>
<td>112</td>
</tr>
</tbody>
</table>
## List of Figures

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Manoa Stream Network</td>
</tr>
<tr>
<td>1.2</td>
<td>GIS map of land use in the Manoa watershed</td>
</tr>
<tr>
<td>1.3</td>
<td>GIS map with locations of 8 sites</td>
</tr>
<tr>
<td>2.1</td>
<td>GIS map of slope with locations of 8 sites</td>
</tr>
<tr>
<td>2.2</td>
<td>Site layout</td>
</tr>
<tr>
<td>2.3</td>
<td>Photo of runoff plot at Roundtop site</td>
</tr>
<tr>
<td>2.4</td>
<td>Location of seedling and sapling counts</td>
</tr>
<tr>
<td>2.5</td>
<td>Ground cover transects</td>
</tr>
<tr>
<td>2.6</td>
<td>Average soil moisture per month prior to rain event</td>
</tr>
<tr>
<td>2.7</td>
<td>Average soil moisture per site prior to rain event</td>
</tr>
<tr>
<td>2.8</td>
<td>Average soil moisture per plot prior to rain event</td>
</tr>
<tr>
<td>2.9</td>
<td>Average throughfall of rain events per month</td>
</tr>
<tr>
<td>2.10</td>
<td>Average throughfall of rain events per site</td>
</tr>
<tr>
<td>2.11</td>
<td>Seedling occurrence per site</td>
</tr>
<tr>
<td>2.12</td>
<td>Sapling occurrence per site</td>
</tr>
<tr>
<td>2.13</td>
<td><em>P. cattleianum</em> seedling and sapling occurrence</td>
</tr>
<tr>
<td>2.14</td>
<td>Ground cover in fenced versus unfenced runoff plots, averaged among sites</td>
</tr>
<tr>
<td>2.15</td>
<td>Photograph of Waahila Ridge site</td>
</tr>
<tr>
<td>2.16</td>
<td>Ground cover at Waahila Ridge, fenced versus unfenced runoff plots</td>
</tr>
<tr>
<td>2.17</td>
<td>Bare soil ground cover, runoff plots, fenced versus unfenced treatment</td>
</tr>
<tr>
<td>2.18</td>
<td>Ground cover at Roundtop, fenced versus unfenced runoff plots</td>
</tr>
<tr>
<td>2.19</td>
<td>Whole plot ground cover, fenced versus unfenced, average among all sites</td>
</tr>
<tr>
<td>2.20</td>
<td>Average runoff volume in liters per rain event among months</td>
</tr>
<tr>
<td>2.21</td>
<td>Average runoff volume in liters, among sites</td>
</tr>
<tr>
<td>2.22</td>
<td>Average runoff volume in liters, among all plots</td>
</tr>
<tr>
<td>2.23</td>
<td>Runoff volume sums from collection buckets and overflow buckets</td>
</tr>
<tr>
<td>2.24</td>
<td>Average TSS per month</td>
</tr>
</tbody>
</table>
2.25. Average TSS per site ........................................................................................................56
2.26. Average TSS per month fenced vs. unfenced treatment ........................................56
2.27. Average TSS per plot .....................................................................................................57
2.28. Isohyetal rainfall pattern and location of sites in Manoa Watershed .......................63
2.29. Rainfall per month from USGS Kanewai Field rain gauge .....................................63
2.30. Game camera photo of feral pig at Manoa Cliffs .....................................................64
3.1. GIS map of Manoa watershed and locations of 8 study sites ..................................75
3.2. Site layout .....................................................................................................................77
3.3. Location of seedling and sapling plots at each site .....................................................83
3.4. Location of ground cover transects .............................................................................84
3.5. Average Enterococci levels in runoff among months ...............................................89
3.6. Average Enterococci levels in runoff among sites .......................................................90
3.7. Average Enterococci levels in runoff between treatments ..........................................90
3.8. Average Enterococci levels in soils among sites .........................................................92
3.9. Average Enterococci levels in soils between treatments .............................................92
4. Lyon Arboretum ground cover ......................................................................................113
5. Manoa Cliffs ground cover ............................................................................................113
6. Manoa Falls ground cover .............................................................................................114
7. Pauoa Flats ground cover ..............................................................................................114
8. Puu Pia ground cover .....................................................................................................115
<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANOVA</td>
<td>analysis of variance</td>
</tr>
<tr>
<td>BA</td>
<td>basal area</td>
</tr>
<tr>
<td>CFU</td>
<td>colony-forming units</td>
</tr>
<tr>
<td>CV</td>
<td>coefficient of variation</td>
</tr>
<tr>
<td>CWD</td>
<td>coarse woody debris</td>
</tr>
<tr>
<td>DBH</td>
<td>diameter at breast height</td>
</tr>
<tr>
<td>DI</td>
<td>de-ionized</td>
</tr>
<tr>
<td>GIS</td>
<td>geographic information system</td>
</tr>
<tr>
<td>GLM</td>
<td>general linear model</td>
</tr>
<tr>
<td>GPS</td>
<td>global positioning system</td>
</tr>
<tr>
<td>HVNP</td>
<td>Hawaii Volcanoes National Park</td>
</tr>
<tr>
<td>Ksat</td>
<td>saturated hydraulic conductivity</td>
</tr>
<tr>
<td>LYF</td>
<td>Lyon (fenced)</td>
</tr>
<tr>
<td>LYU</td>
<td>Lyon (unfenced)</td>
</tr>
<tr>
<td>MCF</td>
<td>Manoa Cliffs (fenced)</td>
</tr>
<tr>
<td>MCU</td>
<td>Manoa Cliffs (unfenced)</td>
</tr>
<tr>
<td>MFF</td>
<td>Manoa Falls (fenced)</td>
</tr>
<tr>
<td>MFU</td>
<td>Manoa Falls (unfenced)</td>
</tr>
<tr>
<td>MRG</td>
<td>Manoa Rain Gauge</td>
</tr>
<tr>
<td>MSR</td>
<td>multiple stepwise regression</td>
</tr>
<tr>
<td>NRCS</td>
<td>Natural Resources Conservation Service</td>
</tr>
<tr>
<td>PFF</td>
<td>Pauoa Flats (fenced site)</td>
</tr>
<tr>
<td>PFU</td>
<td>Pauoa Flats (unfenced site)</td>
</tr>
<tr>
<td>PPF</td>
<td>Puu Pia (fenced site)</td>
</tr>
<tr>
<td>PPF</td>
<td>Puu Pia (unfenced site)</td>
</tr>
<tr>
<td>rRT</td>
<td>Rough Mountainous Land</td>
</tr>
<tr>
<td>RTF</td>
<td>Round Top (fenced site)</td>
</tr>
<tr>
<td>RTR</td>
<td>runoff-throughfall ratio</td>
</tr>
<tr>
<td>RTU</td>
<td>Round Top (unfenced site)</td>
</tr>
<tr>
<td>TSS</td>
<td>total suspended solids</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WRF</td>
<td>Waahila Ridge (fenced site)</td>
</tr>
<tr>
<td>WRU</td>
<td>Waahila Ridge (unfenced site)</td>
</tr>
</tbody>
</table>
CHAPTER 1: INTRODUCTION AND BACKGROUND

1.1 Introduction

Many watersheds on the island of Oahu are characterized by small drainage basins, primarily trade-wind driven precipitation, and steep, forested headwaters. These upper forested areas are often important conservation lands that, amongst other things, supply irrigation and drinking water to many Hawaii residents. The Manoa watershed on Oahu contains both high mountainous and low-level coastal lands within a relatively small area. While precipitation and stream-flow data from Manoa Valley have been recorded for many years, there remain many unanswered questions about throughfall and runoff dynamics in the watershed. Even less is known about the watershed-scale effects of nonnative feral pigs (Sus scrofa) on processes such as erosion, runoff, and pathogen generation.

In Hawaii, feral pigs have invaded many ecosystems and their effect on water quality and microbial contamination is not well understood. Of the hundreds of invasive species in Hawai‘i, the feral pig has arguably caused the most damage, especially in wet forests (Tomich, 1979). Pig activities such as rooting, browsing, digging, and trampling may lead to a loss of biodiversity, propagation of invasive plants, and increased erosion (Hone and Stone, 1990; Huenneke and Vitousek, 1990; USGS, 2006). As a result of these activities, feral pigs in Hawaii are considered by many to be a threat to native flora and fauna, and minimizing their impact is a top priority for many of Hawaii’s parks and reserves (Hone and Stone, 1989; Huenneke and Vitousek, 1990).

The objectives of this study were to improve our understanding of the processes
of runoff and soil erosion in upper forested areas of a Hawaiian watershed, and to identify the effects pigs have on erosion, runoff, water quality, and pathogen transport. It has been hypothesized that feral pigs not only harm native flora and fauna, but may even adversely impact the health and function of entire watersheds (Noguiera-Filho et al., 2009). Such effects raise important concerns for public health. It is, therefore, imperative to investigate how feral pigs influence runoff, soil loss, and bacteria levels to develop appropriate and effective management practices. The data collected from this project will be of interest to managers, the public, and policy makers. Runoff dynamics in upper forested watersheds in Hawaii are not well understood, and while there is much suspicion about negative impacts of feral pigs on the ecology and function of these areas, there is little hard evidence.

1.2 Hawaiian Watersheds, Runoff, and Sediment Transport

Tropical volcanic island ecosystems, such as the Hawaiian Archipelago, are subject to high erosion and sedimentation hazards and, therefore, are extremely sensitive to the impacts of land use and management (El-Swaify, 2000). Native Hawaiians developed a land management system called the ahupua‘a, which was similar to the modern term ‘watershed’ but also integrated the coastline and inshore and offshore ocean waters. Headwater areas in Hawaii are often located in high-rainfall forested mountains, many of which are conservation areas. The two principal sources of surface water in Hawaiian watersheds are overland runoff following rainfall and groundwater discharge. Overland runoff is typically episodic and varies widely in intensity depending on the type of rain. The volume of direct surface runoff depends on the intensity and persistence of
the rain, as well as the size, geology, and morphology of the drainage basin. Previous research has indicated that forested basins in the Koolau Mountain range on Oahu yield a surface runoff volume equal to about 35% of the rainfall of a moderate to heavy rainstorm (Lau and Mink, 2006).

According to Lau and Mink (2006) the only extant observed data of overland flow water quality in forested areas were obtained for a small area in the drainage basin of Aihualama Stream, a tributary of Manoa Stream. The results from 17 rainfall episodes between September 1974 and March 1975 indicated high organic loads with minimal biodegradation in the fast-moving water. The high total solids were largely suspended (81%). The direct overland flow contained high levels of heavy metals, and would have failed to meet current stream water quality standards. The response of runoff to rainfall on annual and regional bases in Hawaii is usually described as a simple linear equation, \( RO = a' + b'P \), where \( a' \) and \( b' \) are constants, and \( P \) is precipitation (Lau and Mink, 2006). A different correlation for central and southern Oahu gives direct runoff as \( RO = 0.0021P^2 \) (Lau and Mink, 2006).

It is widely accepted that vegetative cover can reduce overland flow, and this has been clearly demonstrated in Hawaiian agricultural soils (Ryder and Fares, 2008). Other permeable Hawaiian soils, even though bare, can absorb high amounts of rainwater before overland flow occurs. Initiation of overland flow on bare soils was investigated with simulated rain in ten different soils series from the Islands of Hawaii and Oahu (Lau and Mink, 2006). Results showed that runoff initiation time varies linearly with antecedent saturation deficit. For wet soil with a deficit of less than 5%, the initiation times were just a few minutes. However, in some cases initiation times were greater than
80 minutes. These long times suggest runoff generated by saturation from below the soil layers, rather than limitation by the infiltration capacity of the soils.

Although surface erosion is a natural process, it is exacerbated by surface disturbance and compaction that reduce soil hydraulic conductivity and break down soil aggregates (Sidle et al. 2006). Historically, soil erosion has been a problem in Hawaii at least since the introduction of exotic ungulates soon after European contact (El-Swaify, 2000; Nogueira-Filho et al., 2009). Sediment transport to a stream depends on numerous factors which vary with respect to climate, vegetation cover, and soil type (Lai and Detphachanh, 2006). Sedimentation has multiple negative impacts that affect watersheds and adjacent coastal areas. These include nutrient influx carried by sediments; damage caused to streams, estuaries, and coral reefs from increased turbidity; and the cost of dredging coastal waterways. Given these impacts it is important to quantify runoff and sediment dynamics in the watersheds of Hawaii. It is also important to understand how feral pigs contribute to erosion, runoff, and pathogen transport to best identify and implement proper watershed-based management strategies.

1.3 Infiltration, Permeability and Throughfall

Infiltration is the process by which water enters the ground surface. Infiltration rate depends on soil texture and compaction, initial soil water content, vegetation cover, and rate of water application. Initial water intake may exceed water application rate until ponding occurs. Infiltration capacity denotes the maximum rate that occurs under the ponding conditions. Various studies of Hawaiian soils recorded values from 0.3 to greater than 6.0 m d\(^{-1}\) of infiltration (Lau and Mink, 2006). Values between 0.3 and 1.2 m d\(^{-1}\) are
reported for forest sites near Lyon Arboretum (Lau and Mink, 2006).

Studies have shown the reduction of infiltration as the result of various land uses (Lau and Mink, 2006; Ryder and Fares, 2008). Cultivated lands have infiltration rates four times less than adjacent forest lands (Lau and Mink, 2006). Urban lands have reported losses of infiltration capacity as high as 83%. Hydraulic conductivity, $K$, is a measure of the permeability of soil or rock. Permeability of soils is affected by soil structure, porosity, and texture. Saturated hydraulic conductivity ($K_{sat}$) values of Hawaiian soils are typically a few meters per day, though $K_{sat}$ can be reduced by 50% during wet soil conditions (Lau and Mink, 2006).

In most forests, the infiltration capacity and hydraulic conductivity of surface soils are relatively high (Sidle et al., 2006). High infiltration capacities are supported by continual inputs of organic matter onto the soil surface. Because tropical forest soils experience high rates of decomposition, organic horizons are typically thin compared to temperate soils (Lau and Mink, 2006). In undisturbed forests, precipitation generally infiltrates into the soil and moves to streams as subsurface flow. Exceptions may occur in steep slopes or sites with a low permeability layer near the surface that promotes return flow during storms with wet antecedent conditions. However, many tropical soils exhibit marked decreases in hydraulic conductivity in the upper portion of the soil profile and still transmit most water to streams via subsurface flow.

1.4 Fecal Indicator Bacteria

Indicator organisms (IOs) are commonly used to quantify fecal contamination of water bodies, and are an integral part of water management plans (Plummer and Long,
Inductor organisms reside in the gastrointestinal tracts of humans and animals, and are used throughout the world to assess the microbiological safety of drinking, recreational, and shellfish waters. They are found in fecal material at high concentrations and are easier to measure in the environment than are pathogens. Although IOs do not cause illness under normal conditions, they represent a measure of fecal contamination.

The great diversity of pathogenic microorganisms transmitted by contaminated water and the difficulty and cost of directly measuring all microbial pathogens in environmental samples leads to the use of indicator organisms that may indicate the presence of sewage and fecal contamination (Gersberg et al., 2006; Wade et al., 2006). The U.S. Environmental Protection Agency recommends the use of *Escherichia coli*, a member of the fecal coliform group, as an IO for recreational waters in freshwater bodies and members of the genus *Enterococcus* (the Enterococci) for both freshwater and saltwater (Anderson et al., 2005).

This study employs *Enterococcus* spp. bacteria as an IO to investigate water quality of runoff in the Manoa watershed. Enterococci abundance is one of the three most common water quality tests in the United States (Noblea et al., 2003). From Santa Monica Bay, California to the Great Lakes, levels of indicator bacteria have been shown to correlate well with incidence of illness reported by swimmers (Haile et al., 1999; Wade, 2006). Though some research suggests that Enterococci are free-living in Hawaiian soils (Hardina and Fujioka, 1991), mesocosm experiments have found that Enterococci do not multiply in subtropical waters and sediments (Anderson et al., 2005). Recent unpublished data from remote, undisturbed locations on Oahu revealed extremely low Enterococci levels in surface waters (Ragosta, 2007).
A study in Massachusetts showed the highest IO densities occurred during spring and summer, and the lowest densities during the fall and winter (Plummer and Long, 2007). However, this result was likely caused by the presence of housing complexes in the study area, which seemed to leach consistent amounts of waste throughout the year. Therefore human contamination was greater in dryer months when there was less dilution from rain and surface flow. Another study in California found that feral pigs preferred riparian areas during the summer months (Cushman et al., 2004).

1.5 Feral Pigs and Invasive Species

1.5.1 Feral Pigs in Hawaii

Feral pigs, descended from wild boars native to North Africa and parts of Eurasia, are now found in a diverse range of habitats on all continents except Antarctica, as well as many oceanic islands (Ickes et al., 2001). Early Polynesian settlers first introduced Polynesian pigs to the Hawaiian Islands as an important food source (Katahira et al., 1993). Later Captain Cook brought European pigs during his first voyage to Hawaii. Many other introductions followed, and pigs became feral and dispersed throughout all the major Islands. Now the only main Hawaiian Islands free of feral pigs are Lanai and Kahoolawe (Noguiera et al., 2007).

1.5.2 Health Risks

Feral pigs can harbor and spread many potential human pathogens. It should be noted that most pathogens are not solely spread by feral pigs. Other warm-blooded mammals such as the mongoose and rat also likely play a role in their distribution. There are many possible human health risks caused by feral pig activities in watersheds. For
example, studies of feral pigs in Australia have shown that the foraging and wallowing behavior of pigs can markedly increase the turbidity of water supplies, and more importantly, they can transmit and excrete a number of infectious waterborne organisms pathogenic to humans (Hampton et al., 2006). Specifically, populations of feral pigs may serve as an environmental reservoir of *Cryptosporidium parvum* oocysts and *Giardia* spp. cysts for source water (Atwill et al., 1997). Other important protozoan parasite pathogens, such as *Balantidium*, and *Entamoeba*, were detected from the feces of feral pigs caught in metropolitan drinking water catchments (Hampton et al., 2006). All are potentially important waterborne human pathogens that pose a threat to water quality.

1.5.3 Pig Behavior

Pigs consume and trample understory plants, disperse plant propagules, degrade native bird habitat by disturbing the understory and influencing forest succession, produce breeding sites for mosquitoes, and disrupt nutrient cycling (Katahira et al., 1993, Nogueira et al., 2007). Pigs are omnivorous and have even been shown to threaten endangered shorebirds through predation of eggs (Donlan et al., 2007). Pig foraging activities are known to have impacts on soil erosion, soil horizon mixing, nutrient leaching, and litter layers (Spear and Chown, 2009). These activities can also decrease biodiversity and increase soil bulk density. Foraging can cause introduction of exotic species, especially strawberry guava (*Psidium cattleianum*) which is invading many forests throughout Hawaii. Feral pigs spread *P. cattleianum* seeds through feces, and their rooting behavior causes disturbances that may enhance its spread (Huenneke and Vitousek, 1990).

Feral pig’s effects on ecosystems may often be attributed to rooting behavior
Pigs frequently feed on plants and invertebrates in the soil. A large amount of digging and/or rooting is required for pigs to access these food sources. Digging generally refers to the pig’s browsing activity when searching for soil invertebrates (often earthworms). Rooting occurs when pigs remove roots of typically younger plants. Anderson et al. (2007) reported that a single pig could physically disturb 200 m² of rain forest surface in one day. Rooting is commonly used as an indicator of pig population density (Hone, 1988). In a related measure, the amount of exposed soil in a forested system may be an indicator of the rooting intensity of the site (Campbell and Long, 2009). Pig rooting has been shown to accelerate nutrient leaching, increase soil erosion, limit soil regenerating processes, and reduce soil arthropods (Campbell and Long, 2009).

Pig rooting was found to be more frequent in upper elevations and drainage lines in watersheds in Australia (Hone, 2002). In Hawaii Volcanoes National Park (HVNP), rooting behavior caused 70% of fresh and intermediate disturbance along pig activity transects (Katahira et al., 1993). Pig activity in the 5 x 10 m plots ranged from 0.1-3.6 %, with a mean of 0.7 %. Estimated pig density ranged from 0.8-4.7 pigs km⁻², with a mean of 0.8 pigs km⁻². Pig activity and density in all three units combined had a statistically significant linear relationship. In Australia feral pig disturbance was found to be most common on flat slopes at high elevations, and least common on steep slopes at low elevations (Hone, 1995).

Hone and Stone (1989) found foraging and trampling by pigs can cause severe erosion and may lead to the degradation of watersheds. This can be especially harmful in watersheds such as Manoa because pigs typically inhabit areas of steep terrain (Hone and
Stone, 1989). Pigs also inhibit watershed function by increasing runoff through the compaction of soils. Wallowing, creation of pig trails, and the crushing of vegetation to browse for food and creation of nests all contribute to soil compaction. In a study at HVNP, Vtorov (1993) found total density of microarthropods in soils nearly doubled and biomass increased 2.5 times, seven years after exclusion of feral pigs. These native microarthropods are indicators of soil quality and important contributors to the soil formation process. In sites with pigs, disturbance to litter and compaction of the upper soil horizons created a substrate relatively unsuitable for microarthropod populations. Soil density around tree ferns, a favorite food of feral pigs, was 30% higher than surrounding areas (Vtorov, 1993).

1.5.4 Invasive Species

Introduction of invasive species is of great concern all over the world, but especially for island ecosystems (Donlan and Wilcox, 2008). Invasive species are one of the main reasons Hawaii is home to 31% of the species on the U.S. endangered species list (Allison and Miller, 2000). Hundreds of exotic species are problematic invaders in Hawaii, and feral pigs are considered one of the worst (Nogueira et al., 2007). Indigenous forests on oceanic islands such as New Zealand and the Hawaiian Islands have evolved in isolation from major landmasses and in the absence of mammalian herbivores. As a result, indigenous flora in such areas exhibit a high degree of endemism and are often vulnerable to damage from mammalian herbivory (Sweetapple and Nugent, 2004). Nonnative ungulates carry out novel functions in systems devoid of indigenous large herbivores through herbivory and by increasing soil nitrogen (Spear and Chown, 2009). Introduced ungulates may also alter fire or erosion regimes (Spear and Chown, 2009).
Biological invasions are a global phenomenon that can alter disturbance regimes and facilitate colonization by other nonnative species (Cushman et al., 2004). A study of a California grassland found that feral pigs promoted the colonization of nonnative grass and forb species (Cushman et al., 2004). Introduced ungulates also have the potential to change the rate and trajectory of recovery of patches of forest that have been damaged by natural and human-induced disturbances (Wilson et al., 2006). In the presence of ungulates, vegetation will often reestablish on these patches more slowly and with a different species composition than in the absence of ungulates (Wilson et al., 2006).

In Hawaiian rain forests, an unharvested pig population is potentially capable of doubling every four months (Katahira et al., 1993). Except for malnutrition, disease, or cold weather during farrowing at high elevations, there are no other known natural factors limiting pig populations in Hawaii (Katahira et al., 1993). Feral pigs, through a combination of herbivory, predation, competition, and habitat effects, are considered a threat to biodiversity in the U.S., and seem to be a species of particular concern globally (Spear and Chown, 2009). Impacts of nonnative mammals on plant regeneration and other processes are fairly well known, however watershed-scale effects of feral pigs have rarely been studied in the Pacific Islands, and peer-reviewed research is scarce.

1.6 Study Area: Manoa Watershed

The Manoa Valley watershed is the ideal place for this study for many reasons. Foremost, the University of Hawaii Manoa is situated such that evaluation and analysis of samples are relatively fast and straightforward. Likewise, the timely sampling of streams and runoff plots are expedited when rain events do occur. Manoa Valley is diverse in
terrain, relief, and rainfall, as well as land use and vegetation types. Feral pigs are the only large non-human mammal that occurs in the study area, unlike many of the other Pacific Islands where deer (*Axis axis, Odocoileus hemionus*), cattle (*Bos taurus*) and goats (*Capra aegagrus*) can occupy the same habitat as pigs.

Manoa watershed encompasses approximately 2,528 ha in southeast Oahu. It contains both high mountainous and low-level coastal lands within a relatively small area. Runoff from Manoa watershed is carried by two main streams, Manoa and Palolo Streams, which join each other before emptying into the Ala Wai Canal (Fig. 1.1). Historically, the area surrounding the Ala Wai Canal, as well as all of Waikiki, formed a much larger coastal wetland and the streams of Manoa and Palolo flowed into this area separate from one another. Construction of the Ala Wai Canal was completed in 1928. The canal performed its intended function of draining the surrounding wetlands, including agricultural lands, to allow for further development (Glenn and McMurtry, 1995). However, since its construction issues such as dredging, water quality, and flood control have posed numerous concerns to local residents, engineers and lawmakers.
Figure 1.1. The Manoa stream network shows a majority of water is carried away by the numerous streams in the northwest portion of the watershed.

Currently Manoa is a heavily-populated urban watershed located just north of downtown Honolulu and Waikiki Beach. Although highly-developed in the lower and middle reaches, the upper reaches remain mostly forested and uninhabited by people (Fig. 1.2). Development in the watershed has slowed and primary land use has remained stable for several decades. Therefore, in terms of land cover, the analysis conducted in this study was based on a relatively stable watershed rather than one in transition.
Figure 1.2. A GIS map of land use in the Manoa watershed.

The previous installation of runoff plots in the study area provided a unique opportunity for further study (Browning, 2008). The location of plots allowed for in relief, dominant vegetation, and rainfall. The upper part of the watershed is characterized by steep terrain, higher rainfall rates, and is dominated in places by strawberry guava (*Psidium cattleianum*) and bamboo (*Poaceae spp.*). The lower part of the watershed has flatter terrain and lower rainfall. Runoff plots are situated in areas with varying slope, rainfall, and vegetation cover (Fig. 1.3).
Figure 1.3. GIS map of Manoa Watershed slope with streams, trails, and the eight runoff plot sites.

The presence of pigs in the Manoa watershed is a divisive issue in the surrounding community, and among the many stakeholders who use the area. The pigs are hunted for their meat and for recreation, so a sustainable population is seen as a positive to some local people. However, many scientists, environmentalists, and local residents are concerned about the potential damage pigs may cause to the native vegetation and riparian areas. There are also concerns about the disturbance and danger of hunting the pigs and the use of hunting dogs. The possible threat to human health is an important concern, and the many recreational users of the Manoa Valley should be informed of the risks. There is anecdotal evidence that pig populations are increasing, and that pigs are interacting with humans more often. Pig threats to human health may also be increasing
and the need to study this issue is urgent.

Feral pigs have been shown to have negative effects on soil properties as well as ecosystem functions and biodiversity (Hone, 2002), but no one has ever investigated any link to fecal contamination in runoff to pigs in Manoa Valley or in other tropical island watersheds. In Hawaii, the streams and downstream coastal water are highly prized for recreation, and tourists visit from all over the world to enjoy the abundant natural resources. Any possible threat to public health or environmental quality should be researched.

Manoa Valley has a high annual rainfall, and one study in Hawaii found an exponential increase in feral pigs relating to antecedent rainfall (Caley, 1993). Visual assessment and eyewitness reports have suggested a large pig population living in the Manoa watershed. Reports in the local media have suggested that feral pig interactions in urban areas are increasing as well, worrying homeowners and public health authorities (Nogueira et al., 2007). The data collected from this project will be of interest to managers, the public, and policy makers. The results and recommendations of this research may lead to reduced soil erosion, mitigation of stream degradation, and improved health of estuarine and coral reef ecosystems.

1.7 Research Objectives

The overall objective of this thesis is to investigate runoff processes that occur in the forested upper areas of Manoa watershed and to examine the use of exclusion fencing as a tool to improve water quality. The specific objectives are as follows: (1) Quantify throughfall, runoff amount, total suspended solids (TSS) in runoff, and Enterococci in
runoff and soils from forested areas of Manoa watershed; (2) Determine if feral pigs impact runoff amount, TSS in runoff, and Enterococci in runoff and soils; (3) Investigate temporal and spatial differences in TSS and Enterococci levels in runoff; and (4) Investigate correlations among environmental variables (slope, infiltration rate, soil moisture, stem density, etc) and TSS and Enterococci in runoff. Given what was learned in the literature review, and drawing on the results of previous research at these sites (Browning, 2008), I developed four hypotheses:

**Hypotheses:**

1. Higher storm intensity and higher throughfall inputs will lead to larger runoff amounts, and higher TSS and Enterococci levels in runoff during the wet season (November-April) than in the dry season (May-October);
2. Fecal contamination will lead to higher Enterococci levels in runoff and soil at unfenced plots exposed to feral pig activity;
3. Of all environmental predictors measured, ground cover and soil moisture will have the strongest correlations with TSS and Enterococci in runoff as ground cover influences soil erosion processes, and Enterococci survival is thought to be higher and infiltration is lower under wetter soil conditions which directly affect runoff production;
4. TSS in runoff will positively correlate with Enterococci abundance in runoff as bacteria are thought to associate with soil particles in surface waters.
The hypotheses listed above address a gap in our knowledge as to the contribution of sediments from forested and upper watershed areas in Hawaii, and the effects of feral pigs on runoff and soil loss. Runoff plots have often been employed in agricultural settings in Hawaii (El-Swaify, 1989; Ryder and Fares, 2008) but this is one of the first times they have been used in upper forested watershed areas (Browning, 2008). While feral pig impacts have been theorized and visual evidence is plentiful, few attempts to quantify the actual amount of runoff/soil loss exist, particularly in Hawaiian watersheds. Fecal contamination caused by pigs has rarely been studied in the Pacific Islands, and never in Manoa. This study will aid natural resource managers, helping them identify the effects of feral pigs, and informing them of the effectiveness of fencing as a tool for increasing water quality. This information will also allow landowners to protect the health of riparian areas, and could benefit swimmers and other recreational users of Hawaiian streams and rivers.
CHAPTER 2: SEDIMENT IN RUNOFF

2.1 Introduction

This study aims to improve our understanding of the processes of runoff and soil erosion in upper forested areas of a typical Hawaiian watershed and to identify the effects pigs have on erosion and runoff. Feral pigs can harm native flora and fauna, and may even adversely impact the health and function of entire watersheds (Noguiera-Filho et al., 2009). Runoff dynamics in upper forested watersheds are not well understood, and while there is much suspicion about negative impacts of feral pigs on ecology of these areas there is little hard evidence. Sedimentation has multiple negative impacts that affect watersheds and adjacent coastal areas; including nutrient influx carried by sediments, damage caused to streams, estuaries, and coral reefs from increased turbidity, and the cost of dredging coastal waterways. Given these impacts it is important to quantify runoff and sediment dynamics in the watersheds of Hawaii. It is also important to understand how feral pigs contribute to erosion and runoff in order to best identify and implement appropriate watershed-based management strategies.

The specific objectives of this chapter are to: (1) quantify throughfall, runoff amount, and total suspended solids (TSS) in runoff from selected forested areas of Manoa watershed; (2) determine if feral pigs increase runoff amount and TSS in runoff; (3) examine temporal and spatial differences in TSS levels in runoff; and (4) investigate correlations among environmental variables (slope, infiltration rate, soil moisture, stem density, etc) and TSS. The specific hypotheses tested are as follows: (1) Higher storm intensity and higher throughfall inputs will lead to larger runoff amounts, and higher TSS
levels in runoff during the wet season (November-April) than in the dry season (May-October); (2) pig disturbance will lead to higher TSS levels in runoff at unfenced plots exposed to feral pig activity; (3) of all environmental predictors measured, ground cover and soil moisture will have strongest correlations with TSS in runoff, as ground cover influences soil erosion processes and infiltration is lower under wetter soil conditions which directly affect runoff production.

Materials and Methods

2.2 Site Selection

In the spring of 2007, eight sites were selected to investigate runoff processes and the effects of feral pig exclusion in Manoa watershed. The sites were chosen from the upper forested areas of the watershed, based on attributes of slope, accessibility, and vegetation. Slope was the primary determining factor in initial site selection to allow for construction of exclusion fencing and to ensure collection of accurate runoff data. According to Mutchler et al. (1994) a slope of 9% or less is considered the standard in most agricultural studies that incorporate runoff plots; however areas with <9% slope were not easy to find as the average slope of the watershed is 47%. Using a Geographic Information System (GIS), a map of slope characteristics throughout the watershed was created and areas with slopes between 5-30% were identified as potential sites (Fig. 2.1). Final site selection was based on ease of accessibility and proximity to existing trail networks as well as homogeneity of slope/vegetation at each site (Table 2.1).
Unfortunately, the Palolo Valley site was vandalized repeatedly throughout the study period and had to be abandoned, leaving only seven sites for this research.

Figure 2.1. A GIS map of the variation in slope across the Manoa watershed with the locations of all eight sites of study.
Table 2.1. Characteristics of seven sites in Manoa watershed. Elevation and soil series information was obtained through a GIS analysis, while slopes were recorded on site using a handheld clinometer.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (m)</th>
<th>Slope (%)</th>
<th>Soil Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyon</td>
<td>215</td>
<td>15.5</td>
<td>Lolekaa</td>
</tr>
<tr>
<td>Manoa Cliffs</td>
<td>450</td>
<td>8</td>
<td>Rough Mountainous Land</td>
</tr>
<tr>
<td>Manoa Falls</td>
<td>171</td>
<td>17</td>
<td>Lolekaa</td>
</tr>
<tr>
<td>Pauoa Flats</td>
<td>538</td>
<td>6</td>
<td>Rough Mountainous Land</td>
</tr>
<tr>
<td>Puu Pia</td>
<td>209</td>
<td>26</td>
<td>Lolekaa</td>
</tr>
<tr>
<td>Round Top</td>
<td>340</td>
<td>25.5</td>
<td>Tantalus</td>
</tr>
<tr>
<td>Waahila Ridge</td>
<td>340</td>
<td>14</td>
<td>Manana</td>
</tr>
</tbody>
</table>

2.3 Site Layout

Each site is approximately 10 x 10 m. Two paired 10 m by 5 m runoff plots were established at each site; one runoff plot surrounded by exclusion fencing, the other unexclosed. Runoff plots were oriented down the slope to effectively capture the natural path of overland flow at each site. Fences were constructed of 14-gauge utility fencing 0.91 m tall and held in place with metal posts. Barbed wire was strung along the bottom edge of each fence to provide further protection from pig damage. During initial construction of runoff plots, throughfall gauges were affixed to posts directly centered between the paired plots at each site. In December 2008, four additional throughfall gauges were added to each site (Figure 2.2).
2.4 Runoff Plot Design

Following fence installation, runoff plots were constructed within both unfenced and fenced plots at each site. Runoff plots were approximately 4.2 m long by 1.2 m wide, oriented down the prevailing slope. To prevent additional runoff entering from outside the plot, 15 cm tall plastic dividers were buried roughly 7.5 cm into the soil along the upslope and outer edges of each runoff plot. These plastic pieces formed the framework that channeled runoff to a central collector (Fig. 2.3). This central collector was located at the down slope end of the runoff plot, consisting of a triangular metal runoff collector that funneled all runoff into a 10 by 5 cm opening (Fig. 2.3). A metal feed tray connected the metal collector to an 18.9 L bucket for storing runoff. A rectangular hole was cut into the side of the bucket into which the feed tray drained. Water-tight lids were affixed to
the top of each bucket to prevent throughfall from falling directly into the bucket. Sheet metal collector covers were constructed to also prevent direct throughfall on the metal collector and installed in December 2008.
Figure 2.3. A photo from the Round Top site displaying the runoff collection system.
2.5 Activation Periods and Runoff Sampling

Runoff samples were collected from June 2008 to April 2009 to ensure collection of samples from both the wet and dry seasons. At the beginning of each month a two-day dry period was targeted to activate all plots and initiate runoff collection. Activation of each site included emptying all throughfall gauges, collecting soil samples for moisture analysis, and emptying/cleaning the runoff collection buckets. Runoff was removed with a hand operated suction pump, and then paper towels were used to clean and dry all inside surfaces of collection buckets. Sterile latex gloves were worn at all times during emptying and cleaning procedures. Collection times were determined by observing weather conditions and monitoring the online USGS rain gauge located in Manoa Valley. When the rain gauge recorded a significant rainfall (typically > 2 cm) during the active period, collection was initiated.

The collection process involved measurement of total runoff and collection of runoff sub-samples to be analyzed for TSS. During all activation and collection activities, care was taken to avoid walking within runoff plots. Soil samples were taken within the sites, yet outside the runoff plots so as not to disturb soils. In the duration between observation periods runoff was allowed to continue its natural flow into the buckets. If the buckets began to overflow, runoff simply drained out through the same opening from which it entered and continued flowing down slope. Throughfall gauges were covered with duct tape while not active.
2.6 Estimation of Other Environmental Variables

As this project was designed to monitor runoff and sediment loss from the study areas and to develop correlation and regression equations for TSS in runoff, it was important to quantify a variety of different variables that influence these processes. This required recording of site characteristics throughout the duration of the study, as well as prior to rain events, and also the analysis of runoff after the events. The other environmental variables recorded were slope, soil series, soil water content, throughfall, infiltration rate, forest canopy and understory species composition, stem density, basal area of trees, seedling/sapling counts, and ground cover assessment. The following paragraphs summarize the methodology used to determine these characteristics.

2.6.1 Slope Recordings

Slopes were measured using a handheld clinometer and ranged from 5% to 27%. No site was recorded to have greater than a 2% difference between the fenced and unfenced plots. Ultimately, all seven sites represented a range of different slope types as shown in Table 2.1.

2.6.2 Soil Series Determination

Soil series for each site were obtained from digital NRCS soil maps. Additionally, global positioning system (GPS) coordinates for each site recorded in the field. These two data layers were overlaid to identify the soil series of each site based on the latest soil survey of Oahu (Foote et al. 1965). The seven sites represented four different soil series; Tantalus, Lolekaa, Manana, and Rough Mountainous Land (rRT) (Table 2.1).
2.6.3 Calculation of Soil Water Content

Gravimetric soil water content was determined during the activation phase of each month. A 2 cm diameter soil corer was used to collect samples from approximately the upper 5 cm of the soil profile. One composite sample was collected during site activation from both the fenced and unfenced areas. The composite sample consisted of three separate randomly-located individual samples from each area, combined in a sterile plastic bag. No soil samples were taken from within runoff plots to avoid disturbing soils. Percent gravimetric soil moisture was calculated by the equation:

\[
\text{% Gravimetric Soil moisture} = (1 - (\text{dry mass soil} / \text{wet mass soil})) \times 100
\]

2.6.4 Throughfall Recording

A standard all-weather rain gauge (Productive Alternatives, Fergus Falls, MN) was used to measure throughfall (mm) of rain events. As part of the activation process, each throughfall gauge was emptied and a thin layer of vegetable oil was added to prevent evaporation.

2.6.5. Infiltration Rates

Infiltration rate and the coefficient of saturation (Ksat) were determined at each plot using a Tension Infiltrometer (8 cm model, Soil Measurement Systems, Tucson, AZ). The most level and uniform area of each fenced/unfenced plot (although not within the runoff plot areas) was chosen as the infiltration measurement site. A metal spatula was used to cut out a shallow hole in the litter layer the same size/shape as the
infiltrometer base to expose the soil surface. A layer of fine sand was added to the hole. The infiltrometer was then filled with water and placed on the sand layer. The tension was set to 11 cm. If infiltration did not commence, tension was lowered to 10 cm. Readings of water level were taken every 30 seconds for 10 minutes, then every 60 seconds for another 10 minutes, and a final reading was taken after five more minutes. The tension was then lowered to 8 cm if initial tension was 11 cm, or 7.5 cm if initial tension was 10 cm. This was to ensure enough of a tension difference between the two readings to allow for calculation of Ksat.

Equilibrium infiltration slopes were determined graphically. The slope was then multiplied by the area of the infiltrometer’s base to determine the volume of water infiltrated per time. Ksat was calculated from the equation:

$$\alpha = \frac{\ln \left( \text{Infiltration rate X / Infiltration rate Y} \right)}{(\text{Tension X} - \text{Tension Y})}$$

$$\text{Ksat} = \frac{\text{Infiltration rate X}}{\text{Area of base} ^ {\alpha \cdot \text{Tension X} \times (1 + \frac{4}{\text{Area of base} \cdot \alpha})}}$$

Where X = tension 1, and Y = tension 2

2.6.6 Forest Structure Characterization

The seven sites in Manoa Valley varied in terms of forest structure and species composition. To quantify these differences, a 20 m by 20 m plot directly surrounding each site was established and all trees > 2 cm diameter at breast height (DBH) were measured. DBH is defined as diameter at 1.32 m from the ground surface. Species was recorded for each tree in the plot. If a tree could not be identified to the species level in
the field, a leaf sample was taken back to the lab for identification. Stem density (# stems ha\(^{-1}\)) was calculated by counting the number of stems in the 400 m\(^2\) plot and scaling to a hectare basis. Basal area (m\(^2\) ha\(^{-1}\)) of each tree was calculated from individual DBH measurements, and summed to give total basal area in the 400 m\(^2\) plot, which was scaled to a hectare basis.

2.6.7 Seedling and Sapling Counts

Seedlings and saplings were measured in two 1 m\(^2\) plots within each fenced and unfenced plot (Figure 2.4). Measurements were taken at the upper and lower outside corner (the only corners without rain gauges) of each plot. This was done to minimize any effects of trampling or disturbance from previous research activities in the plots (e.g. throughfall gauge sampling). Seedlings were defined as any plant < 15 cm in height. Saplings were defined as all plants > 15 cm in height, but less than 2 cm DBH. Species identification was determined in the field or with voucher specimens.

![Figure 2.4. Location of seedling and sapling plots at each site.](image)
2.6.8 Estimation of Ground Cover

Ground cover at the sites was recorded for both the runoff plots and the larger fenced/unfenced area. A measuring tape was used to establish a transect line and a visual assessment of ground cover was made at predetermined distances along the transects. For the whole plot, measurements were taken every 25 cm along two separate 10 m transects (Figure 2.5). Ground cover measurements in the runoff plot were taken every 3 cm along three 1.2 m transects equally spaced along the runoff plot. Visual determination of ground cover was made from a direct top-down view above the transects. Ground cover was divided into the following categories: live plant, standing dead plant, coarse woody debris, litter, bare soil, rock, and root. Coarse woody debris was defined as woody debris/branches > 2 cm diameter. Litter included detritus, leaves, and any woody debris < 2 cm diameter.
2.7 Runoff Collection and Analysis

2.7.1 Runoff Volume

Runoff volume was measured for each rainfall event, prior to collection of runoff for analysis in the laboratory. During initial site selection, three of the eight sites (Pauoa Flats, Manoa Cliffs, and Lyon) were observed to receive particularly large amounts of throughfall. In an attempt to prevent collection buckets from overflowing, these three sites were fitted with a feed tray that diverted half of all runoff into the collection buckets instead of receiving 100%. The other half was diverted around the bucket and continued down slope. For these sites, the volume was doubled after initial calculation to account for this adjustment. Before any samples were removed from the collection bucket, the depth of runoff in the collection bucket was recorded to calculate the total volume. A yardstick was used to determine depth of runoff in each collection bucket. The yardstick

*Figure 2.5. Ground cover transects for whole plot (left) and runoff plot (right). Both transects were sampled on all plots.*
was cleaned with paper towels after each use. Sterile latex gloves were worn at all times, and changed prior to each new measurement.

2.7.2 Runoff Overflow Buckets

During the initial months of this study, it was recognized that runoff collection buckets were in many cases too small to collect the total amount of runoff from certain rainfall events. A small hole was drilled in the downslope edge of each collection bucket and a length of rubber hose was inserted in the hole. The rubber hose was layed downslope and inserted into another hole drilled into a larger plastic tub (the “overflow bucket”). This overflow bucket captured extra runoff to a volume of 97.7 L. A yard stick was used to record runoff overflow volume as above.

2.7.3 Quantification of Total Suspended Solids in Runoff

After the depth was recorded, the contents of the collection bucket were thoroughly mixed with the yardstick and a runoff water sample was collected in an acid-washed 500 mL bottle. Samples were taken back to the lab on ice and refrigerated before analysis for total suspended solids (TSS). Total SS were measured by vacuum filtration of 100 mL of sample. First a Whatman 5 filter paper (Whatman, Kent, United Kingdom) was placed on a watch glass and weighed on an electronic balance. Samples were homogenized and a 100 mL aliquot was extracted and poured onto filter paper placed on a Buchner funnel attached to a 500 mL vacuum flask. Each filter paper and watch glass were then placed into a 105°C oven and dried for 24 hours. Afterwards the filters were
weighed and the original weight was subtracted from the dry weight to calculate the TSS in g L⁻¹ (EPA, 1971).

2.8 Statistical Analyses

All statistical analyses were performed using SAS version 9.1 (SAS Institute, Cary, NC). A Repeated Measures ANOVA (Proc MIXED) was used to distinguish differences between fenced and unfenced treatments, among months, and among sites. Month was the repeated measure in these analyses. Proc MIXED uses the ‘containment method’ and, depending on the homogeneity of variances, denominator degrees of freedom may vary from one model to another. Post hoc comparisons of means were conducted with least squares method. A Linear Model GLM ANOVA was used to distinguish differences between treatments and among sites for environmental variables that were only measured once. In these cases, a one-way ANOVA was used to make a distinction between ground cover in fenced and unfenced sites and post-hoc comparisons of means were carried out using the Duncan’s Multiple Range Test. A Spearman correlation was used to evaluate associations among TSS and all environmental variables. A multiple stepwise regression (MSR) was also used to determine the best predictors of TSS in runoff.

Results

2.9 Soils
Soil moisture was significantly different among months and sites, though there was also a significant site by month interaction (Table 2.2). April had the highest mean soil moisture, which was significantly higher than November, December, and February; but not January or March (Figure 2.6). These mean differences highlighted a trend of wetter soils as the wet season progressed.

![Figure 2.6. Mean soil moisture per month prior to rain events. Error bars represent ± 1 standard error. Letters represent differences according to least squared means.](image)

**Figure 2.6.** Mean soil moisture per month prior to rain events. Error bars represent ± 1 standard error. Letters represent differences according to least squared means.

<table>
<thead>
<tr>
<th>Source</th>
<th>Num df</th>
<th>Den df</th>
<th>Chi-Square</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>5</td>
<td>30</td>
<td>32.21</td>
<td>6.44</td>
<td>0.0004</td>
</tr>
<tr>
<td>Month</td>
<td>6</td>
<td>6</td>
<td>165.71</td>
<td>27.62</td>
<td>0.0004</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>6</td>
<td>0.05</td>
<td>0.05</td>
<td>0.83</td>
</tr>
<tr>
<td>Month x Site</td>
<td>30</td>
<td>30</td>
<td>73.38</td>
<td>2.45</td>
<td>0.0084</td>
</tr>
<tr>
<td>Month x Treatment</td>
<td>5</td>
<td>30</td>
<td>2.86</td>
<td>0.57</td>
<td>0.72</td>
</tr>
</tbody>
</table>

On average, across the study period, gravimetric soil moisture was significantly higher at Manoa Cliffs (64.1%) than any other site (Figure 2.7). Roundtop (33.1%) had significantly lower soil moisture than any site except Waahila Ridge (38.5%). Waahila
Ridge was the driest site (least throughfall) but had wetter soils on average than Roundtop. Soil moisture varied from a low of 34.1% at Roundtop prior to the December rain event, to a high of 67.3% at Manoa Cliffs prior to the April event.

Figure 2.7. Mean soil moisture per site prior to rain event. Error bars represent ± 1 standard error. Letters represent differences according to least squared means.

The repeated measures ANOVA indicated that there was no significant difference in soil moisture between fenced and unfenced treatments (Table 2.3) although five of the seven sites had lower average soil moisture in the unfenced plots (Figure 2.8). Lyon Arboretum had the largest average difference in soil moisture between fenced (47.6%) and unfenced (53.6%) plots.
Throughfall amounts were significantly different among months and among sites (Table 2.3). The site by month interaction could not be tested because of a lack of replication of throughfall measurements at the sites. Throughfall per rain event varied from a mean of 11.6 mm in July to 122.3 mm in December (Figure 2.9). The December event was significantly greater than all other months. March had the next highest throughfall (89.6 mm), and was also significantly different from all other months. January was the next smallest event after July; averaging 17.2 mm. February was the fourth-smallest event, 20.0 mm, averaging less than 1 mm more than June (19.2 mm). From July through December average throughfall increased steadily, then after December average throughfall decreased. The dry season months of June and July were not significantly different from the wet season months of January, February and April (Table 2.3).
Table 2.3. Repeated measures ANOVA for throughfall.

<table>
<thead>
<tr>
<th>Source</th>
<th>Num df</th>
<th>Den df</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>10</td>
<td>59</td>
<td>17.20</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Site</td>
<td>6</td>
<td>59</td>
<td>4.73</td>
<td>0.0005</td>
</tr>
</tbody>
</table>

In terms of site differences, Lyon Arboretum had the highest mean throughfall at 62.5 mm per rain event, significantly greater than Roundtop (31.3 mm), Waahila Ridge (26.2 mm), Manoa Cliffs (47.0 mm), and Puu Pia (42.3 mm), but not significantly different from Manoa Falls (52.8 mm) or Pauoa Flats (59.7 mm) (Figure 2.10). Waahila Ridge had the smallest mean throughfall, significantly less than any site except Roundtop.
Infiltration rates and saturated hydraulic conductivity (Ksat) varied greatly among sites and between fenced and unfenced plots (Table 2.4). There was a difference of four orders of magnitude between the largest and smallest Ksat values. Even between fenced and unfenced plots there were huge differences in Ksat. The Waahila Ridge fenced plot had a Ksat that was ~1,400 times greater than the Ksat in the unfenced plot. The Puu Pia unfenced plot had the highest Ksat of 723 m hr⁻¹, while the Waahila Ridge unfenced plot had the lowest with <0.01 m hr⁻¹.

### Table 2.4. Saturated hydraulic conductivity (Ksat) values (m hr⁻¹) across all sites and plots.

<table>
<thead>
<tr>
<th>Site - Plot</th>
<th>Ksat (m hr⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyon Arboretum - Fenced</td>
<td>21.75</td>
</tr>
<tr>
<td>Lyon Arboretum - Unfenced</td>
<td>0.055</td>
</tr>
<tr>
<td>Manoa Cliffs - Fenced</td>
<td>0.21</td>
</tr>
<tr>
<td>Manoa Cliffs - Unfenced</td>
<td>0.48</td>
</tr>
<tr>
<td>Manoa Falls - Fenced</td>
<td>1.41</td>
</tr>
<tr>
<td>Manoa Falls - Unfenced</td>
<td>91.08</td>
</tr>
</tbody>
</table>
Species, Stem Density, and Basal Areas of the Study Sites

Stem density ranged from less than 1,500 stems hectare\(^{-1}\) (ha) at Pauoa Flats, dominated by large *Elaeocarpus grandis* (blue marble) trees, to more than 9,000 stems ha\(^{-1}\) at Puu Pia (Table 2.5). Basal area ranged from just over 20 m\(^2\) ha\(^{-1}\) to >132 m\(^2\) ha\(^{-1}\).

*Psidium cattleianum* (strawberry guava) tended to form dense monocultures of small trees, particularly at Manoa Falls and Waahila Ridge, contributing to the high stem densities at these sites. *Schefflera actinophylla* (octopus tree) also formed dense stands, though with larger average DBH than *P. cattleianum*, at Puu Pia and Roundtop.

<table>
<thead>
<tr>
<th>Site</th>
<th>Stem Density (stems ha(^{-1}))</th>
<th>Basal Area (m(^2) ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyon Arboretum</td>
<td>1,900</td>
<td>41.0</td>
</tr>
<tr>
<td>Manoa Cliffs</td>
<td>3,375</td>
<td>20.0</td>
</tr>
<tr>
<td>Manoa Falls</td>
<td>5,175</td>
<td>74.0</td>
</tr>
<tr>
<td>Pauoa Flats</td>
<td>1,475</td>
<td>37.7</td>
</tr>
<tr>
<td>Puu Pia</td>
<td>9,300</td>
<td>132.7</td>
</tr>
<tr>
<td>Roundtop</td>
<td>2,400</td>
<td>93.8</td>
</tr>
<tr>
<td>Waahila Ridge</td>
<td>4,625</td>
<td>47.6</td>
</tr>
</tbody>
</table>

A total of 14 different canopy tree species were observed at the seven sites (Table 2.6). Each site also had a different mix of species (Appendix A). Another five woody plant species were found in the mid-story range (Table 2.7) and *Ardisia crenata* (Hilo...
holly) was measured only as a seedling or sapling. *Ardisia elliptica* (shoebutton ardisia) was the most common species, found at six of seven sites, though typically in individuals <2.0 cm DBH.

**Table 2.6. List of canopy tree species observed at the seven sites.**

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Casaurina glauca</em></td>
<td>Ironwood</td>
</tr>
<tr>
<td><em>Cinnamomum burmanni</em></td>
<td>padang cassia</td>
</tr>
<tr>
<td><em>Elaeocarpus grandis</em></td>
<td>blue marble</td>
</tr>
<tr>
<td><em>Eucalyptus robusta</em></td>
<td>swamp mahogany</td>
</tr>
<tr>
<td><em>Ficus microcarpa</em></td>
<td>Chinese banyan</td>
</tr>
<tr>
<td><em>Hibiscus tiliaceus</em></td>
<td>Hau</td>
</tr>
<tr>
<td><em>Hibiscus arnottianus</em></td>
<td>kokio keokeo</td>
</tr>
<tr>
<td><em>Persea americana</em></td>
<td>Avocado</td>
</tr>
<tr>
<td><em>Pisonia umbellifera</em></td>
<td>pepala kepau</td>
</tr>
<tr>
<td><em>Psidium cattleianum</em></td>
<td>strawberry guava</td>
</tr>
<tr>
<td><em>Psidium guajava</em></td>
<td>common guava</td>
</tr>
<tr>
<td><em>Schefflera actinophylla</em></td>
<td>octopus tree</td>
</tr>
<tr>
<td>Unknown #2</td>
<td></td>
</tr>
<tr>
<td>Unknown #3</td>
<td></td>
</tr>
<tr>
<td>Unknown #7</td>
<td></td>
</tr>
<tr>
<td>Unknown #8</td>
<td></td>
</tr>
</tbody>
</table>

**Table 2.7. List of mid-story woody plant species observed at the seven sites.**

<table>
<thead>
<tr>
<th>Species Name</th>
<th>Common Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ardisia elliptica</em></td>
<td>shoebutton ardisia</td>
</tr>
<tr>
<td><em>Dracaena sp.</em></td>
<td>money tree</td>
</tr>
<tr>
<td><em>Cestrum nocturnum</em></td>
<td>night-blooming jasmine</td>
</tr>
<tr>
<td><em>Cordyline terminalis</em></td>
<td>ti or ki</td>
</tr>
<tr>
<td><em>Livistona chinensis</em></td>
<td>Chinese fan palm</td>
</tr>
</tbody>
</table>

Seedling and sapling counts revealed differences from the canopy composition (Figures 2.11, 2.12). Mid-story species, especially *A. elliptica*, appeared in high numbers in sapling and seedling counts. Two sites, Waahila Ridge and Roundtop, contained no seedlings or saplings. Waahila Ridge was dominated by *Casaurina glauca* (ironwood)
trees in a monotypic stand directly over the runoff plots, and the thick litter layer appears to prevent other species from establishing there. Within the larger 400 m² area there was also a dense stand of *P. cattleianum* trees, as mentioned above, but none of these trees were within either the fenced or unfenced plot.

At the Manoa Cliffs fenced plot, seedling counts of *Cinnamomum burmannii* were greater than 70 individuals m⁻². This area was dominated in places by thick *C. burmannii* canopy that shades out most other plants. Other understory plants observed at Manoa Cliffs were *Hedychium sp.* (ginger) and *Cestrum nocturnum* (night-blooming jasmine). Pauoa Flats was another site with high counts of *C. burmannii*, averaging almost 23 seedlings m⁻². The understory at Pauoa Flats also included large numbers of *A. elliptica*, more than 10 seedlings m⁻².

![Figure 2.11. Seedling occurrence across the fenced and unfenced plots of each site.](image-url)
A fenced versus unfenced comparison (Figure 2.13) demonstrated almost twice as many *P. cattleianum* seedlings and saplings in the unfenced plots. Canopy cover of *P. cattleianum* appeared to be most prevalent at Manoa Falls (197 individuals), yet seedling and sapling counts at that site were dominated by both the *Ardisia* species. Waahila Ridge was another site with large numbers of *P. cattleianum* in the canopy (38 individuals) but all trees were located outside of the runoff plot areas, to the south and west of the plots.
Ground cover in the runoff plots was never disturbed by researchers during this study, but the whole plot was used for soil samples, infiltration studies, and was walked on during collection and activation procedures. Such disturbance was considered equal for both fenced and unfenced whole plot areas. The following results apply only to runoff plot areas unless otherwise specified. The mean litter cover in fenced plots was 81.2%, and was 77.9% in unfenced plots (Figure 2.14). Mean bare soil cover was only 2.9% in fenced plots and 8.2% in unfenced plots. Mean live plant cover was 11.0% in fenced plots and 9.0% in unfenced plots. Coarse woody debris was only found in two of the runoff plots. There was no root or standing dead cover measured in either fenced or unfenced runoff plots. No significant differences in litter, bare ground, and live plant cover were observed between fenced or unfenced plots (Table 2.8).
Table 2.8. One-way ANOVA for ground cover fenced versus unfenced treatment means among sites.

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Litter</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>0.0213</td>
<td>0.0213</td>
<td>1.56</td>
<td>0.25</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.109</td>
<td>0.0137</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>0.131</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bare</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>0.0122</td>
<td>0.0122</td>
<td>1.28</td>
<td>0.29</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.0769</td>
<td>0.0096</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>0.0891</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Live</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td>1</td>
<td>0.000589</td>
<td>0.000589</td>
<td>0.04</td>
<td>0.83</td>
</tr>
<tr>
<td>Error</td>
<td>8</td>
<td>0.105</td>
<td>0.0131</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>9</td>
<td>0.105</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 2.14. Ground cover in fenced versus unfenced runoff plots, averaged among sites.

The most noticeable pig disturbance at any of the sites was seen at Waahila Ridge (Figure 2.15). Results show a major difference between fenced and unfenced ground
cover at this site (Figure 2.16). In the fenced runoff plot, litter cover was measured at 100% due to large amounts of litter from the dominant canopy of *C. glauca*. However, the unfenced runoff plot had <92% litter, with ~7% bare soil cover. Pigs rooting appeared to have disturbed the litter surface, in some cases digging to depth >5 cm. Puu Pia also had higher bare soil levels in the unfenced plot (Appendix B).

Figure 2.15. Photograph of Waahila Ridge site, with the unfenced runoff plot on left and the fenced plot on right.
There were no significant differences in bare soil cover among sites (Table 2.9). Soil cover was measured in August 2009, because of a lack of replication; no interaction effect could be tested in the ANOVA. Lyon Arboretum, Manoa Falls, Puu Pia, Roundtop, and Waahila Ridge all had slightly higher average levels of bare soil in their unfenced plots (Figure 2.17). Roundtop had higher average bare soil levels than any other site in both unfenced and fenced plots.

**Figure 2.16. Ground cover in the fenced versus unfenced runoff plots at the Waahila Ridge site.**
Another site with high levels of pig activity was Roundtop. Game cameras captured images of pigs walking across and through the unfenced runoff plot on multiple instances. Chickens were also seen on many occasions in the area, and captured with the game camera, but were not observed in the runoff plot itself. The Roundtop site was characterized by large amounts of bare soil and steep slopes, as well as lots of animal activity possibly associated with the many *Persea americana* (avocado) and *Diospyros discolor* (velvet apple) trees nearby. Litter cover was 83.8% in the fenced plot and only
65.8% in the unfenced plot (Figure 2.18). Bare soil cover was 2.9% in the fenced plot and 8.2% in the unfenced plot. Live plant cover was higher in the fenced plot (11.0% vs. 9.0%), while coarse woody debris was higher in the unfenced plot (4.3% vs. 3.8%).

![Ground cover in fenced versus unfenced runoff plots at the Roundtop site.](image)

Finally, looking at the whole plot groundcover data (Figure 2.19), the percent litter cover was slightly higher in the unfenced than the fenced plots, opposite to what was seen in the runoff plots. However, levels of bare soil are similar (7.2% fenced and 7.0% unfenced), and the live plant, root, and rock cover all are higher in the fenced areas. The only other ground cover higher in unfenced plots was standing dead vegetation.
2.14 Runoff Volume

Across the study period runoff volumes ranged from <0.1 to >120 L. Runoff volume on many occasions was greater than bucket capacity of 13.25 L, even with collection feeder trays splitting off 50% of the runoff from Lyon Arboretum, Manoa Cliffs, and Pauoa Flats. Overflow buckets results were analyzed separately because they were installed only at Lyon Arboretum and Manoa Falls, even though many of the other sites overflowed. Thus, runoff volumes in many cases are conservative estimates as during the larger rain events almost every site exceeded runoff bucket capacity. For example, during the large December event, every site except Waahila Ridge and the Roundtop unfenced plot overflowed. In March, only the Waahila Ridge plots and the Manoa Falls fenced plot did not overflow.

The repeated measures ANOVA indicated that month, site, site by month interaction, and the site by treatment interaction all accounted for a significant proportion
of the variance in the runoff volume data (Table 2.10). While runoff volume was significantly different among months, there was also a significant site by month interaction.

<table>
<thead>
<tr>
<th>Source</th>
<th>Num df</th>
<th>Den Df</th>
<th>Chi-Square</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>10</td>
<td>60</td>
<td>948.40</td>
<td>94.84</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Site</td>
<td>6</td>
<td>60</td>
<td>1980.03</td>
<td>330.00</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>60</td>
<td>3.83</td>
<td>0.0503</td>
<td>0.055</td>
</tr>
<tr>
<td>Site x Month</td>
<td>60</td>
<td>60</td>
<td>1219.76</td>
<td>20.33</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Treatment x Month</td>
<td>10</td>
<td>60</td>
<td>8.31</td>
<td>0.83</td>
<td>.60</td>
</tr>
<tr>
<td>Site x Treatment</td>
<td>6</td>
<td>60</td>
<td>15.46</td>
<td>2.58</td>
<td>0.0275</td>
</tr>
</tbody>
</table>

The monthly pattern of runoff volumes followed a similar trend to throughfall amounts, though there were some differences. December, as well as being the largest throughfall event, was also the largest runoff event with 12.2 L (Figure 2.20). March was the second-largest runoff event; averaging only 0.3 L less than December with 11.9 L. July was the smallest throughfall event, and also by far the smallest average runoff event, capturing less than half the volume of any other month. The month of October was an exception to the trend, and had the second-lowest runoff volume (6.9 L, same amount as June) despite being the fourth-largest throughfall event. The data also showed a seasonal trend, with the wet season months of November, December, and March being significantly larger runoff events than any dry season month except September. Besides the September event, average runoff volume was higher in every wet season month than any of the dry season months.
Average runoff volume among sites showed a different pattern from the average throughfall among sites. Lyon Arboretum received the most throughfall and also had the highest average runoff volume (Figure 2.21). Manoa Cliffs, on the other hand, received the fourth-highest throughfall but had the second-most runoff volume. Manoa Falls, Pauoa Flats, and Puu Pia had statistically similar mean runoff amounts. The driest sites, Roundtop and Waahila Ridge, showed no statistical difference in runoff amount.

Figure 2.20. Mean runoff volume in liters per rain event, among months. Error bars represent ± 1 standard error. Letters indicate significantly different means according to least squares means test.
The site by treatment interaction was a significant effect in the model. Manoa Cliffs, Manoa Falls, Pauoa Flats, and Puu Pia had larger average runoff amounts from unfenced plots (Figure 2.22). Conversely, Lyon Arboretum, Roundtop, and Waahila Ridge had larger average runoff amounts from fenced plots. The largest average difference between treatments was seen at Manoa Cliffs, with 15.4 L from the fenced plot, and 18.46 L from the unfenced plot.

Figure 2.21. Mean runoff volume among sites in Liters per rain event. Error bars represent ± 1 standard error. Letters indicate significantly differences from least squared means.

Figure 2.22. Mean runoff volume in liters per rain event averaged across all plots. Error bars represent ± 1 standard error.
During the December and March rain events, both plots at Lyon Arboretum generated amounts of runoff in excess of the 128 L combined capacity of collection and overflow buckets (Figure 2.23). This was a large volume of runoff from a 5.04 m² area, and was unexpected. However, this represents approximately 12-19% of the total throughfall volume from the December and March events at Lyon Arboretum. After overflow bucket instillation, runoff at Manoa Falls exceeded the collection buckets only during the December and March events. The largest total amount of runoff at Manoa Falls was from the unfenced plot during the December event, with 43.3 L captured. This represented 6-8% of the total throughfall volume. Overall, the total runoff volume varied from <1–16% of total throughfall volume among the months. Lyon Arboretum had the largest average runoff to throughfall ratio (7.8%), while Waahila Ridge had the lowest average runoff to throughfall ratio (2.9%).

Figure 2.23. Combined runoff volume from collection buckets and overflow buckets. Asterisks represent upper limit of volume (overflow of both buckets).
2.15 Total Suspended Solids in Runoff

Across the study period, levels of TSS in runoff ranged from <0.01 to 7.05 g L\(^{-1}\) from individual plots. The repeated measures ANOVA indicated that TSS in runoff differed significantly among months, but not among sites or between treatments (Table 2.11). There was also a significant site by month interaction. As indicated by the site by month interaction, TSS levels were at times highly variable among sites, with CVs of 0.32-2.25.

Table 2.11. Repeated Measures ANOVA for TSS in runoff.

<table>
<thead>
<tr>
<th>Source</th>
<th>Num Df</th>
<th>Den df</th>
<th>Chi-Square</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>10</td>
<td>60</td>
<td>599.14</td>
<td>59.91</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Site</td>
<td>6</td>
<td>1</td>
<td>194.76</td>
<td>32.46</td>
<td>0.13</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>1</td>
<td>1.40</td>
<td>1.40</td>
<td>0.45</td>
</tr>
<tr>
<td>Site x Month</td>
<td>60</td>
<td>60</td>
<td>623.48</td>
<td>10.39</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Treatment x Month</td>
<td>10</td>
<td>60</td>
<td>9.87</td>
<td>0.99</td>
<td>0.46</td>
</tr>
<tr>
<td>Site x Treatment</td>
<td>6</td>
<td>1</td>
<td>8.65</td>
<td>1.44</td>
<td>0.56</td>
</tr>
</tbody>
</table>

December had the largest rain event with the most throughfall and also the highest average TSS (Figure 2.24), more than double the amount of any other month. Though February and April were small events overall the seasonal trend was still evident. The wet season months of November, December, January, and March had higher mean TSS in runoff than any of the dry season months. June, July, and August had the lowest mean TSS in runoff, averaging >0.1 g L\(^{-1}\).
The site effect was not significant, but there were trends seen in the data. Pauoa Flats had the highest mean TSS per rain event, 1.24 g L$^{-1}$ (Figure 2.25). Puu Pia (1.17 g L$^{-1}$) and Lyon Arboretum (1.03 g L$^{-1}$) had slightly lower mean TSS in runoff. Manoa Cliffs had the next lowest mean TSS in runoff, 0.52 g L$^{-1}$; followed by Roundtop (0.31 g L$^{-1}$) and Manoa Falls (0.17 g L$^{-1}$). Waahila Ridge had the lowest mean TSS in runoff, 0.12 g L$^{-1}$.

**Figure 2.24.** Mean total suspended solids in runoff per month averaged across all sites. Error bars represent ±1 standard error. Letters indicate significantly different means according to least squared means.
The month by treatment interaction was not significant, but there did appear to be a slight trend in the data. Seven of the eleven months had higher mean TSS in runoff from unfenced plots, while only three months had higher mean TSS from the fenced plots (Figure 2.26). In April, mean TSS in runoff was equal between fenced and unfenced plots.

Figure 2.25. Mean total suspended solids in runoff per site averaged across all months. Error bars represent ± standard error. Letters indicate significantly different means according to least squared means.
No evidence of feral pigs was ever seen at Pauoa Flats or Lyon Arboretum, but pig rooting was seen on multiple occasions at Puu Pia, and the unfenced plot at Puu Pia did have higher levels of TSS on average than the fenced plot (Figure 2.27). Manoa Falls and Waahila Ridge had the lowest average TSS per rain event. Both sites also showed slightly higher levels of TSS from the unfenced plot, and both sites had evidence of pig rooting on multiple occasions throughout the study duration. Waahila Ridge had the most extensive pig rooting seen inside any runoff plot. Despite these trends, no statistically significant differences were detected between the fenced versus unfenced treatments at any of the sites.

Figure 2.26. Mean total suspended solids in runoff per month in fenced versus unfenced plots. Error bars represent ±1 standard error.
Many variables are thought to be associated with runoff generation and erosion. In order to understand their relationships and influence on TSS, a Spearman correlation was conducted. A correlation matrix (Table 2.12) showed TSS to be positively correlated with throughfall, soil moisture, and coarse woody debris cover. Coarse woody debris had the highest correlation with TSS ($r = 0.73$, $p = 0.003$). The other ground cover variables (bare, litter, live, rock, root) did not significantly correlate with TSS. Neither basal area nor stem density were significantly correlated with TSS, but they were positively correlated with each other ($r = 0.61$, $p = 0.02$). Ksat values did not correlate with any other variable, though basal area and Ksat were correlated ($r = 0.51$, $p = 0.06$).

Overall, the most influential variable in the correlation analysis was throughfall, as it was correlated to five other variables. In addition to TSS, throughfall was also correlated with soil moisture, rock cover, live cover, and runoff amount. The relationship

![Figure 2.27. Mean total suspended solids (TSS) per plot. Error bars represent ±1 standard error.](image-url)
among throughfall, soil moisture, and runoff amount seems straightforward, given
general knowledge of the hydrologic cycle. The relationship of throughfall with the other
two ground cover variables is less obvious. Live plant cover had the highest correlation
with throughfall (p = 0.0003) of all environmental variables. Slope and soil moisture
were also important variables in the correlation. Both of these variables were
significantly correlated with four of the other environmental variables. Slope was
negatively correlated with soil moisture, and positively correlated with bare soil cover,
stem density, and basal area. It is interesting that slope was correlated positively with
both the forest structure variables, suggesting more and larger trees at the sites with
steeper slopes. Soil moisture was negatively correlated with basal area, and positively
correlated with slope. Slope was positively correlated with TSS and throughfall. Among
the ground cover variables, only litter did not correlate with any other factor. Rock cover
was positively correlated with throughfall and runoff amount.
Table 2.12. Spearman correlation matrix for the environmental variables and total suspended solids (TSS) in runoff. Non-significant results labeled as NS.

<table>
<thead>
<tr>
<th></th>
<th>TSS</th>
<th>Thrufall</th>
<th>SMoist</th>
<th>Litter</th>
<th>Bare</th>
<th>Rock</th>
<th>Live</th>
<th>CWD</th>
<th>ROVol</th>
<th>Stem</th>
<th>BA</th>
<th>Slope</th>
<th>Ksat</th>
<th>RTR</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>0.58</td>
<td>0.58</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.73</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.66</td>
</tr>
<tr>
<td>Thrufall</td>
<td>0.55</td>
<td>-</td>
<td>-</td>
<td>0.61</td>
<td>0.82</td>
<td>-</td>
<td>0.59</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
</tr>
<tr>
<td>SMoist</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.71</td>
</tr>
<tr>
<td>Litter</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bare</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.59</td>
<td>0.62</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rock</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.61</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.61</td>
</tr>
<tr>
<td>Live</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CWD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ROVol</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.87</td>
</tr>
<tr>
<td>Stem</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.61</td>
<td>0.61</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>BA</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>0.93</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Slope</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ksat</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RTR</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
Throughfall, soil moisture, and coarse woody debris were input into a multiple-stepwise regression. The analysis indicated all three were significant predictors of TSS (Equation 1).

**Equation 1. Model for predicting TSS, based on multiple-stepwise regression \( (r = 0.58, p = 0.05) \).**

\[
\text{TSS} = -0.63 + 0.1(\text{Throughfall}) + 1.68(\text{SoilMoisture}) + 10.50(\text{CoarseWoodyDebris})
\]

### 2.17 Discussion

The first objective of this chapter was to quantify throughfall, runoff volume, and TSS in runoff from forested areas of the Manoa watershed. Runoff and throughfall were recorded from one rainfall event per month for each of the 7 sites, from June 2008 through April 2009. Runoff volumes overwhelmed the collection capacity at many of the sites, but the installation of overflow buckets helped better quantify the extremely large volumes of runoff generated during wet season rain events in the upper watershed. As predicted, runoff volumes were significantly higher in many of the wet season months than the dry season months. November, December and March were the largest runoff events, all in the wet season, and significantly larger than any dry season month except September. Though September was a larger runoff event than February and April, it was the only dry season month that had larger runoff volumes than any of the wet season months.

The Repeated Measures ANOVA showed a significant difference between treatments at \( \alpha = 0.1 \), but this was confounded by a significant site by treatment interaction. Runoff volumes were also different among sites but this was confounded by a significant site by month interaction. In general, Lyon Arboretum had more runoff than
any other site, as well as more throughfall. Pauoa Flats, Puu Pia, and Manoa Falls all had similar amounts of runoff, despite being quite different in terms of forest structure, slopes and soils. Pauoa Flats was an interesting site because during many of the dry season months (June, July, September, and October) no runoff was produced; however during the larger wet season events (December and March) runoff exceeded collection bucket capacity. Lau and Mink (2006) show initiation times for runoff varies considerably in Hawaiian soils, from just a few minutes to more than 60-80 minutes, depending on antecedent saturation deficit and soil type. Another important result was the sheer amount of runoff generated from these small plots. Despite the fact that runoff plots drained an area of only 5.04 m², the amounts of runoff were extremely large, ranging from 7.5 to 26.5 L in December, especially when factoring in the overflow bucket data from Lyon Arboretum (at least 128 L total runoff). In a study of agricultural runoff plots in Hawaii, Ryder and Fares (2008) found runoff volume varied from 0.37 – 12.23 L, though it appears runoff may have exceeded bucket capacity during the largest event in their study.

Throughfall quantification was aided by the installation of four extra gauges at each site. The additional gauges gave a more extensive view of throughfall levels and the within site variability of throughfall at these sites. The average throughfall per site matched rainfall distributions (Figure 2.28), the only discrepancy being that the Manoa Falls site had higher average throughfall than the Manoa Cliffs site even though Manoa Cliffs was in a higher rainfall area. The Manoa Cliffs canopy, with Hibiscus arnottianus, C. nocturnum, and C. burmanni had a much different composition than Manoa Falls, which was heavily dominated (>95% stems) by P. cattleianum. Only one rain event per month was captured, and yet monthly rainfall data (Figure 2.29) from the USGS Real-
Time Manoa Rain Gauge (USGS 211747157485601 711.6, Kanewai Fld, Honolulu, Oahu, HI), showed a similar pattern to throughfall. December had the largest amount of rainfall at Manoa Rain Gauge (MRG) and the highest average throughfall at the study sites, followed by March and November with the next highest rainfall levels at MRG and the next highest average throughfall. The rainfall data also showed the ‘wet season’ months of January and February having less rainfall then the ‘dry season’ month of October.

Quantification of TSS in runoff showed significant differences among months and a significant site by month interaction. Though the estimates of runoff amount were conservative (i.e. underestimated during certain high rainfall events), TSS was measured on a g L\(^{-1}\) basis and therefore did not depend on the quantification of full runoff amount. These results showed TSS levels that for certain events appeared quite large for heavily forested areas. For example, the Puu Pia unfenced runoff plot yielded 7.05 g L\(^{-1}\) during the December event, which was comparable to agricultural studies that measured TSS in runoff from cultivated fields at >10 g L\(^{-1}\) (Borina et al., 2005). Ryder and Fares (2008) found TSS levels ranged from 41.3 g L\(^{-1}\) in a fallow plot after an extremely large rain event, to 0.04 g L\(^{-1}\) after a small rain event in a plot with vegetative cover of oats. A hydrological study of TSS in streams and channels in Georgia (Shelby et al., 2006) found levels ranged from 0.02 – 0.35 g L\(^{-1}\). De Carlo et al. (2007) found TSS levels at the outlet of three streams into Kaneohe Bay, Oahu (0.0008 - 0.019 g L\(^{-1}\)) were often several orders of magnitude less than levels found from the runoff plots in this study.
Figure 2.27. Isohyetal rainfall pattern and location of sites in Manoa Watershed.

Figure 2.29. Rainfall per month from USGS Kanewai Field rain gauge. Asterix denote provisional data subject to revision.
Objective two involved determining if feral pigs increase both runoff amount and TSS in runoff. While some interesting site and seasonal patterns were observed, the data did not show significant feral pig influence on runoff volume or composition. Difference in runoff volume between treatments was significant at $\alpha = 0.1$, but there was a significant treatment by month interaction. Many variables are involved in runoff generation and erosion processes, and Manoa Valley is characterized by extremely heterogeneous physical and biological properties, which made this objective particularly hard to address. This research indicated that feral pigs are visiting runoff plots (Figure 2.30), and may even be disturbing soils and introducing exotic plant species.

![Game camera photo of feral pig at Manoa Cliffs with front hooves inside unfenced runoff plot.](image)

**Figure 2.30.** Game camera photo of feral pig at Manoa Cliffs with front hooves inside unfenced runoff plot.

Feral pig effects on soils (and therefore runoff) may take a longer time period to appear than the two years that the runoff plots and exclusion fencing have been in place.
The effect of feral chickens (*Gallus gallus domesticus*), mongooses (*Herpestes javanicus*), and rats (*Rattus sp.*), particularly at the Roundtop site, was another variable that was not quantified and which had the ability unlike the feral pigs, to bypass exclusion fencing by climbing through or over, or flying above fences to disturb litter and soils and potentially increase erosion.

The third objective was to investigate temporal and spatial differences in TSS levels in runoff. Results show TSS levels exhibited strong seasonal trends, with significantly higher values in many of the wet season months than the dry season months. For example, November, December, January, and March all had significantly larger TSS amounts than any of the dry season months. Total SS appeared to be highly influenced by the magnitude of throughfall of an individual rain event, and TSS and throughfall were significantly correlated. The December rain event had significantly higher throughfall than any other month, and significantly higher levels of TSS. Spatial variation of TSS levels was high, with Puu Pia and Pauoa Flats >1.1 g L⁻¹; while Manoa Falls and Waahila Ridge were both <0.2 g L⁻¹. Puu Pia and Pauoa Flats were physically different sites, yet had similar average levels of TSS in runoff. Puu Pia had the highest stem density and basal area of any site, while Pauoa Flats had the lowest stem and the second smallest basal area. Puu Pia also had the steepest slope, while Pauoa Flats, as the name suggests, had the lowest slope. No pig disturbance was ever seen at Pauoa Flats, while evidence of pig rooting was seen on multiple occasions at Puu Pia. The pig activity at Puu Pia could be an explanation of why TSS in runoff was so high despite the high stem density and lower levels of throughfall.
The final objective of this study was to investigate correlations between environmental variables and TSS in runoff. Total SS was significantly correlated with throughfall, soil moisture, and coarse woody debris cover. The correlation with throughfall could indicate that more throughfall means more opportunity for physical detachment of soil particles. Also, because overland flow is blocked from entering the runoff plots, the process of soil erosion from the plots was assumed to be caused by detachment of soil particles from the physical impact of falling droplets inside the plot.

Since the rainfall events were typically only one or two day episodes, it would seem likely that the larger rainfall events involved higher rainfall intensity. In field experiments, Grace (2008) found total precipitation, average rainfall intensity, and maximum 30-minute rainfall intensity were detected as the most influential storm characteristics in determining soil erosion. It was surprising that coarse woody debris had the strongest correlation with TSS, and it was not obvious why such a relationship would exist. It could be that the coarse woody debris (defined as tree litter with >2.0 cm diameter) are related to the larger tree species (e.g. *E. grandis*) with taller canopies that cause throughfall to have greater velocity when striking the soil surface, causing soil particle detachment. Though I hypothesized that ground cover in general would correlate with TSS in runoff, it seemed more likely that bare soil or litter would have a stronger relationship with TSS than coarse woody debris. However, neither bare soil nor litter had significant correlations with TSS. This may have to do with the highest levels of bare soil being at Roundtop, which was one of the driest sites and averaged low levels of TSS. Bare soil levels were overall quite low, considering the high amounts of sediment coming off the plots at times. Besides Roundtop, litter cover levels were overall quite high, above
60% even at Roundtop, and as high as 100% at Waahila Ridge. Litter protects the soil surface from raindrop impact and slows overland flow, reducing erosion.

Soil moisture is a significant factor in determining runoff generation (Lau and Mink, 2006). Browning’s (2008) study at the same sites found that TSS in runoff was also correlated with soil moisture. He found that TSS was also correlated with runoff amount, canopy cover, and bare soil cover. However, his estimation of bare soil cover involved a different (and coarser visual estimation) method than the line-transect method I employed. There also could have been an even higher correlation between TSS and soil moisture except for the fact that soil samples were taken in the first dry period of each month during the activation process. Because rain events are hard to predict and activation was initiated regardless of the long-term weather pattern, there was often a lag time between site activation/soil sampling and rainfall events. This lag time ranged from three days to almost two weeks. This meant that soil moisture levels could be quite different from what was originally measured once the rain event arrived.

Most Hawaiian soils are known to absorb water readily (Lau and Mink, 2006) with infiltration rates ranging from 0.043-0.51 m hr⁻¹ depending on soil type (USDA, 1972). Reduction in infiltration as a result of various land uses (crop production, urbanization) was also reported. Ksat values between 0.3 and 1.2 m day⁻¹ (0.0125 and 0.05 m hr⁻¹) were reported from forested sites near Lyon Arboretum (Lau and Mink, 2006). Antecedent soil conditions, however, were seen to affect infiltration, with an approximately 50% reduction during wet conditions. The data showed large differences among sites, and even among plots at the same site. For example, Ksat at the Lyon Arboretum site in this study was calculated to be 0.055 m hr⁻¹ in the unfenced plot, but
the fenced plot was calculated at 21.75 m hr⁻¹, or almost 500 times larger. Some of the calculated values from other sites are in that 0.013-0.05 m hr⁻¹ range, but many are orders of magnitude larger, and some even smaller. There could be several reasons why data was so variable. First, was the fact that this instrument was designed to be used on level ground, and the sites in this study had slopes ranging from 6-26%. Second, there was also the problem of finding a homogenous soil surface inside the site without roots, rocks, or other debris, and without being inside the runoff plot itself.

Though the basal area and stem density were not correlated to TSS, they did help illustrate the heterogeneity of the watershed and the physical and biological differences between sites. The seedling and sapling data may help illuminate the effects of feral pigs in the upper watershed areas. *Psidium cattleianum* was of particular interest because it is a well-documented food source of feral pigs (Huenneke et al., 1990; Noguiera et al., 2007), and its seeds are spread in pig feces (Diong, 1982). Pigs also increase soil fertility, which may impede the reestablishment of native plant species adapted to nutrient-poor environments (Noguiera-Filho et al., 2009). The sapling and seedling counts showed close to twice as many individuals in the unfenced versus the fenced plots. This could be an effect of pig presence, and though this data was not a main focus of the study, it is nonetheless an interesting result. A study in Big Thicket National Preserve, Texas, found exotic *Sapium sebiferum* (Chinese tallow tree) was twice as abundant in plots with feral pigs present (Siemann et al., 2009). *Cinnamomum burmanni* seedlings are not thought to be spread by feral pigs, but the many seedlings found are indicative of the highly invasive nature of this tree in Hawaii (Starr et al., 2003). It is actively invading many mesic forests and is known for dense monotypic stands and extremely high seedling recruitment, even...
in low light conditions. Pig disturbance could help create favorable conditions for seedling recruitment. The tree produces small fruits that are thought to be dispersed by birds.

2.18 Conclusions

Hypothesis one predicted that TSS would be higher in the wet season than the dry season, and the results of this study generally supported this hypothesis. The repeated measures ANOVA showed significantly different levels of TSS among months although there was also a significant site by month interaction, indicating that the trends were not always consistent across all sites. This suggests that resource managers should be more concerned about runoff and sedimentation from the upper forested areas of Hawaiian watersheds during the months of November-April. Sediment traps, such as those used at construction sites, coir logs, or vegetative strips could be applied to areas with high overland flow to help decrease the amount of sediments reaching streams and waterways. Certain activities, such as construction and trail maintenance could be curtailed during the wet season. The wet season may also be a time when feral pigs are more active, and move lower in the watershed (Hone, 2002). Pig population control methods could be encouraged during the wet season, and perhaps hunting limitations relaxed.

Hypothesis two predicted that TSS would be higher in unfenced plots than fenced plots. My data did not support this hypothesis. The repeated measures ANOVA showed no significant difference between plots. Many factors influence runoff generation and erosion, and the heterogeneity of the landscape in the upper forested areas of Manoa watershed made it hard to determine what, if any, effects feral pigs were having on
runoff. Also, the plots had only been in place for one year prior to the start of this study, and differences may yet manifest. Some of the sites (Puu Pia, Roundtop) had much higher levels of TSS in the unfenced plots, and these sites did see multiple occurrences of pig rooting.

Hypothesis three predicted that ground cover and soil moisture would have the highest correlation with TSS in runoff. This hypothesis was partially supported by the data. Soil moisture and coarse woody debris, along with throughfall amount, were significantly correlated with TSS. A correlation with soil moisture was also found in an earlier study at these sites by Browning (2008). Soil particles in wetter soils may be more susceptible to dislodgement by water droplet impact or overland flow. There could also be a relationship among sites with moister soils and higher levels of TSS in runoff. Soil moisture was determined by laboratory methods, but handheld devices exist that allow for instantaneous determination of soil moisture in the field. Such devices may assist resource managers in identifying areas of concern for high TSS generation.

Coarse woody debris was not the ground cover variable expected to correlate best with TSS. Litter cover and bare soil cover were expected to be more important in determining TSS in runoff. Coarse woody debris may be associated with another factor that is important to runoff generation and TSS in runoff. Coarse woody debris were defined as litter >2.0 cm diameter, which are therefore associated with larger trees. Many of the *P. cattleainum, C. nocturnum*, and other species of tree measured DBH only slightly larger than 2.0 cm in diameter. Most litter from these trees would be expected to have diameter <2.0 cm. Perhaps TSS in runoff is associated with trees such as *E. grandis* and *E. robusta* that were on average much larger in diameter. Such a relationship could
help guide resource managers charged with protecting water quality in targeting efforts of exotic tree removal or containment. Coarse woody debris may also represent canopy gaps where raindrops fall unhindered, striking the soil surface with greater force and more often detaching soil particles.

Comparative studies of fencing to exclude feral pigs or inhibit their access into sensitive forested areas are few (Campbell and Long, 2009), and these runoff plots provide an excellent opportunity to study feral pig impacts on water quality, soils, and vegetation. Using paired runoff plots in a forested setting is a novel approach; the literature review found no other similar studies besides Browning’s (2008) research at these same plots. Besides elucidating site and seasonal differences in runoff, this study provides baseline conditions for further research at the runoff plots. As time goes on, I expect differences between fenced and unfenced plots will continue to develop, and further research is needed at these sites to document these dynamics.
CHAPTER 3: ENTEROCOCCI IN RUNOFF AND SOILS

3.1 Introduction

This study aims to improve our understanding of the processes of runoff and soil erosion in upper forested areas of a Hawaiian watershed and to identify the effects pigs have on erosion, runoff, water quality, and fecal indicator bacteria (*Enterococcus* sp.). It is thought that feral pigs can not only harm native flora and fauna but may even adversely impact the health and function of entire watersheds (Noguiera-Filho et al., 2009). Such effects also raise important concerns for public health. From Santa Monica Bay, CA to the Great Lakes, levels of indicator bacteria have been shown to correlate with incidence of illness reported by swimmers (Haile et al., 1999; Wade, 2006). Though some research suggests that Enterococci are free-living and reproduce in Hawaiian soils (Hardina and Fujioka, 1991), mesocosm experiments have found that Enterococci do not multiply in subtropical waters and sediments (Anderson et al., 2005). This study will aid natural resource managers and policy makers, helping them identify the effects of feral pigs, if any, and informing them of the effectiveness of fencing as a tool for improving water quality.

The specific objectives of this chapter are as follows: (1) Quantify Enterococci in runoff and soils from forested areas of Manoa watershed; (2) Determine if feral pigs impact Enterococci in runoff and soils; (3) Investigate temporal and spatial differences in Enterococci levels in runoff; and (4) Investigate correlations among environmental variables (slope, infiltration rate, soil moisture, stem density, etc) and Enterococci in runoff. Given what was learned in the literature review, and drawing on the results of
previous research at these sites (Browning, 2008), I developed four hypotheses: (1) Higher storm intensity and higher throughfall inputs will lead to higher Enterococci levels in runoff during the wet season (November-April) than in the dry season (May-October); (2) Fecal contamination will lead to higher Enterococci levels in runoff and soil at unfenced plots exposed to feral pig activity; (3) Of all environmental predictors measured, ground cover and soil moisture will have strongest correlations with Enterococci in runoff as ground cover influences soil erosion processes, and Enterococci survival is thought to be higher, and infiltration is lower under wetter soil conditions which directly affect runoff production; (4) TSS in runoff will positively correlate with Enterococci abundance in runoff as bacteria are thought to associate with soil particles in surface waters.

Materials and Methods

3.2 Site Selection

In the spring of 2007, eight sites were selected to investigate runoff processes and the effects of feral pig exclusion in the Manoa watershed. The sites were chosen from the upper forested areas of the watershed, based on attributes of slope, accessibility, and vegetation. Slope was the primary determining factor in initial site selection to allow for construction of exclusion fencing and to ensure collection of accurate runoff data. According to Mutchler et al. (1994) a slope of 9% or less is considered the standard in most agricultural studies that incorporate runoff plots; however areas with <9% slope were not easy to find as the average slope of the watershed is 47%. Using a Geographic
Information System (GIS), a map of slope characteristics throughout the watershed was created and areas with slopes between 5-30% were identified as potential sites (Fig. 3.1). Final site selection was based on ease of accessibility and proximity to existing trail networks as well as homogeneity of slope/vegetation at each site (Table 3.1). Unfortunately the Palolo site was vandalized repeatedly throughout the study period and had to be abandoned, leaving only seven sites for this study.

Figure 3.1. A GIS map of the variation in slope across the Manoa watershed with the locations of original eight sites of study.
Table 3.1. Characteristics of the seven sites in Manoa watershed. Elevation and soil series information were obtained through a GIS analysis, while slopes were recorded on site using a handheld clinometer.

<table>
<thead>
<tr>
<th>Site</th>
<th>Elevation (m)</th>
<th>Slope (%)</th>
<th>Soil Series</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyon</td>
<td>215</td>
<td>15.5</td>
<td>Lolek aa</td>
</tr>
<tr>
<td>Mānoa Cliffs</td>
<td>450</td>
<td>8</td>
<td>Rough Mountainous Land</td>
</tr>
<tr>
<td>Mānoa Falls</td>
<td>171</td>
<td>17</td>
<td>Lolek aa</td>
</tr>
<tr>
<td>Pauoa Flats</td>
<td>538</td>
<td>6</td>
<td>Rough Mountainous Land</td>
</tr>
<tr>
<td>Puu Pia</td>
<td>209</td>
<td>26</td>
<td>Lolek aa</td>
</tr>
<tr>
<td>Round Top</td>
<td>340</td>
<td>25.5</td>
<td>Tantalus</td>
</tr>
<tr>
<td>Waahila Ridge</td>
<td>340</td>
<td>14</td>
<td>Manana</td>
</tr>
</tbody>
</table>

3.3 Site Layout

Each site is approximately 10 meters long by 10 meters wide. Two paired 10 m by 5 m runoff plots were established at each site; one runoff plot surrounded by exclusion fencing, the other unexclosed. Runoff plots were oriented down the slope to effectively capture the natural path of overland flow at each site. Fences were constructed of 14-gauge utility fencing 0.91 m tall and held in place with metal posts. Barbed wire was strung along the bottom edge of each fence to provide further protection from pig damage. During construction, throughfall gauges were affixed to posts directly centered between the paired plots at each site. In December 2008, four more throughfall gauges were added to each site (Figure 3.2).
3.4 Runoff Plot Design

Following fence installation, runoff plots were constructed within both unfenced and fenced plots at each site. Runoff plots are approximately 4.2 m long by 1.2 m wide, oriented down the prevailing slope of each site. To prevent additional runoff entering from outside the plot, 15 cm tall plastic dividers were buried roughly 7.5 cm into the soil along the upslope and outer edges of each runoff plot. These plastic pieces formed the framework that channeled runoff to a central collector (Fig. 3.2). This central collector was located at the down slope end of the runoff plot, consisting of a triangular metal runoff collector that funneled all runoff into a 10 by 5 cm opening (Fig. 3.2). A metal feed tray connected the metal collector to an 18.9 L bucket for storing runoff. A

Figure 3.2. The basic layout of each of the seven sites. Each site was oriented so both fenced and unfenced plots had similar slope and vegetation.
rectangular hole was cut into the side of the bucket into which the feed tray drained. Water-tight lids were affixed to the top of each bucket to prevent throughfall from directly falling into the bucket. Sheet metal collector covers were constructed to also prevent direct throughfall on the metal collector and installed in December 2008.

3.5 Activation Periods and Runoff Sampling

Runoff samples were collected from June 2008 to April 2009 to ensure collection of samples from both the wet and dry seasons. At the beginning of each month a two-day dry period was targeted to activate all plots and initiate runoff collection. Activation of each site included emptying all throughfall gauges, collecting soil samples for moisture analysis, and emptying/cleaning the runoff collection buckets. Runoff was removed with a hand operated suction pump, and then paper towels were used to clean and dry all inside surfaces of collection buckets. Sterile latex gloves were worn at all times during emptying and cleaning procedures. Collection times were determined by observing weather conditions and monitoring the online USGS rain gauge located in Mānoa Valley. When the rain gauge recorded a significant rainfall (typically > 2 cm) during the active period, collection was initiated.

The collection process involved measurement of total runoff and collection of runoff sub-samples to be analyzed for TSS. During all activation and collection activities, care was taken to avoid walking within runoff plots. Soil samples were taken within the sites, yet outside the runoff plots so as not to disturb soils. In the duration between observation periods runoff was allowed to continue its natural flow into the buckets. If the buckets began to overflow, runoff simply drained out through the same
opening from which it entered and continued flowing down slope. Throughfall gauges were covered with duct tape while not active.

3.6 Estimation of Other Environmental Variables

As this project was designed to monitor runoff and sediment loss from the study areas and to develop correlation and regression equations for TSS in runoff, it was important to quantify a variety of different variables that influence these processes. This required recording of site characteristics throughout the duration of the study, as well as prior to rain events, and also the analysis of runoff after the events. The other environmental variables recorded were slope, soil series, soil water content, throughfall, infiltration rate, forest canopy and understory species composition, stem density, basal area of trees, seedling/sapling counts, and ground cover assessment. The following paragraphs summarize the methodology used to determine these characteristics.

3.6.1 Slope Recordings

Slopes were measured using a handheld clinometer and ranged from 5% to 27%. No site was recorded to have greater than a 2% difference between the fenced and unfenced plots. Ultimately, all seven sites represented a range of different slope types as shown in Table 3.1.

3.6.2 Soil Series Determination

Soil series for each site were retrieved from NRCS soil maps. Additionally, global positioning system (GPS) coordinates for each site recorded in the field were
added to the GIS. These two data layers were overlaid to identify the soil series of each site based on the latest soil survey of Oahu (Foote et al. 1965). The seven sites represented four different soil series; Tantalus, Lolekaa, Manana, and Rough Mountainous Land (rRT) (Table 3.1).

3.6.3 Calculation of Soil Water Content

Gravimetric soil water content, was determined during the activation phase of each month. A 2 cm diameter soil corer was used to collect samples from approximately the upper 5 cm of the soil profile. One composite sample was collected during site activation from both the fenced and unfenced areas. The composite sample consisted of three separate randomly-located individual samples from each area, combined in a sterile plastic bag. No soil samples were taken from within runoff plots to avoid disturbing soils. Percent gravimetric soil moisture was calculated by the equation:

\[
\% \text{ Gravimetric Soil Moisture} = (1 - \frac{\text{dry mass soil}}{\text{wet mass soil}}) \times 100
\]

3.6.3. Infiltration Rates

Infiltration rate and the coefficient of saturation (Ksat) were determined at each plot using a Tension Infiltrometer (8 cm model, Soil Measurement Systems, Tucson, AZ). The most level and uniform area of each fenced/unfenced plot (although not within the runoff plot areas) was chosen as the infiltration measurement site. A metal spatula was used to cut out a shallow hole in the litter layer the same size/shape as the infiltrometer base to expose the soil surface. A layer of fine sand was added to the hole. The infiltrometer was then filled with water and placed on the sand layer. The tension
was set to 11 cm. If infiltration did not commence, tension was lowered to 10 cm. Readings of water level were taken every 30 seconds for 10 minutes, then every 60 seconds for another 10 minutes, and a final reading was taken after five more minutes. The tension was then lowered to 8 cm if initial tension was 11 cm, 7.5 cm if initial tension was 10 cm. This was to ensure enough of a tension difference between the two readings to allow for calculation of Ksat.

Equilibrium infiltration slopes were determined graphically. The slope was then multiplied by the area of the infiltrometer’s base to determine the volume of water infiltrated per time. Ksat was calculated from the equation:

\[
\alpha = \frac{\ln \left( \frac{\text{Infiltration rate } X}{\text{Infiltration rate } Y} \right)}{(- \text{Tension } X - \text{Tension } Y)}
\]

\[
Ksat = \frac{\text{Infiltration rate } X}{\text{Area of base}^{(\alpha * \text{Tension } X) \times (1 + 4 / \text{Area of base} * \alpha)}}
\]

Where X = tension 1, and Y = tension 2

3.6.4 Throughfall Recording

A standard all-weather rain gauge (Productive Alternatives, Fergus Falls, MN) was used to measure throughfall (mm) of rain events. As part of the activation process, each throughfall gauge was emptied and a thin layer of mineral oil was added to prevent evaporation

3.6.5 Forest Structure Characterization

The seven sites in Manoa Valley varied in terms of forest structure and species composition. To quantify these differences, a 20 m by 20 m plot directly surrounding
each site was established and all trees > 2 cm diameter at breast height (DBH) were measured. DBH is defined as diameter at 1.32 m from the ground surface. Species was recorded for each tree in the plot. If a tree could not be identified to the species level in the field, a leaf sample was taken back to the lab for identification. Stem density (# stems ha\(^{-1}\)) was calculated by counting the number of stems in the 400 m\(^2\) plot and scaling to a hectare basis. Basal area (cm\(^2\) ha\(^{-1}\)) of each tree was calculated from individual DBH measurements, and summed to give total basal area in the 400 m\(^2\) plot, which was scaled to a hectare basis.

3.6.6 Seedling and Sapling Counts

Seedlings and saplings were measured in two 1 m\(^2\) plots within each fenced and unfenced plot (Figure 3.3). Measurements were taken at the upper and lower outside corner (the only corners without rain gauges) of each plot. This was done to minimize any effects of trampling or disturbance from previous research activities in the plots (e.g. throughfall gauge sampling). Seedlings were defined as any plant < 15 cm in height. Saplings were defined as all plants > 15 cm in height, but less than 2 cm DBH. Species identification was determined in the field or with voucher specimens.
3.6.7 Estimation of Ground Cover

Ground cover at the sites was recorded for both the runoff plots and the larger fenced/unfenced area. A measuring tape was used to establish a transect line and a visual assessment of ground cover was made at predetermined distances along the transects. For the whole plot, measurements were taken every 25 cm along two separate 10 m transects (Figure 3.4). Ground cover measurements in the runoff plot were taken every 3 cm along three 1.2 m transects equally spaced along the runoff plot. Visual determination of ground cover was made from a direct top-down view above the transects. Ground cover was divided into the following categories: live plant, standing dead plant, coarse woody debris, litter, bare soil, rock, and root. Coarse woody debris was defined as woody debris/branches > 2 cm diameter. Litter included detritus, leaves, and any woody debris < 2 cm diameter.
3.7 Runoff Collection and Analysis

3.7.1 Runoff Amount

Runoff amount was measured for each rainfall event, prior to collection of runoff for analysis in the laboratory. During initial site selection, three of the eight sites (Pauoa Flats, Manoa Cliffs, and Lyon) were observed to receive particularly large amounts of throughfall. In an attempt to prevent collection buckets from overflowing, these three sites were fitted with a feed tray that diverted half of all runoff into the collection buckets instead of receiving 100%. The other half was diverted around the bucket and continued down slope. For these sites, the volume was doubled after initial calculation to account for this adjustment. Before any samples were removed from the collection bucket, the depth of runoff in the collection bucket was recorded to calculate the total volume. A yardstick was used to determine depth of runoff in each collection bucket. The yardstick
was cleaned with paper towels after each use. Sterile latex gloves were worn at all times, and changed prior to each new measurement.

2.7.2 Runoff Overflow Buckets

During the initial months of this study, it was recognized that runoff collection buckets were in many cases too small to collect the total amount of runoff from certain rainfall events. A small hole was drilled in the downslope edge of each collection bucket and a length of rubber hose was inserted in the hole. The rubber hose was layed downslope and inserted into another hole drilled into a larger plastic tub (the “overflow bucket”). This overflow bucket captured extra runoff to a volume of 97.7 L. A yard stick was used to record runoff overflow volume as above.

2.7.3 Runoff TSS Analysis

After the depth was recorded, the contents of the collection bucket were thoroughly mixed with the yardstick and a runoff water sample was collected in an acid-washed 500 mL bottle. Samples were taken back to the lab on ice and refrigerated before analysis for total suspended solids (TSS). Total SS were measured by vacuum filtration of 100 mL of sample. First a Whatman 5 filter paper (Whatman, Kent, United Kingdom) was placed on a watch glass and weighed on an electronic balance. Samples were homogenized and a 100 mL aliquot was extracted and poured onto filter paper placed on a Buchner funnel attached to a 500 mL vacuum flask. Each filter paper and watch glass were then placed into a 105°C oven and dried for 24 hours. Afterwards the filters were
weighed and the original weight was subtracted from the dry weight to calculate the TSS in g L\(^{-1}\) (EPA, 1971).

### 3.7.3 Runoff Enterococci Analysis

After the depth was recorded, the contents of the collection bucket were thoroughly mixed and a runoff water sample was taken in a sterile 100 mL IDEXX container (IDEXX Laboratories, Westbrook, ME). Samples were taken to the laboratory on ice, and then refrigerated until analysis, within 36 hours of sample collection. In the lab, 100 mL of sample was transferred with a pipette using sterile, disposable tips, to a new sterile container and mixed with Enterolert reagent. Samples were shaken by hand a minimum of 40 times to ensure proper mixing. Samples were diluted when runoff samples contained high levels of sediment, or if previous samples were found Enterococci levels to be higher than 2,500 CFU. At least one duplicate was made per sample per sampling event. A control sample consisting of 100 mL of DI water was also processed according to the same methods.

After mixing, samples were poured into labeled Quanti-Tray 2000 trays. The trays were heat sealed and placed into a 41°C incubator for 24-28 hours. After incubation, samples were removed and placed under an ultraviolet light to count the number of fluorescing wells. Wells were counted only if fluorescence was complete (only brightest wells were counted as positive). To determine Most Probable Number (MPN) of CFU, the IDEXX Quanti-Tray MPN sheet was used. MPN for 90% dilutions was multiplied by a factor of 10. MPN for 99% dilutions was multiplied by a factor of 100.
3.8 Enterococci in Soils

Surface soil samples were taken in August 2009 from each of the 14 plots and analyzed for Enterococci. Soils were sampled with disposable plastic food-grade spoons to ensure no cross contamination between plots. An aggregate sample was prepared from four locations within each plot, from the top 0-5 cm of soil surface, approximately 30 cm from each corner of the runoff channelizing plot. Samples were stored in sterile disposable Ziploc bags and transported on ice to the laboratory. Enterococci analysis methods were based on recommended USGS techniques (Myers et al., 2007) and Ragosta (2007). Approximately 5 g of soil was weighed and placed in a sterile IDEXX bottle. One hundred mL of sterile 0.15 M NaCl dispersant solution was added to the sample. Sample bottles were then placed on a rotary shaker table for 45 minutes.

After shaking, samples were left to settle for 30 seconds then a 10 mL aliquot was removed from the top 30-40% of solution by sterile pipette and transferred to a new sterile IDEXX bottle. 90 mL of sterile DI water was added along with the Enterolert reagent. Samples were placed on a shaker table for another 5 minutes. After the final shaking, samples were then heat sealed in Quanti-Tray 2000 trays and processed identical to the methods described in section 3.7.3.

3.9 Statistical Analyses

All statistic analyses were performed using SAS version 9.1 (SAS Institute, Cary, NC). A GLM ANOVA was used to investigate differences in variables that were only measured once such as ground cover and soil Enterococci among sites. For the GLM ANOVAs, a post-hoc comparison of means was carried out using Duncan’s Multiple
Range Test. A repeated measures ANOVA was used to differentiate between Enterococci levels in among months and sites, and in fenced versus unfenced treatments. Month was the repeated factor in these analyses. A least squares procedure was used for post-hoc mean comparisons. Spearman correlation was used to evaluate relationships among Enterococci and all environmental variables. A multiple stepwise regression (MSR) was also used to determine the best predictors of Enterococci in runoff.

Results

3.10 Enterococci in Runoff

Enterococci levels in runoff were highly variable, ranging from <1 cfu 100 mL$^{-1}$ to >72,000 CFU 100 mL$^{-1}$ for individual measurements. The average level of Enterococci in runoff was 6620.5 CFU 100 mL$^{-1}$. The repeated measures ANOVA indicated that month, site, and the month by site interaction accounted for a significant proportion of the variance in the Enterococci data (Table 3.2). Treatment, while not significant at $\alpha = 0.05$, was significant at $\alpha = 0.1$.

Table 3.2. Repeated Measures ANOVA model for Enterococci levels in runoff.

<table>
<thead>
<tr>
<th>Source</th>
<th>Num df</th>
<th>Den df</th>
<th>Chi-Square</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Month</td>
<td>10</td>
<td>60</td>
<td>213.86</td>
<td>21.39</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Site</td>
<td>6</td>
<td>60</td>
<td>65.52</td>
<td>10.92</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Treatment</td>
<td>1</td>
<td>60</td>
<td>2.90</td>
<td>2.90</td>
<td>0.094</td>
</tr>
<tr>
<td>Month x Site</td>
<td>60</td>
<td>60</td>
<td>166.14</td>
<td>2.77</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Month x Treatment</td>
<td>10</td>
<td>60</td>
<td>14.11</td>
<td>1.41</td>
<td>0.20</td>
</tr>
<tr>
<td>Site x Treatment</td>
<td>6</td>
<td>60</td>
<td>1.34</td>
<td>0.22</td>
<td>0.97</td>
</tr>
</tbody>
</table>

October and December had significantly higher Enterococci levels than any other month, though they were the third and fourth largest rain events, respectively. October
and December had more than twice the Enterococci CFU, on average, than any other month. The other months were all statistically similar. December, as well as having the highest mean Enterococci levels, also had the largest rain event and the highest TSS levels. June, September, and March had the lowest Enterococci levels, with <1,000 CFU 100 mL\(^{-1}\) average in runoff (Figure 3.5). The data shows a seasonal trend with the three months having the highest Enterococci levels sequentially in October, November, and December.

![Figure 3.5. Mean Enterococci levels in runoff per month averaged across all sites. Error bars represent ± 1 standard error. Letters indicated significant difference according to least squared means.](image)

Enterococci in runoff were, on average, highest at Manoa Cliffs and lowest at Waahila Ridge (Figure 3.6). Manoa Cliffs had significantly higher mean Enterococci in runoff than only Pauoa Flats and Waahila Ridge. Pauoa Flats had the highest mean TSS in runoff, and yet had the second-lowest mean Enterococci in runoff as well as in soil samples. Waahila Ridge had the lowest mean Enterococci in runoff, as well as the lowest mean throughfall and lowest mean runoff among all sites.
The fenced and unfenced treatment means showed a significant difference at $\alpha=0.1$ (Figure 3.7). The fenced plots averaged 6,248 CFU 100 mL$^{-1}$, while the unfenced plots average 6,326 CFU 100 mL$^{-1}$.

Figure 3.6. Mean Enterococci levels in runoff per site averaged across all month. Error bars represent ± 1 standard error. Letters indicate significantly different means according to least squared means.

Figure 3.7. Mean Enterococci levels in fenced versus unfenced plots averaged across all months and sites. Error bars represent ± 1 standard error.
3.10 Enterococci in Soils

Enterococci in soils from August 2009 ranged from 3 CFU g\(^{-1}\) to 611 CFU g\(^{-1}\).

Because of a lack of replication, that data were analyzed as two one-way ANOVAs, the first comparing means across sites (Table 3.3), and the second comparing means of the two treatments (Table 3.4). The first one-way ANOVA indicated significant differences in soil enterococci across the sites (Table 3.3). Specifically, Lyon Arboretum had the highest average Enterococci levels in soils, followed by Manoa Cliffs and Manoa Falls (Figure 3.8). Waahila Ridge had the lowest average Enterococci levels, with Roundtop and Pauoa Flats having the next lowest averages. The second one-way ANOVA indicated no significant difference between treatments (Table 3.4).

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Site</td>
<td>6</td>
<td>321449.72</td>
<td>53574.95</td>
<td>46.09</td>
<td>&lt;.0001</td>
</tr>
<tr>
<td>Error</td>
<td>7</td>
<td>8136.87</td>
<td>1162.41</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>329586.59</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>df</th>
<th>Sum of Squares</th>
<th>Mean Squares</th>
<th>F-statistic</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treatment</td>
<td>1</td>
<td>165.07</td>
<td>165.07</td>
<td>0.01</td>
<td>0.94</td>
</tr>
<tr>
<td>Error</td>
<td>12</td>
<td>329421.53</td>
<td>27451.79</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>13</td>
<td>329586.59</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
While the treatment effect was not significant, Enterococci levels were slightly higher in soils of unfenced (124.7 CFU g\(^{-1}\)) versus fenced plots (131.5 CFU g\(^{-1}\)) (Figure 3.9).

Figure 3.9. Mean soil Enterococci levels in fenced versus unfenced plots in colony forming units g\(^{-1}\) dry weight soil. Error bars represent ± 1 standard error.
There was also a trend of the sites with the greatest occurrence of pig disturbance having more Enterococci in soils of the unfenced plots (Figure 3.11). For example, Puu Pia had higher average levels in the unfenced (114 CFU g\(^{-1}\)) than the fenced plot (14 CFU g\(^{-1}\)). Roundtop had higher Enterococci levels in the unfenced (39 CFU g\(^{-1}\)) than the fenced (20 CFU g\(^{-1}\)).

![Figure 3.11. Mean Enterococci levels in soils among fenced versus unfenced plots across all sites. Error bars represent ± 1 standard error.](image)

### 3.16 Correlation of Enterococci with Environmental Variables

The only variables that had significant Spearman correlations with Enterococci in runoff were runoff amount, runoff-throughfall ratio (RTR), and soil Enterococci from Aug. 2009. The strongest correlation of Enterococci in runoff was with Enterococci in soils (\(r = 0.74, p = 0.0024\)). Enterococci levels in runoff and soils were positively correlated, yet neither was correlated with TSS or soil moisture. Throughfall, soil moisture, and bare soil cover were thought to perhaps be important environmental
predictors of Enterococci in runoff, however none of these variables were significant even at $\alpha = 0.1$.

Soil Enterococci was also positively correlated with runoff amount, RTR, and rock cover. Runoff amount had the highest Spearman correlation with Soil Enterococci ($r = 0.67$, $p = 0.0081$), which was stronger than the correlation of runoff amount with Enterococci in runoff. Soil Enterococci was correlated with throughfall, though only at 93% significance ($r = 0.50$, $p = 0.071$). Soil Enterococci was not significantly correlated with soil moisture or soil carbon.

The correlation of Enterococci in runoff with environmental variables were also tested separately for dry season and wet season months. During the dry season, none of the environmental variables except RTR were significantly correlated with Enterococci in runoff. Dry season Enterococci in runoff were negatively correlated with RTR, while overall and in the wet season they were positively correlated. Runoff-throughfall ratio was negatively correlated with dry season Enterococci in runoff. During the wet season, Enterococci levels in runoff were significantly correlated with runoff amount, RTR, and soil Enterococci.
Table 3.5. Spearman correlation coefficients for Enterococci and environmental predictor variables. Non-significant results labeled with a hyphen. The first column represents average Enterococci levels across all months. The second column represents soil Enterococci in August 2009. The third column represents Enterococci averaged across the dry season months and the fourth column represents Enterococci averaged across wet season months.

<table>
<thead>
<tr>
<th></th>
<th>Enterococci</th>
<th>Soil Entero</th>
<th>Entero Dry</th>
<th>Entero Wet</th>
</tr>
</thead>
<tbody>
<tr>
<td>TSS</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Throughfall</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soil Moisture</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Litter</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Bare</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Rock</td>
<td>-</td>
<td>0.61</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Live</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CWD</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>ROVol</td>
<td>0.60</td>
<td>0.67</td>
<td>-</td>
<td>0.68</td>
</tr>
<tr>
<td>Stem Density</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Basal Area</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Slope</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Ksat</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Soil Entero</td>
<td>0.74</td>
<td>-</td>
<td>-</td>
<td>0.55</td>
</tr>
<tr>
<td>Soil Carbon</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>RTR</td>
<td>0.53</td>
<td>0.66</td>
<td>-0.53</td>
<td>0.65</td>
</tr>
</tbody>
</table>
Soil Enterococci and runoff volume were selected as important predictor variables and entered into a multiple-stepwise regression. The runoff-throughfall ratio was not selected as an important predictor variable because of the direct relationship with runoff volume. At the $\alpha = 0.05$ level no model was significant so $\alpha$ was raised 0.1. Runoff amount then became a significant predictor of Enterococci in runoff ($r = 0.49$, $p = 0.067$).

Equation 2. Model for predicting Enterococci in runoff, based on multiple-stepwise regression ($r^2 = 0.27$, $p = 0.056$).

$$\text{Enterococci} = 2526.69 + 519.30(\text{RO Volume})$$

3.12 Discussion

The first objective of this chapter was to quantify Enterococci in runoff and soils from forested areas of the Manoa watershed. Previous research has suggested that Enterococci are free-living and reproduce in the moist, warm environment of subtropical islands such as Hawaii, Guam, and Puerto Rico (Fujioka et al., 1999; Byappanahalli and Fujioka, 2004; Hartel et al., 2005), and these results partially agreed with their findings. Every site contained Enterococci in runoff during multiple rain events, regardless of the fenced or unfenced treatment. The exclusion fences had been in place over one year at the start of the study, so soils were free of pig influence for at least that amount of time. The Manoa Cliffs site had the highest Enterococci levels in runoff, despite fairly low levels of TSS, averaging 10,072 CFU 100 mL$^{-1}$. Pig rooting was observed several times at this site and pig disturbance of the unfenced runoff plot was confirmed on multiple occasions by game cameras. At this site the unfenced plot averaged almost 1,400 CFU 100 mL$^{-1}$ more than the fenced plot. The least amount of Enterococci in runoff occurred at the site with
the lowest throughfall and lowest TSS levels: Waahila Ridge. Waahila Ridge was another site where pig rooting evidence was seen in the unfenced plot, and Enterococci levels were, on average, almost three times as high in the unfenced treatment compared to the fenced treatment (4,756 100 mL$^{-1}$ versus 1,204 CFU 100 mL$^{-1}$).

Some commonality in the data for runoff and for soils was the high monthly and intersite variability. The coefficient of variation (CV) ranged from 1.0-2.1 for individual sites between months. Measurements showed high variability in Enterococci levels. Even between duplicate samples, there were large amounts of variation; CVs ranging from 0.2-1.2 among the sites. Enterococci levels in soil were standardized per gram of dry-weight soil. On occasion there was even one order of magnitude difference between duplicate samples (from Manoa Falls and Manoa Cliffs in April runoff event; Manoa Cliffs, Manoa Falls, and Waahila Ridge soils) a result that was also found by Hartel et al. (2005) in a study of Enterococci in coastal sediments and runoff. That study also investigated the occurrence of false positives in Enterolert wells, finding that such artificial flourescences resulted in decreases between the original and corrected MPN ranging from 0 to >99.9%. Hartel et al. (2005) concluded that “the Enterolert system should be used with caution in waters containing high amounts of sediment” which may be seen as a warning against future use of the method in runoff and soil samples. However they also noted that, in their opinion, there is not a better alternative to Enterococci as fecal indicator bacteria. They proposed that care should be taken not to disturb the sediment when sampling water for fecal contamination, or if the sediment is already disturbed (for instance on windy days or when sampling runoff), then “the influence of sediment should be considered.”
The second objective was to determine whether feral pigs increase Enterococci levels in runoff and soils. This objective was difficult to accomplish because of the previously mentioned variability and potential for false positives. The inter-site and temporal variability appeared to have greater influence on runoff amounts and composition than did pig exclusion. However, the pig exclusion fencing treatment showed a significant difference at $\alpha=0.1$, suggesting that feral pigs increase Enterococci in runoff. In an exclusion fencing study, Doupé et al. (2009) found that feral pigs disturbed sediments in unfenced wetlands, affecting turbidity, pH, and anoxia; though they also found that temporal effects had a greater influence on the environmental variables measured than did the pigs. There were other interesting trends that developed in the data, with higher Enterococci in soils and runoff from unfenced plots at certain sites with higher occurrence of pig disturbance.

The increase in Enterococci may suggest fecal contamination. However, the use of Enterococci as an indicator of fecal contamination is a contentious subject, particularly in tropical and subtropical environments. Soil, water, and even plants are thought to be reservoirs or sources of Enterococci (Mundt, 1961; Fujioka, 1999; Byappanahalli and Fujioka, 2004). Fujioka in particular has intimated that Enterococci are not an ideal fecal indicator in Hawaii and other tropical environments. Ragosta (2007) takes an opposing view, believing Enterococci are valuable in Hawaii as an indicator of fecal contamination and disturbance of exotic animals. Ragosta (2009) has also shared personal data, gathered while working for the Koolau Mountain Watershed Partnership, from difficult to access, high altitude areas of Oahu that showed little or no Enterococci presence. This data
indicates that Enterococci are not ubiquitous in Hawaiian soils, and are associated with feral animals or even human activities.

The data from this study suggested that feral pigs may increase Enterococci in runoff. Feral pig rooting could be increasing Enterococci in runoff by disturbing soils and Enterococci already present in the soils. However, TSS was not significantly different between fenced and unfenced treatments; therefore, it seems more likely that the increase in Enterococci is coming directly from the pigs themselves. This is an important result because although Enterococci are not themselves dangerous, feral pigs have been shown to be reservoirs for human pathogens (Hampton et al., 2006). Research has also found that Enterococci in surface waters correlate with incidence of sickness in bathers (Wade, 2006).

The third objective was to investigate temporal and spatial differences in Enterococci presence in runoff. The data showed that Enterococci levels measured in runoff and soils were temporally and spatially variable, differing greatly across sites and months as evidenced by the month by site interaction. Enterococci in runoff ranged by many orders of magnitude from <1 CFU 100 mL⁻¹ during many of the smaller runoff events, to >70,000 CFU 100 mL⁻¹ from the Lyon Arboretum fenced site during the December event. Similarly high variability was found by Hartel et al. (2005) in their study of sediments from Georgia, New Hampshire, and Puerto Rico. October and December had significantly higher Enterococci levels than any other months. Though December was the largest runoff event, and Enterococci in runoff were found to correlate with runoff amount, October was the third-smallest runoff event. October is a month
when strawberry guava (*P. cattleainum*), a food source of feral pigs, is fruiting in many parts of the watershed, and several of the sites are near large strawberry guava stands.

While month and site accounted for a significant proportion of the variance in the Enterococci levels in runoff, the month by site interaction was also significant. In general, Manoa Cliffs and Manoa Falls had the two highest average Enterococci levels, and both sites also showed evidence of pig disturbance on multiple occasions; however, Lyon Arboretum had the next highest levels despite a lack of evidence of pig presence. This is not to say pigs were never present at the Lyon Arboretum site, but the Arboretum does encourage hunting, and has even set up a pig blind in an area several hundred yards upslope from the runoff plots. The site did show higher averages in the unfenced plot however, and Arboretum employees indicated that many rats live in the area. Manoa Cliffs, Manoa Falls, and Lyon Arboretum also have high throughfall levels, but another site with high throughfall levels, Pauoa Flats, had the second lowest Enterococci levels in runoff.

Quantification of Enterococci in soils was accomplished in August 2009, though it required a more extensive analysis process than the runoff. The Lyon site contained the highest levels of Enterococci in soils, averaging 476 CFU g\(^{-1}\); this was more than double the level of any other site, but lower than levels found in sediments from Georgia, New Hampshire, and Puerto Rico (Hartel et al., 2005). Just as with the runoff Enterococci, Waahila Ridge showed the lowest soil Enterococci levels, averaging 24 CFU g\(^{-1}\). This range is similar to Hartel et al. (2005) where Enterococci numbers occasionally exceeded 1,000 g\(^{-1}\) of soil, but frequently were as low as 10 g\(^{-1}\), when present. In a study in the Waipa watershed on the northern side of the island of Kauai, Ragosta (2007) found a
much lower range of Enterococci presence in soils. Samples from multiple locations in the Waipa watershed contained <3.3-60 CFU g⁻¹ and 75% of samples had below detectable (<3.3 CFU g⁻¹) levels of Enterococci (Ragosta, 2007).

Results for Enterococci in soils likewise did not show significant differences between fenced or unfenced treatments, though there were significant site differences. Unfortunately soils were only sampled in August 2009, so seasonal differences remain unmeasured. Lyon Arboretum had by far the highest average amounts of Enterococci in soils, though in this case the fenced plot contained higher levels than the unfenced plot (511 CFU g⁻¹ versus 441 CFU g⁻¹). It was surprising that Lyon Arboretum contained more than twice the levels of Enterococci than any other site. Soil moisture averaged just over 50%, less than Manoa Cliffs or Pauoa Flats, and as mentioned above, Lyon Arboretum also had only the third highest levels of Enterococci in runoff. The site had a unique canopy composition, though the dominant *E. grandis* (blue marble) trees were also found at Pauoa Flats. Lyon Arboretum also contained higher levels of rock cover than any of the other sites, and averaged greater amounts of runoff.

Some of the most interesting soil results came from Puu Pia, which measured an average of more than eight times as many Enterococci CFU g⁻¹ in the unfenced than the fenced plot. This site had showed pig disturbance during at least six of the 11 months of study, and also contained much higher levels of TSS and Enterococci in runoff in the unfenced versus the fenced plot. The site was characterized by extremely high stem density and basal area, and is dominated by *S. actinophylla*. An obvious pig trail was cut through the ground cover approximately 20 m south from the plots, and pig rooting was common throughout the general area.
The final objective of this study was to investigate correlations between environmental variables and Enterococci in runoff. This was accomplished, though the some of the results were unexpected. Of the 14 environmental variables recorded, only runoff volume and soil Enterococci significantly correlated with Enterococci in runoff. The positive correlation with runoff volume could result because larger runoff events also may correlate with higher intensity throughfall events, and therefore may be more likely to disturb Enterococci from soils and other surfaces. The positive correlation of Enterococci in runoff with Enterococci in soils seems obvious; sites with more Enterococci in soils would likely have more Enterococci in runoff. It was surprising that there were no other significant correlations in the data. The lack of correlation with soil moisture was surprising, as wet soils were thought to be more accommodating to survival of the bacteria (Cools et al., 2001; Hartel et al., 2005). Likewise, the lack of correlation with TSS was also unexpected. Bacteria are known to associate with sediment particle surfaces, and sediments in water protect bacteria from environmental conditions that could be hazardous to their survival (Anderson et al., 2005). Soil carbon levels measured at the seven sites by Browning (2008) were significantly correlated with soil moisture, basal area, and slope but had no relationship with Enterococci in runoff or soils.

3.13 Conclusions

Hypothesis one predicted that Enterococci levels in runoff would be higher in the wet season (November-April) than dry season (May-October). The data did not support this hypothesis, as a month by site interaction indicated that seasonal (monthly) trends were not consistent across the sites. In general, October and December had significantly
higher Enterococci levels in runoff than the other months, both averaging >20,000 CFU 100 mL$^{-1}$. Both months had larger than average runoff events, which may relate to the correlation of Enterococci with runoff amount.

Hypothesis two predicted that Enterococci levels in runoff and soil would be increased by the presence of feral pigs. This was partially supported by the data. Unfenced versus fenced comparisons of runoff showed a significant ($\alpha = 0.1$) difference in Enterococci levels. There were higher average Enterococci levels in unfenced plots in both soils and runoff from several sites, such as Puu Pia, Waahila Ridge, and Roundtop; the sites with highest recorded pig disturbance. However, fenced plots also showed high levels of Enterococci in runoff and soils. Several factors could explain this result. First is the potential presence of rats (\textit{Rattus spp.}) and/or mongoose (\textit{Herpestes javanicus}) inside the fenced plots. At Roundtop in particular, avocado fruits that fell inside the fenced plot were seen to be partially eaten, and tooth marks were evident in the flesh. Both of these animals are potential vectors for Enterococci, and both could presumably access the fenced plot.

Hypothesis three predicted that of all environmental predictors, ground cover and soil moisture would have strongest correlation with Enterococci in runoff. Ground cover was thought to correlate with pig disturbance, and soil moisture was thought to allow for greater chance of Enterococci survival in soils. The data did not support this hypothesis as Enterococci in runoff were significantly correlated with runoff volume and with Enterococci in soils, but not with soil moisture or any of the ground cover variables. Enterococci in soils were significantly correlated with the percent cover of rock in the runoff plots. This result was unexpected, and there does not seem to be a logical reason
for such a relationship. Moist soils were expected to be more conducive to bacterial
growth (Anderson et al., 2007), but this relationship was not found. This suggests that
some other factors are responsible, and more research is needed on Enterococci levels in
surface waters and soils in Hawaiian watersheds.

Hypothesis four stated that TSS in runoff would positively correlate with
Enterococci abundance in runoff. This hypothesis was also not supported by the data.
Enterococci in runoff did not significantly correlate with TSS. It was expected that
Enterococci would be present in soils, and as sediment levels in runoff increased so
would levels of Enterococci. This result was not seen, and it could be that the bacteria are
more prevalent on the ground surface, and therefore are carried in runoff regardless of
sediment disturbance. Though Enterococci were present in soils, the levels were
relatively low, and as mentioned in section 3.16, they were less than the upper limits of
levels seen in studies of sediments from areas on the continental U.S. This may suggest
that Enterococci are associated with animals and deposited on litter, rocks, plants, and the
soil surface. Birds are known to be a major source of Enterococci contamination at
beaches (Haack et al., 2003), and could have deposited these bacteria inside both fenced
and unfenced areas.

Comparative studies of fencing to exclude feral pigs or inhibit their access into
sensitive forested areas are few (Campbell and Long, 2009), and these runoff plots
provide an excellent opportunity to study feral pig impacts on water quality, soils, and
vegetation. Other than previous research at these same runoff plots (Browning, 2008), no
other study has been found to use runoff plots and exclusion fencing in the upper forested
areas of a watershed. In addition to elucidating monthly and site differences in runoff and
their interactions, this research provides baseline conditions for further research at the runoff plots. As time goes on, differences between fenced and unfenced plots are expected to continue to develop, and further research is needed at these sites.
CHAPTER 4: CONCLUSIONS

This study was designed to elucidate the runoff dynamics and processes occurring in the upper forested areas of a Hawaiian watershed and the effects of feral pigs on water quality and fecal indicator bacteria. The large amount of runoff captured from some of these plots was an unexpected result. The high levels of TSS in runoff were also an important finding. These high levels of TSS in runoff were more likely in the wet season and from certain areas in the watershed, particularly Puu Pia, Pauoa Flats, and Lyon Arboretum. These were high throughfall sites, which were mostly dominated by nonnative vegetation. Total SS in runoff was predicted by soil moisture, throughfall, and coarse woody debris cover. While the Manoa Cliffs site had high throughfall, it also had the most native vegetation, and had correspondingly low TSS levels. This research suggests that TSS levels in runoff are of more concern during the wet season, from certain areas in the upper watershed.

While Enterococci in runoff were found to be significantly higher in unfenced plots at $\alpha=0.1$, they were also highly variable among months and sites. The data suggests that other factors such as location, animal presence, or soil type may be important in influencing Enterococci levels in runoff. Enterococci levels were also significantly correlated with runoff volume and with Enterococci levels in soils. Enterococci were present in soils from all sites tested, but at levels similar to those seen in studies of sediments from areas in the continental U.S. There were higher average Enterococci levels in unfenced plots in both soils and runoff from several sites, such as Puu Pia, Waahila Ridge, and Roundtop; the sites with the highest recorded levels of pig
disturbance.

Effects of pig disturbance on runoff and soils were difficult to elucidate. Certain sites that showed high amounts of pig rooting and disturbance evidence, in particular Puu Pia and Waahila Ridge, had greater levels of TSS from unfenced plots. Enterococci in runoff and Soil Enterococci were also higher in unfenced plots from Puu Pia and Waahila Ridge. *Psidium cattleianum* is known to be spread by feral pigs, and seedlings and sapling counts were higher in unfenced plots. Bare ground cover was on average higher in the unfenced than the fenced plots.

The only other study found to have a similar approach was previous research on the same runoff plots (Browning, 2008). Besides elucidating monthly and site differences in runoff and their interactions, this study provides baseline conditions for further research at the runoff plots. As time goes on, I expect differences between fenced and unfenced plots will continue to develop. The complexity of runoff processes and the presence of other exotic animals in the study area present a problem when trying to study solely the impacts of feral pigs. However, I believe this can be accomplished, and this study has identified many ways to improve monitoring of runoff plots and feral pigs. The presence of pigs is a divisive issue in many Hawaiian communities, pitting pig hunters and residents who depend on the pigs for food against conservationists and others who worry about the damage afflicted by these exotic mammals. Regardless of which side of the debate one takes, it is of the utmost importance that the ecological and watershed effects of feral pigs be understood.
4.1 Further Research

Comparative studies of fencing to exclude feral pigs or inhibit their access into sensitive forested areas are few (Campbell and Long, 2009), and these runoff plots provide an excellent opportunity to study feral pig impacts on water quality, soils, and vegetation. More than two years have passed since exclusion fences were installed, and I expect that differences between fenced and unfenced plots will become more pronounced as time goes on. Soil organisms are a known indicator of disturbance (Vtorov, 1993), and may respond to change quicker than other soil properties (Moody and Jones, 2000). Analysis of soil organisms, and other soil properties such as pH, nutrients, and bulk density could be important in determining pig impacts.

The research sites encompass a great variety in vegetation and canopy structure, with 14 different canopy tree species, and at least 21 total different woody plant species. The difference in *P. cattleianum* seedlings between fenced and unfenced sites highlighted the potential impacts of feral pigs on vegetation and forest structure. Though the fenced areas are small, this study has provided a necessary baseline to continue conducting research on vegetation differences between plots; particularly with regard to exotic fruiting trees such as *P. cattleianum* and *Persea americana*.

The deployment of game cameras midway through the study proved that feral pigs did access several of the unfenced plots. Further research with game cameras could allow for estimation of pig populations and shed light on the behavior of these secretive and shy mammals. Using camera trapping rate is a promising and cost-effective for the rapid assessment of animal abundance in remote areas or where alternative methods are unfeasible (Rovero and Marshall, 2009). Camera trapping has the potential to simplify
data collection and reduce human error that can be a problem in other abundance survey methods.

Though pigs were conclusively seen to visit several of the sites, only at Waahila Ridge was extensive rooting seen inside the runoff plot. One potential avenue for further research would be to lure pigs to the plots. Bananas or other fruit could be spread throughout each unfenced area, encouraging the pigs to spend more time inside the unfenced runoff plots. Thus, the effects on runoff and soils could become more pronounced. Though this could artificially increase pig effects at the runoff, nonnative fruit trees are common throughout many Hawaiian wet forests so such disturbance may not be unusual in areas of the watershed.

4.2 Recommendations for Improvement

Considering the large amounts of runoff, and the problem of exceeding bucket capacity, I would recommend that overflow buckets be installed at every site to better quantify runoff amounts. Collection splitters could also be deployed at every site. Lyon Arboretum exceeded the overflow bucket capacity on several occasions; therefore larger overflow buckets may also be needed. Perhaps an automated system could be used that measured total runoff without having to store the entire amount. Another area of missing data is throughfall intensity. This is an important factor in runoff generation, and the throughfall gauges used in this study did not provide any information on intensity of throughfall events. A tipping-bucket or similar throughfall gauge installed at each site would be a valuable addition to further studies.
The game cameras provided indisputable evidence that pigs are present at certain sites. Installation of cameras at every site would allow for a better understanding of pig movements and permit comparison of pig presence/populations among sites. Ground cover was measured at the closing stages of this study but I would recommend that any further research entail ground cover estimation at the outset as well, to allow for more robust analysis of pig effects on ground cover. Canopy cover is an environmental variable potentially very important for runoff processes. Canopy cover above each site could be estimated with a LAI-2000 or other such device to aid in better understanding runoff processes in these forested areas.

The data suggested a difference between fenced and unfenced treatments for Enterococci in runoff. There were no statistically significant differences seen in TSS in runoff or ground cover. A potential problem with drawing conclusions from this type of study is the proximity of the runoff plot to the fence. Exclusion fences may alter pig behavior and impede normal movements, magnifying pig effects (Noguiera-Filho et al., 2009). If additional runoff plots are added to the study, a larger separation between fenced and unfenced plots may be advisable to avoid a bias in ground cover and soils measurements.

Finally, I believe a second method for enumerating Enterococci should be used to confirm the accuracy of the IDEXX method. As mentioned in section 3.18, literature has been published that brings into question the reliability of this method, particularly when testing water samples containing high levels of sediment, which runoff often does. Since Enterococci is still an accepted water quality indicator according to the US EPA, this would be an important addition to further research involving Enterococci.
### APPENDIX A: TREE SPECIES LISTS

#### Table 4. List of canopy tree species at Lyon Arboretum.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Ficus microcarpa</em> (Chinese banyan)</td>
<td>48</td>
</tr>
<tr>
<td><em>Elaeocarpus grandis</em> (blue marble)</td>
<td>17</td>
</tr>
<tr>
<td>Unknown #2</td>
<td>7</td>
</tr>
<tr>
<td><em>Dracaena sp.</em> (money tree)</td>
<td>2</td>
</tr>
<tr>
<td><em>Livistona chinensis</em> (Chinese fan palm)</td>
<td>2</td>
</tr>
</tbody>
</table>

#### Table 5. List of canopy tree species at Manoa Cliffs.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Hibiscus arnottianus</em> (kokio keokeo)</td>
<td>62</td>
</tr>
<tr>
<td><em>Cestrum nocturnum</em> (night-blooming jasmine)</td>
<td>34</td>
</tr>
<tr>
<td><em>Cinnamomum burmanni</em> (Indonesian cinnamon)</td>
<td>13</td>
</tr>
<tr>
<td><em>Pisonia umbellifera</em> (pepala kepau)</td>
<td>7</td>
</tr>
<tr>
<td><em>Psidium guajava</em> (common guava)</td>
<td>7</td>
</tr>
<tr>
<td><em>Cordyline fruticosa</em> (ti)</td>
<td>6</td>
</tr>
<tr>
<td><em>Ardisia elliptica</em> (shoebutton Ardisia)</td>
<td>6</td>
</tr>
</tbody>
</table>

#### Table 6. List of canopy tree species at Manoa Falls.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Psidium cattleianum</em> (strawberry guava)</td>
<td>197</td>
</tr>
<tr>
<td>Unknown #8</td>
<td>5</td>
</tr>
<tr>
<td><em>Ficus microcarpa</em> (Chinese banyan)</td>
<td>3</td>
</tr>
<tr>
<td><em>Cinnamomum burmanni</em> (Indonesian cinnamon)</td>
<td>1</td>
</tr>
<tr>
<td>Unknown #7</td>
<td>1</td>
</tr>
</tbody>
</table>
### Table 7. List of canopy tree species at Pauoa Flats.

<table>
<thead>
<tr>
<th>Species</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Cinnamomum burmanni</em> (Indonesian cinnamon)</td>
<td>42</td>
</tr>
<tr>
<td><em>Elaeocarpus grandis</em> (blue marble)</td>
<td>7</td>
</tr>
<tr>
<td><em>Ardisia elliptica</em></td>
<td>3</td>
</tr>
<tr>
<td>Unknown #7</td>
<td>3</td>
</tr>
<tr>
<td><em>Ficus microcarpa</em> (Chinese banyan)</td>
<td>2</td>
</tr>
<tr>
<td><em>Schefflera actinophylla</em> (octopus tree)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 8. List of canopy tree species at Puu Pia.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Schefflera actinophylla</em> (octopus tree)</td>
<td>333</td>
</tr>
<tr>
<td><em>Eucalyptus robusta</em> (swamp mahogany)</td>
<td>35</td>
</tr>
<tr>
<td><em>Ardisia elliptica</em> (shoebutt Ardisia)</td>
<td>3</td>
</tr>
<tr>
<td><em>Psidium cattleianum</em> (strawberry guava)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 9. List of canopy tree species at Roundtop.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Schefflera actinophylla</em> (octopus tree)</td>
<td>67</td>
</tr>
<tr>
<td><em>Livistona chinensis</em> (Chinese fan palm)</td>
<td>13</td>
</tr>
<tr>
<td><em>Persea americana</em> (avocado)</td>
<td>8</td>
</tr>
<tr>
<td><em>Psidium cattleianum</em> (strawberry guava)</td>
<td>2</td>
</tr>
<tr>
<td><em>Cordyline fruticosa</em> (ti)</td>
<td>2</td>
</tr>
<tr>
<td><em>Hibiscus tiliaceus</em> (hau)</td>
<td>1</td>
</tr>
</tbody>
</table>

### Table 10. List of canopy tree species at Waahila Ridge.

<table>
<thead>
<tr>
<th>Species</th>
<th>Count</th>
</tr>
</thead>
<tbody>
<tr>
<td><em>Casuarina glauca</em> (Ironwood)</td>
<td>146</td>
</tr>
<tr>
<td><em>Psidium cattleianum</em> (strawberry guava)</td>
<td>38</td>
</tr>
<tr>
<td>Unknown #3</td>
<td>1</td>
</tr>
</tbody>
</table>
APPENDIX B: RUNOFF PLOT GROUND COVER MEASUREMENTS

Figure 4. Lyon Arboretum ground cover, fenced versus unfenced plot.

Figure 5. Manoa Cliffs ground cover, fenced versus unfenced plot.
Figure 6. Manoa Falls ground cover, fenced versus unfenced plot.

Figure 7. Pauoa Flats ground cover, fenced versus unfenced plot.
Figure 8. Puu Pia ground cover, fenced versus unfenced plot.
APPENDIX C: RAW DATA

Table 11. Enterococci, TSS, and runoff volume (ROVol) data from June 2008 through April 2009. Enterococci results in units of CFU 100 mL\(^{-1}\). TSS results in units of g L\(^{-1}\). Runoff volume results in units of liters. LY signifies Lyon Arboretum, MC signifies Manoa Cliffs, MF signifies Manoa Falls, PF signifies Pauoa Flats, PP signifies Puu Pia, RT signifies Roundtop, WR signifies Waahila Ridge.

<table>
<thead>
<tr>
<th>Site</th>
<th>Treatment</th>
<th>Month</th>
<th>Enterococci</th>
<th>TSS</th>
<th>ROVol</th>
</tr>
</thead>
<tbody>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>June</td>
<td>142.55</td>
<td>0.1</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>June</td>
<td>217.6</td>
<td>0</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>June</td>
<td>0</td>
<td>0.1</td>
<td>2.864307</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>June</td>
<td>0</td>
<td>0.1</td>
<td>9.308998</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>June</td>
<td>0</td>
<td>0</td>
<td>8.592922</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>June</td>
<td>236.05</td>
<td>0.1</td>
<td>8.95096</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>June</td>
<td>1</td>
<td>0.1</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>June</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>June</td>
<td>0</td>
<td>0.2</td>
<td>2.14823</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>June</td>
<td>0</td>
<td>0.1</td>
<td>2.864307</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>June</td>
<td>0</td>
<td>0.3</td>
<td>2.864307</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>June</td>
<td>0</td>
<td>0.1</td>
<td>2.864307</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>June</td>
<td>0</td>
<td>0</td>
<td>1.611173</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>June</td>
<td>0</td>
<td>0.1724138</td>
<td>1.790192</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>July</td>
<td>6</td>
<td>0.05</td>
<td>5.370576</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>July</td>
<td>10.5</td>
<td>0.0980392</td>
<td>2.864307</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>July</td>
<td>0</td>
<td>0</td>
<td>0.358038</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>July</td>
<td>0</td>
<td>0</td>
<td>1.432154</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>July</td>
<td>3795.8</td>
<td>0.05</td>
<td>1.790192</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>July</td>
<td>412.6</td>
<td>0.125</td>
<td>4.47548</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>July</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>July</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>July</td>
<td>22</td>
<td>0.1</td>
<td>2.685288</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>July</td>
<td>4164.2</td>
<td>0.126</td>
<td>3.580384</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>July</td>
<td>24196</td>
<td>0.092</td>
<td>1.969211</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>July</td>
<td>24196</td>
<td>0.15</td>
<td>2.14823</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>July</td>
<td>24196</td>
<td>0.15</td>
<td>2.506269</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>July</td>
<td>13.55</td>
<td>0.05</td>
<td>2.685288</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>August</td>
<td>58.35</td>
<td>0.05</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>August</td>
<td>37</td>
<td>0.05</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>August</td>
<td>168</td>
<td>0.05</td>
<td>5.728614</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>August</td>
<td>103</td>
<td>0.106</td>
<td>6.444691</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>August</td>
<td>50.1</td>
<td>0.05</td>
<td>13.25024</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>August</td>
<td>156</td>
<td>0.125</td>
<td>13.25024</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>August</td>
<td>0</td>
<td>0</td>
<td>0.716077</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>August</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>August</td>
<td>82.9</td>
<td>0.1</td>
<td>6.265672</td>
</tr>
<tr>
<td>Site</td>
<td>Treatment</td>
<td>Month</td>
<td>Enterococci</td>
<td>TSS</td>
<td>ROAmt</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>-------------</td>
<td>-------------</td>
<td>-------</td>
<td>--------</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>August</td>
<td>1</td>
<td>0.126</td>
<td>7.160768</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>August</td>
<td>12099.5</td>
<td>0</td>
<td>3.938422</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>August</td>
<td>107</td>
<td>0</td>
<td>3.759403</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>August</td>
<td>1341.3</td>
<td>0.15</td>
<td>2.506269</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>August</td>
<td>13091.15</td>
<td>0.05</td>
<td>2.685288</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>September</td>
<td>118.05</td>
<td>0.666667</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>September</td>
<td>20.25</td>
<td>0.366667</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>September</td>
<td>154</td>
<td>0</td>
<td>16.8278</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>September</td>
<td>14.5</td>
<td>0</td>
<td>17.54388</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>September</td>
<td>48</td>
<td>0</td>
<td>13.25024</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>September</td>
<td>1093</td>
<td>0.266667</td>
<td>13.25024</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>September</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>September</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>September</td>
<td>12</td>
<td>0.166667</td>
<td>6.62371</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>September</td>
<td>1949.75</td>
<td>0.366667</td>
<td>7.339787</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>September</td>
<td>59.05</td>
<td>0</td>
<td>8.055864</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>September</td>
<td>1006.2</td>
<td>0</td>
<td>6.981749</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>September</td>
<td>183.35</td>
<td>0.166667</td>
<td>13.25024</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>September</td>
<td>5.5</td>
<td>0.566667</td>
<td>8.771941</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>October</td>
<td>24196</td>
<td>0.6</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>0.1</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>October</td>
<td>24196</td>
<td>0</td>
<td>2.864307</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>0.4</td>
<td>9.308998</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>October</td>
<td>24196</td>
<td>0</td>
<td>8.592922</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>0.1</td>
<td>8.95096</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>October</td>
<td>24196</td>
<td>0.2</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>October</td>
<td>3322.3</td>
<td>1.5</td>
<td>0</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>October</td>
<td>6111.8</td>
<td>0.1</td>
<td>2.14823</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>1</td>
<td>2.864307</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>October</td>
<td>24196</td>
<td>0.1</td>
<td>2.864307</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>0.2</td>
<td>2.864307</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>October</td>
<td>8975.3</td>
<td>0</td>
<td>1.611173</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>October</td>
<td>24196</td>
<td>0</td>
<td>1.790192</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>November</td>
<td>3358</td>
<td>1.5</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>November</td>
<td>15248</td>
<td>0.9</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>November</td>
<td>8558</td>
<td>0.3</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>November</td>
<td>13073</td>
<td>0.4</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>November</td>
<td>5649</td>
<td>0.1</td>
<td>13.25024</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>November</td>
<td>35895</td>
<td>0.4</td>
<td>13.25024</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>November</td>
<td>1154</td>
<td>2</td>
<td>25.06269</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>November</td>
<td>1159</td>
<td>2.5</td>
<td>25.77876</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>November</td>
<td>4082.5</td>
<td>1.3</td>
<td>13.25024</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>November</td>
<td>9813.5</td>
<td>2.1</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>November</td>
<td>14313</td>
<td>0.5</td>
<td>5.907634</td>
</tr>
<tr>
<td>Site</td>
<td>Treatment</td>
<td>Month</td>
<td>Enterococci</td>
<td>TSS</td>
<td>ROAmt</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>-----------</td>
<td>-------------</td>
<td>------</td>
<td>--------</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>November</td>
<td>576.5</td>
<td>0.3</td>
<td>4.296461</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>November</td>
<td>10</td>
<td>0</td>
<td>3.222346</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>November</td>
<td>93.5</td>
<td>0.1</td>
<td>3.043326</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>December</td>
<td>51200</td>
<td>2.95</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>December</td>
<td>38700</td>
<td>5.35</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>December</td>
<td>57300</td>
<td>2.15</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>December</td>
<td>50500</td>
<td>2.25</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>December</td>
<td>72700</td>
<td>0.79</td>
<td>13.25024</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>December</td>
<td>1273.5</td>
<td>0.35</td>
<td>13.25024</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>December</td>
<td>610</td>
<td>3.95</td>
<td>26.50048</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>December</td>
<td>1371.5</td>
<td>2.75</td>
<td>26.50048</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>December</td>
<td>8773</td>
<td>5.65</td>
<td>13.25024</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>December</td>
<td>5620.5</td>
<td>7.05</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>December</td>
<td>3920.5</td>
<td>0.05</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>December</td>
<td>2320</td>
<td>0</td>
<td>10.02508</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>December</td>
<td>0</td>
<td>0</td>
<td>7.518806</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>December</td>
<td>0</td>
<td>0.15</td>
<td>7.518806</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>January</td>
<td>1313.5</td>
<td>2.75</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>January</td>
<td>9800</td>
<td>2.25</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>January</td>
<td>673</td>
<td>1.25</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>January</td>
<td>3237.5</td>
<td>1.05</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>January</td>
<td>4321.5</td>
<td>0.25</td>
<td>1.969211</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>January</td>
<td>206.5</td>
<td>0</td>
<td>1.790192</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>January</td>
<td>1058.5</td>
<td>2.3</td>
<td>19.33407</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>January</td>
<td>755</td>
<td>0.8</td>
<td>26.50048</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>January</td>
<td>132</td>
<td>0.2</td>
<td>13.25024</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>January</td>
<td>3736</td>
<td>0.4</td>
<td>9.308998</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>January</td>
<td>130</td>
<td>0</td>
<td>0.716077</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>January</td>
<td>14433</td>
<td>0</td>
<td>0.179019</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>January</td>
<td>10</td>
<td>0</td>
<td>1.611173</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>January</td>
<td>5</td>
<td>0</td>
<td>1.611173</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>February</td>
<td>2393</td>
<td>0.05</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>February</td>
<td>2227</td>
<td>0</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>February</td>
<td>944.5</td>
<td>0</td>
<td>8.234883</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>February</td>
<td>14833.5</td>
<td>0</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>February</td>
<td>4371</td>
<td>0</td>
<td>2.685288</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>February</td>
<td>6524</td>
<td>0</td>
<td>3.580384</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>February</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>February</td>
<td>22029.5</td>
<td>0</td>
<td>0.716077</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>February</td>
<td>3719.5</td>
<td>0.45</td>
<td>13.25024</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>February</td>
<td>7717</td>
<td>0.65</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>February</td>
<td>63</td>
<td>0</td>
<td>3.222346</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>February</td>
<td>1622</td>
<td>0.05</td>
<td>1.432154</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>February</td>
<td>0</td>
<td>0.25</td>
<td>3.043326</td>
</tr>
<tr>
<td>Site</td>
<td>Treatment</td>
<td>Month</td>
<td>Enterococci</td>
<td>TSS</td>
<td>ROAml</td>
</tr>
<tr>
<td>------</td>
<td>-----------</td>
<td>----------</td>
<td>-------------</td>
<td>-------</td>
<td>-------</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>February</td>
<td>417.5</td>
<td>0</td>
<td>2.864307</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>March</td>
<td>1261.5</td>
<td>1.1</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>March</td>
<td>238.5</td>
<td>0.9</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>March</td>
<td>1713.333333</td>
<td>1.2</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>March</td>
<td>767.6666667</td>
<td>0.8</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>March</td>
<td>13.66666667</td>
<td>0.2</td>
<td>5.728614</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>March</td>
<td>37</td>
<td>0.5</td>
<td>13.25024</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>March</td>
<td>49</td>
<td>1.1</td>
<td>26.50048</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>March</td>
<td>30.66666667</td>
<td>0.9</td>
<td>26.50048</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>March</td>
<td>691</td>
<td>1.9</td>
<td>13.25024</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>March</td>
<td>1605</td>
<td>3.1</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>March</td>
<td>398</td>
<td>1.6</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>March</td>
<td>1615</td>
<td>1.9</td>
<td>13.25024</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>March</td>
<td>302</td>
<td>0.2</td>
<td>6.444691</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>March</td>
<td>109</td>
<td>0.4</td>
<td>8.771941</td>
</tr>
<tr>
<td>LY</td>
<td>Fenced</td>
<td>April</td>
<td>1588.5</td>
<td>0.5</td>
<td>26.50048</td>
</tr>
<tr>
<td>LY</td>
<td>Unfenced</td>
<td>April</td>
<td>1498.5</td>
<td>0.4</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Fenced</td>
<td>April</td>
<td>96</td>
<td>0.2</td>
<td>26.50048</td>
</tr>
<tr>
<td>MC</td>
<td>Unfenced</td>
<td>April</td>
<td>996.5</td>
<td>0.1</td>
<td>26.50048</td>
</tr>
<tr>
<td>MF</td>
<td>Fenced</td>
<td>April</td>
<td>65</td>
<td>0.1</td>
<td>1.790192</td>
</tr>
<tr>
<td>MF</td>
<td>Unfenced</td>
<td>April</td>
<td>70.5</td>
<td>0.2</td>
<td>2.14823</td>
</tr>
<tr>
<td>PF</td>
<td>Fenced</td>
<td>April</td>
<td>15</td>
<td>0.1</td>
<td>0.716077</td>
</tr>
<tr>
<td>PF</td>
<td>Unfenced</td>
<td>April</td>
<td>20</td>
<td>0.3</td>
<td>4.654499</td>
</tr>
<tr>
<td>PP</td>
<td>Fenced</td>
<td>April</td>
<td>3005</td>
<td>0.2</td>
<td>11.81527</td>
</tr>
<tr>
<td>PP</td>
<td>Unfenced</td>
<td>April</td>
<td>2463</td>
<td>0.3</td>
<td>13.25024</td>
</tr>
<tr>
<td>RT</td>
<td>Fenced</td>
<td>April</td>
<td>1048.5</td>
<td>0.2</td>
<td>0.895096</td>
</tr>
<tr>
<td>RT</td>
<td>Unfenced</td>
<td>April</td>
<td>575.5</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WR</td>
<td>Fenced</td>
<td>April</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>WR</td>
<td>Unfenced</td>
<td>April</td>
<td>14385</td>
<td>0</td>
<td>0.358038</td>
</tr>
</tbody>
</table>


De Carlo, E. H., D. J. Hoover, C. W. Young, R. S. Hoover, and F. T. Mackenzie(2007) “Impact of storm runoff from tropical watersheds on coastal water quality and


