ASSESSING THE WATER QUALITY OF THE WAIMANALO WATERSHED BY MEASURING INDICATOR BACTERIA DENSITIES IN WAIMANALO STREAM, INOA'OLE STREAM, AND IN WAIMANALO BAY.

A PAPER SUBMITTED TO THE GRADUATE DIVISION OF THE UNIVERSITY OF HAWAI'I SCHOOL OF PUBLIC HEALTH IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE DEGREE OF MASTERS OF PUBLIC HEALTH

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PART I: INTRODUCTION

A. Recreational Water Quality and Standards

The recreational water quality in the United States is protected by the Federal Water Pollution Control Act of 1972 (the Clean Water act (CWA)). Federal water quality standards promulgated by the United States Environmental Protection Agency (EPA) limit the monthly geometric means in stream waters to less than 33 enterococci per 100 ml or 126 *E. coli* per 100 ml, and for marine waters to less than 35 enterococci 100 ml.

Regulatory authority for the implementation of the CWA in Hawai'i is delegated by the Federal government to the Hawai'i State Department of Health (DOH). Recreational water quality standards that apply to all stream and coastal waters of the state have been adopted by the DOH. These water quality standards limit the monthly geometric means in stream waters to less than 200 fecal coliforms per 100 ml, and in ocean waters to less than 7 enterococci per 100 ml. Both federal and state regulations also stipulate that recreational waters must be clear, toxin-free, and aesthetically pleasing in sight and smell.

Fecal bacterial indicators such as enterococci and fecal coliforms were originally used as a sensitive method of detecting possible sewage contamination of drinking water supplies (Pipes 1982, 21-22). The fecal-oral route of transmission of many diseases is well documented, particularly for instances of fecal contamination of drinking water supplies and shellfish (Pipes 1982, 21-22).

The incidental ingestion of water when swimming is the primary premise for using these same bacterial indicators to evaluate health risks associated with recreational water use. The level of exposure due to incidental ingestion of water varies between individuals and activities, but it is probably never as high as levels identified with ingesting sewage contaminated drinking waters

and/or shellfish (Cartwright 1992, 93).

Other types of exposure faced by recreational water users include direct contact and inhalation. Bathers and waders are particularly susceptible to direct contact exposures where the skin is broken, and in sensitive areas like the eyes and mucus membranes. By the inhalation of water spray, pathogens may be carried down the respiratory tract. (Cartwright 1992, 93)

Individual susceptibility to infections varies among recreational users. Microbial infections are complex processes governed by the virulence of the pathogen and the immunity of the host (Barrow 1981, 223). If the recreational user is healthy, then their immune systems may stave off infection even after exposure to the pathogenic organisms.

Table 1 lists some common diseases associated with the recreational use of water.

Table 1. Diseases Commonly Associated with the Recreational use of Water

Disease	Organism
Gastrointestinal Infections	*Campylobacter*
	Cryptosporidium
	Salmonella typhi
	Salmonella paratyphi
	Shigella sonnei
	Viruses
Infectious hepatitis	Enterovirus 72
Skin infections	*Trichobilharzia ocellata*
Leptospirosis	*Leptospira icterohaemorrhagiae*
Cyanobacterial poisoning	*Microsystis aeruginosa*
Viral infections	Various

Source: (Fewtrel 1991, 216)

Comprehensive monitoring of recreational water quality by isolating and identifying all pathogenic microorganisms is impractical; there are too many pathogens to test for. Furthermore, incubation times for these isolated microorganisms ranges from a few days to a few weeks. In all likelihood, by the time an outbreak is identified, the pathogen will no longer be in the water. (Laws 1993, 159).

Since many pathogenic microorganisms are found in human feces, certain species of human fecal bacteria are used as indicators of possible sewage pollution. Ideally, the sample concentration of the indicator bacteria in the sample should be proportional to that of pathogenic microorganisms. There should thus be a dose-response relationship between indicator bacteria concentrations and disease occurrence for recreational water users. Assuming the validity of this dose-response relationship, a water quality criterion may be established.

Current Federal recreational water quality standards are based on an extensive prospective epidemiologic study conducted for the EPA by Cabelli *et al* (1982). This study found that the presence of enterococci in marine recreational waters and swimming-associated gastrointestinal (GI) symptoms were strongly associated. The study also found that even relatively low densities of enterococci and *E. coli* (10 CFU per 100ml) were associated with high attack rates (10 illnesses per 1000) of GI symptoms. The current EPA recreational water quality standard for marine waters is set at 35 enterococci per 100 ml that the Cabelli study shows is associated with 16 GI illnesses per 1000 swimmers. Not surprisingly, some public health officials (Laws 1992, 173) and the public (Papanek 1994) finds this level of risk unacceptable.

Whether the results of the EPA study can be extrapolated to other locations is also the source of much debate. The dose-response relationship established in the 1983 EPA study has not been

replicated in other epidemiological studies (Godfree *et al* 1990). Fleisher (1991) contends that the 1983 EPA study was critically flawed because it pooled the results of three separate bathing beaches.

In particular, the applicability of the EPA standards to Hawai'i is also uncertain. Several recent studies have shown that very high levels of indicator bacteria occur in freshwater streams on O'ahu contain where there are no obvious sources of sewage contamination (Hardina and Fujioka 1991, Oshiro 1989, Ahuna 1992, Roll 1992). Because of the apparent unreliability and unsuitablility of standard fecal indicator bacteria, Fujioka and Shizumura (1983) have proposed using *C. perfringens* as an indicator bacteria. They have proposed a standard of 50 CFU *C. perfringens* per 100 ml to show possible sewage contamination for Hawai'i and other tropical waters. Until there is epidemiological data for nonpoint source pollutant contamination of Hawai'i's stream and ocean waters, the relationship between indicator bacteria densities, pathogenic microorganisms, and disease incidence among recreational users in Hawai'i, remain uncertain.

B. RECREATIONAL WATER QUALITY PROBLEMS IN HAWAI'I

Recreational water quality in Hawai'i is of intense public concern. Our beaches attract millions of visitors yearly and are an integral part of our island lifestyle. Therefore, beach closures receive much attention. The closures of Kailua and Waimanalo beaches due to the sewage overflows following the heavy rains in March 1994, were front page stories on a local newspaper (Dayton 1994, A1). There have been at least three beach closures in 1994 (Dayton 1994, A1). A Natural Resources Defense Council report tallies at least 189 beach closures and advisories in Hawai'i between 1988 and 1992 (Adler 1993, 34-35).

Many of Hawai'i's recreational waters regularly exceed the DOH's water quality standards.

Environment Hawai'i cites the Department of Health's 1992 water quality measurements listing 14 beaches across the state as having "very poor" water quality, where "very poor" beaches were those whose average enterococci levels exceeded 14 CFU per 100ml (11). In a survey of 17 streams on O'ahu, only four met the DOH's standard of 200 CFU fecal coliforms per 100ml (Oshiro 1989, 88). Primarily in response to leptospirosis, the DOH has placed warning signs along many streams on O'ahu. However, the DOH closes beaches only after suspected contamination from treated or partially treated sewage, and not necessarily based on high enterococci levels alone (*Environment Hawai'i* 1994, 12).

C. CURRENT WATER QUALITY MANAGEMENT POLICIES

Water quality management policies are implemented through water quality standards. Water quality standards are the definite rules and principles used to regulate water quality (Miller 1971, 17). These standards are based on some water quality criteria, which are derived from the scientific evidence of the effect pollution has on the environment (Miller 1971, 17).

Historically, water quality standards have followed two fundamental strategies: the water quality (or ecology-based) approach, and the technology-based approach. The water quality approach sets standards according to the planned uses of the stream (Novotny and Olem 1994, 16). The technology-based approach sets effluent standards on point source effluent discharges to the limits currently attainable under current water pollution control technology (Novotny and Olem 1994, 16).

The prevailing water quality management strategy since the Clean Water Act (CWA) of 1972, has been the technology-based approach (National Research Council (NRC) 1993, 77). The

goals of the CWA were " . . . to restore and maintain the chemical, physical, and biological integrity of the Nation's waters." The 1972 Act intended to have "swimmable and fishable waters" by 1983 and "zero discharge" by 1985. To achieve these ambitious goals, the 1972 act relied on a strict set of discharge controls called the National Pollution Discharge Elimination System (NPDES). The NPDES set specific effluent limits on all point sources' discharges (Novotny and Olem 1994, 87). As a result, since 1972, federal, state and local governments have spent over $128 billion for the construction and improvements of wastewater treatment plants (Adler 1993, 14).

Despite the significant water quality improvements nationwide following implementation of the CWA, it soon became apparent that serious problems remained (NRC 1993, 34-41). The technology-based approach proved effective in reducing point source pollution; still, problems associated with nonpoint source pollution persisted (Novotny and Olem 1994, 10). Even after substantial reductions in point source pollution, many bays and estuaries next to urbanized watersheds continued to suffer from problems like algal blooms, contaminated shellfish, and closed bathing beaches (NRC 1993, 33). Thus, in 1987, Congress amended the CWA to address the problem of nonpoint source pollution. The 1987 amendments to the CWA called for each state to design and set up nonpoint source pollution management programs.

With this increased attention to nonpoint sources of pollution, technology-based solutions currently are being augmented by water quality- or ecologically-based strategies (NRC 1993, 77). However, management of nonpoint source pollution is inherently problematic because of the diversity and extent of potential contaminants. Because of the complex and ambiguous nature of nonpoint source pollution, ecologically-based solutions must necessarily be comprehensive.

D. WATER QUALITY-BASED SOLUTIONS

Water quality-based standards are harder to enforce than technology-based standards because the causal relationship between a polluter, and the water quality of the receiving water is difficult to prove (Novotny and Olem 1994, 81). Before the 1972 Clean Water Act, most water quality standards were ecologically- based. Nonetheless, because those standards were inconsistently applied and ineffectively enforced, the CWA turned to technology-based standards (NRA 1992, 77). Due to advances in technology, an increased scientific understanding of ecosystem processes, and renewed public awareness of environmental issues, water quality-based standards are more likely to be effective today.

The National Research Council has proposed an approach called Integrated Coastal Management (ICM) to address the complex and interrelated issues regarding the control of coastal pollution. ICM is an attempt to remedy the shortcomings in current technology-based approaches to water pollution, particularly in response to nonpoint sources of pollution (NRC 1993, 13). Table 2 illustrates the main principles of ICM.

ICM may be particularly applicable in Hawaiian watersheds where there are few point sources of pollution. This report presents results of a preliminary study implementing principles of ICM in the articulation of a community-based water quality management strategy for Waimanalo watershed on O'ahu, Hawai'i.

Table 2. The Main Principles of Integrated Coastal Management

- Management actions are based on the best available scientific information about ecological functions, and a comprehensive understanding of human needs and expectations, which are both tangible and intangible.
- Management objectives are expressed as water and sediment quality based and other environmentally and health based goals.
- Comparative assessments of both risks scenarios and available management options drive selection of management strategies.
- Transdisciplinary perspectives are critical.
- The ICM process functions in a context that is responsive to scientific uncertainty about the functions of coastal ecosystems.
- ICM is driven by science and engineering together with public expectations.

Source: (NRC 1993, 79)

PART II. THE PROPOSED STUDY.

A. MOTIVATION OF STUDY

There is a general perception within the Waimanalo community that the water quality of their streams and beaches has degraded. In a Waimanalo Neighborhood Board meeting held on February 16, 1993, residents identified several potential sources of pollution in their community, including point sources such as dairy and other livestock effluent, injection wells at the Waimanalo Sewage Treatment Plant, and Olomana golf course. They also expressed deep concern over nonpoint sources of pollution such as agricultural runoff, leaking cesspools on unsewered farm and beach lots, soil erosion, storm drains, junked cars, and litter. In short, they sought to evaluate the effects of pollution introduced by Waimanalo and Inoa'ole Streams into Waimanalo Bay, from both a public health and an ecological perspective, and to identify potential measures to mitigate and remedy such effects. This study originated from concerns voiced by Waimanalo community members over the perceived deterioration of the water quality of their streams and beaches. The intent of this project is to conduct a rangefinding of the water quality in the Waimanalo watershed as a precursor to the development of a comprehensive plan to control nonpoint sources of pollution.

Funding for this project was provided through the Water Resources Institute Program (WRIP), and analyses were performed at the Water Resources Research Center (WRRC).

B. PROJECT GOALS

As part of a preliminary survey of the Waimanalo watershed, the primary goal of this study is range-finding. The intent is to establish baseline levels and storm event levels of indicator bacteria densities along Waimanalo Stream and Waimanalo Beach. Ultimately, this preliminary study will

form the basis of a proposal and plan for an ongoing and comprehensive program of testing, surveying, monitoring, and ameliorating water quality in the Waimanalo watershed.

The specific objectives of this study were:

1. To characterize the bacterial occurrences (fecal coliform, *E. coli*, enterococci, and *C. perfringens*), and physical parameters (pH, turbidity, and salinity) within Waimanalo Stream, and waters off Waimanalo beach.
2. To characterize the effect of rain events on the bacterial and physical characteristics of water in the Waimanalo watershed.

D. STUDY SITE

The Waimanalo Hydrologic Unit, bounded by the Anianinui and Ka'iwa ridges to the northwest, Waimanalo Bay to the northeast, and the Ko'olau mountains to the south (see Figure 1), occupies approximately 6,000 acres and has a resident population of about 10,000. Waimanalo is a rural agricultural community whose primary industries include ornamental plant nurseries, flower nurseries, truck crops, banana and other fruit orchards, poultry farms, and a dairy. In 1981 the Waimanalo area produced about 35% of the diversified agriculture on O'ahu (DLNR 1988, 4-4).

Two main streams flow through the Waimanalo hydrologic unit into Waimanalo Bay: Waimanalo Stream, a perennial stream, and Inoa'ole Stream, an intermittent stream. Waimanalo Stream is designated by the State of Hawai'i as a Class 2 stream system; thus the beneficial uses

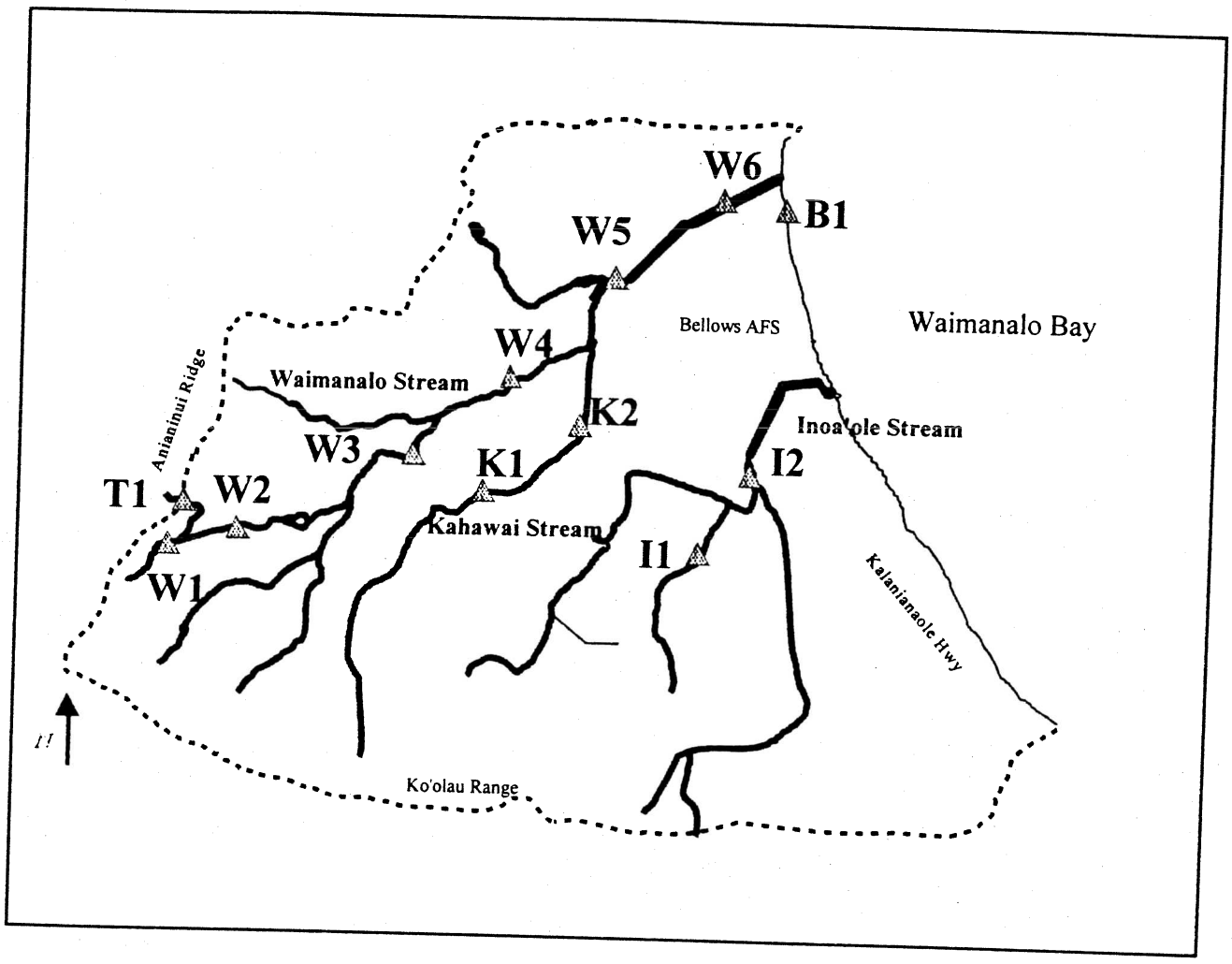

Figure 1. Map of the Waimanalo Watershed and Sampling Sites. Source: (USDA-SCS 1981)

Table 3. Sampling Site Designations and Locations in the Waimanalo Watershed

Site Designation	Location
T1	Anianinui Tunnel, Waimanalo side of Anianinui Ridge.
W1	Waimanalo Stream 0.25 miles upstream of Olomana Ranch.
W2	Waimanalo Stream at Waikupanaha St, near Olomana Ranch.
W3	Waimanalo Stream at Kumuhao St, 1 mile from KalanianaoleHwy.
W4	Waimanalo Stream at Kalanianaole Hwy near Flamingo St.
W5	Waimanalo Stream at Tinker Road, Bellows AFS.
W6	Waimanalo Stream about 100 yards from Waimanalo Stream mouth.
K1	Waimanalo Stream at Mahailua St near Kakaina St.
K2	Kahawai Stream at Kalanianaole Hwy near Frankie's Drive In.
I1	Inoa'ole Stream at Hihimanu St.
I2	Inoa'ole Stream at Kalanianaole Hwy.
B1	Waimanalo Bay about 50 yards south of Waimanalo Stream mouth.

to be protected are bathing, swimming, recreation, and agricultural and industrial water supplies (DPW, 6-26). The lower reaches of Waimanalo stream have been identified by the DLNR (1983, 21) as having a high potential for water-based recreation, particularly for wading, fishing, and boating. Waimanalo beach is among the most popular beaches in the State of Hawai'i and has the longest continuous sand beach on O'ahu, stretching for over three miles (Clark, 177).

E. SAMPLING LOCATIONS.

Because Inoa'ole Stream flowed only intermittently, only Waimanalo Stream was sampled regularly. Sampling locations were chosen to evaluate upper, middle, and lower segments of the Waimanalo watershed. Waimanalo Stream flows for about five miles from the base of the Ko'olau Mountains through the primarily rural and agricultural community of Waimanalo, then entering

Bellows Air Force Base, it flows into a wetland before entering Waimanalo Bay. The regularly sampled sites are shown in Figure 1 and detailed in Table 3.

1. Upper Watershed.

The upper watershed contains the head waters of Waimanalo Stream. Human influences at this reach of Waimanalo stream are minimal, limited to horseback riders and water introduced into the stream from Maunawili as part of the Waimanalo Irrigation System.

Site T1: Anianinui Tunnel. (500 feet above sea level).

The water collected from this site comes directly from Maunawili Valley after passing through several miles of open ditches as part of the Waimanalo Irrigation System. Due to inputs during its course through Maunawili, this water does not strictly represent unaltered headwaters of the Waimanalo stream system.

Site W1. Waimanalo Stream. (200 feet above sea level)

This site is relatively pristine as it is located 0.25 miles upstream of Olomana Ranch. There appears to be little, if any, human impacts at this site. This sampling station is located just upstream of where water from Site T1 enters Waimanalo Stream. The stream is narrow and fast-flowing.

Site W2. Waimanalo Stream. (100 feet above sea level).

This site receives water inputs from Anianinui tunnel and is located just downstream from Olomana Ranch. The stream is narrow and fast flowing.

2. Middle Watershed.

The waters of the middle watershed of Waimanalo Stream are influenced by agricultural and urban land use.

Site W3. Waimanalo Stream. (60 feet above sea level).

This site is rural and downstream from Kailua reservoir. It is surrounded by nurseries and truck crops. The stream bed is natural and the water flow is moderate.

Site W4. Waimanalo Stream. (20 feet above sea level).

This site is in a channelized reach of Waimanalo Stream underneath the highway. Just upstream of this site are several nurseries. The water level at this site is typically only a few inches deep and overgrown with algae.

Site K2. Kahawai Stream. (20 feet above sea level).

This site is at a tributary of Waimanalo Stream (also known as Kahawai Stream). This reach of the stream is channelized and flows through the center of urban Waimanalo, joining Waimanalo Stream just above Bellows Air Force Station (AFS). The water flow at this site is constant, but usually only a few inches deep on a channelized bed. This is the most urban of all sampling locations. This stream bed was usually strewn with litter and debris.

3. Lower Watershed.

The lower watershed of Waimanalo Stream is located within Bellows AFS. This area is an estuary under tidal influence. The Waimanalo Stream mouth is always open to Waimanalo Bay.

Site W5. Waimanalo Stream. (Sea level).

This site is at the confluence of Waimanalo Stream and a tributary from Olomana Golf course. This site is at the entrance to the Bellows AFS Secondary Wetlands Site and is overgrown with mangroves on the northern bank of the stream.

Site W6. Waimanalo Stream. (Sea level).

This site is located near the mouth of Waimanalo Stream. The channel is over 50 feet wide and looks quite deep. The northern bank of the stream is overgrown with mangroves.

Site B1. Waimanalo Bay. (Sea level).

The water samples at this site were taken in the ocean about 50 yards south of the mouth of Waimanalo Stream.

E. METHODOLOGY

1. Sample Collection

Water samples were taken in sterile 1 liter nalgene containers. The samples were collected aseptically from flowing waters by hand following procedures outlined in *Standard Methods* (APHA 1992). Off bridges, the water samples were collected aseptically by affixing a sterile container to the end of a long pole. After collection, the samples were immediately stored in the dark at 4°C and analyzed within 6 hours at the Water Resources Research Center.

2. Enumeration of Bacteria

Indicator bacteria densities were determined by the membrane filtration technique. The selective growth media for the isolation of fecal coliforms, *Escherichia coli*, and enterococci (mFC, mTEC, and mE, respectively) were prepared in accordance with *Standard Methods* (APHA 1992). The selective growth medium for *Clostridium perfringens*, mCP, was prepared as described by Bisson and Cabelli (1979).

The Esculin iron agar (EIA) used for the confirmation of enterococci was prepared as specified in *Standard Methods* (APHA 1992).

The urease reagent used for the confirmation of *E. coli* was prepared as specified in *Standard*

Methods (APHA 1992).

The dilution water used for dilution blanks and membrane filtration rinse water was prepared as specified in *Standard Methods* (APHA 1992). A phosphate buffer blank was filtered for each sample on mFC media as a negative control for the dilution water.

The fecal coliforms, *Escherichia coli*, and enterococci were enumerated with the membrane filtration methods as directed in *Standard Methods* (APHA 1992) using Gelman GN6 0.45 μm membrane filters under vacuum pressure. *C. perfringens* were enumerated with the membrane filtration technique described by Bisson and Cabelli (1979).

The colonies were counted randomly to reduce bias.

3. Replicate Analysis

Two types of replicate analysis were performed. Replicate samples were taken at one sampling site and analyzed in parallel. In addition, replicate plates were filtered for the samples of another four sites. The Cochran's dispersion test (Havelaar *et al* 1993, 6-7) was used to test replicate variation.

4. Physical and Chemical Measurements

The pH was measured using an Orion Research pH meter. The pH meter was calibrated before each measurement according to the instructions.

The salinity was measured using a salinity refractometer.

PART III. RESULTS.

A. SAMPLING SCHEDULE.

Regular sampling was conducted from 19 July 1993 through 20 October 1993, weekly from 19 July through 6 September, and every other week to the end of regular sampling. Samples were also taken during a storm event on 26 September. Additional sampling was performed from 9 June to 28 June 1994. A total of twelve sites was sampled in the Waimanalo and Inoa'ole streams and in Waimanalo Bay. Sites T1, W2, W3, W4, and K2 were sampled throughout the course of the study. Sampling locations, W5, W6, and B1 on Bellows Air Force were sampled only from 18 August on. Four additional samples were taken weekly at stations W1 and W2 during June 1994. The other sites were sampled only occasionally and those results are tabulated in the Appendix.

B. INDICATOR BACTERIA CONCENTRATIONS IN WAIMANALO STREAM AND WAIMANALO BAY.

Figures 2 through 5 shows the maximum and minimum and geometric means of fecal coliforms, *E.coli*, enterococci, and *C. perfringens* densities at Site W1 and W2, tested during June 1994. The concentration of all indicator bacteria densities increased between Sites W1 and W2. Both federal and state water quality standards were exceeded even at the relatively pristine W1. However, both W1 and W2 met the proposed standard of 50 CFU *C. perfringens* per 100ml.

Figures 6 through 9 shows the maximum/minimum and geometric means of fecal coliform, *E.coli*, enterococci, and *C. perfringens* densities at all the regularly sampled locations: T1, W2, W3, W4, K2, and W5. The geometric means generally rose from sites T1 through W5. Kahawai stream, Site K2, joins Waimanalo Stream just above Site W6, has significantly higher concentrations of fecal

indicator bacteria than any other site sampled. Fecal coliforms, *E. coli*, and enterococci concentrations varied from few hundred CFU per 100 ml to over 100,000 CFU per 100 ml, and *C. perfringens* varied from <1 CFU per 100 ml to a few thousand CFU per 100 ml. Again, none of the sampling stations met the state and federal water quality standards. Sites T1, W2, W3, and W4 all met the proposed standard for *C. perfringens* 50 CFU per 100 ml.

Figures 10 shows the maximum and minimum and geometric means of fecal coliforms, *E.coli*, enterococci, and *C. perfringens* densities at Site B1, Waimanalo Bay at Bellows AFS. Although maximum levels at B1 occasionally exceeded 50 CFUs per 100 ml for all fecal bacterial indicators, the enterococci geometric means were well within the federal water quality standards of 35 CFUs per 100 ml, and just below the state standard of 7 CFUs per 100 ml.

C. TEMPORAL VARIATIONS IN INDICATOR BACTERIA CONCENTRATIONS.

Figures 11 through 15 show the monthly geometric mean concentrations of fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at Sites T1, W2, W3, W4, and K2. The fecal coliforms, *E. coli*, and enterococci, and *C. perfringens* concentrations do not appear to vary significantly during the testing period.

D. EFFECT OF A RAIN EVENT ON INDICATOR BACTERIA CONCENTRATIONS.

Figures 16 through 19 shows the indicator bacteria concentrations at Sites W2, W3, W4, and K2 during a rain event on 26 September 1993. The rain-event indicator bacteria concentrations increased one hundred times over the geometric mean concentrations of the eleven samples taken between 19 July 1993 and 20 October 1993.

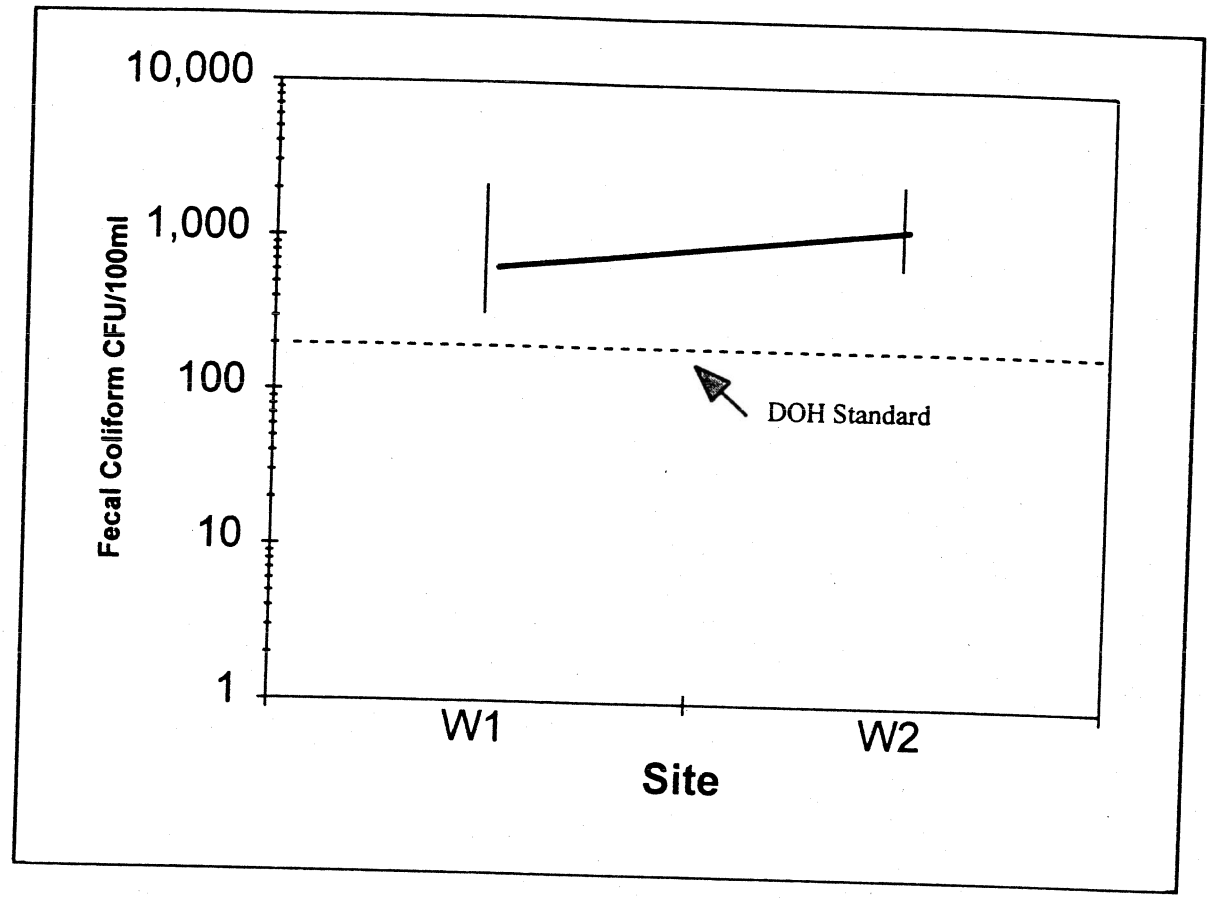

Figure 2. Fecal coliforms densities at sites W1 and W2 for four samples collected between 9 and 27 June 1994. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The state recreational water quality standard for fresh waters is 200 CFUs fecal coliforms per 100ml.

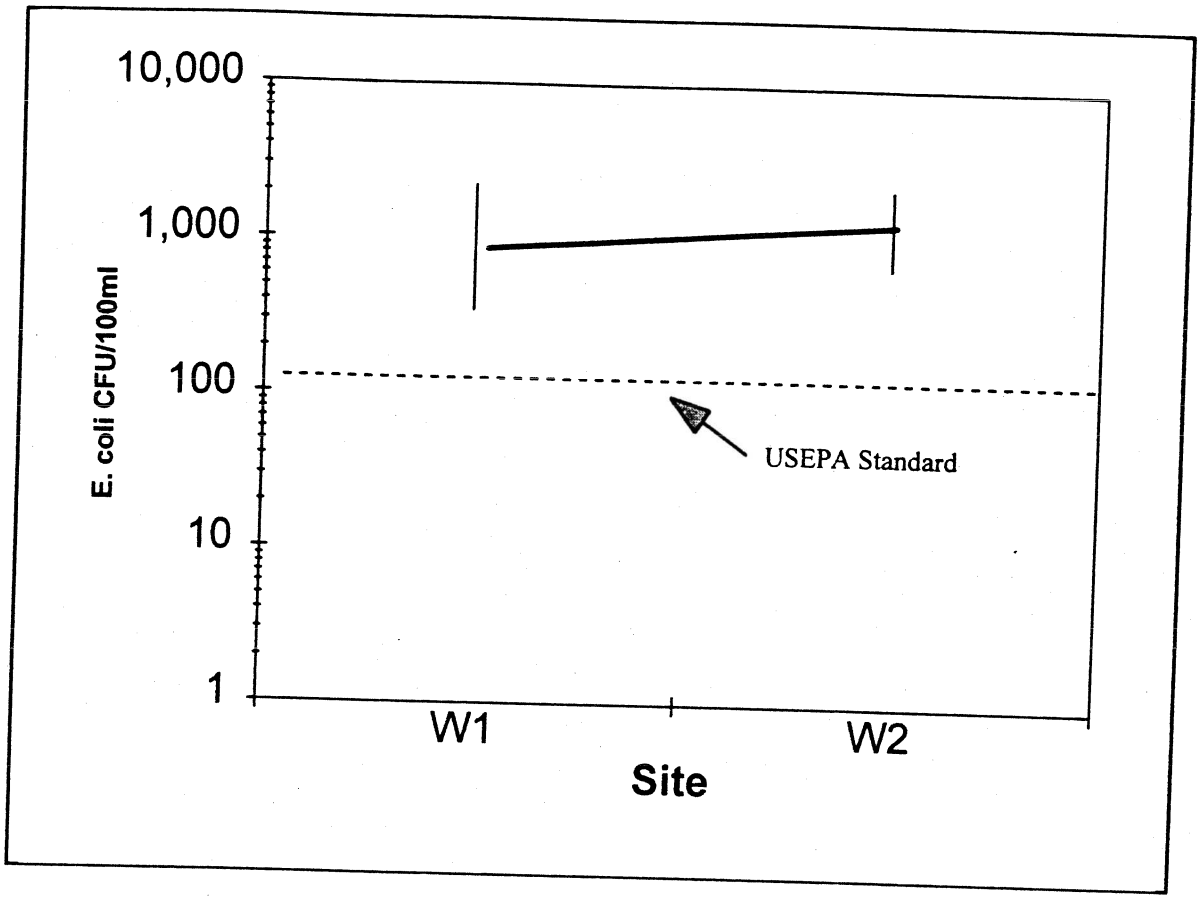

Figure 3. *E. coli* densities at sites W1 and W2 for four samples collected between 9 and 27 June 1994. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The federal recreational water quality standard for fresh waters is 33 CFU enterococci per 100 ml or 126 CFU *E. coli* per 100 ml.

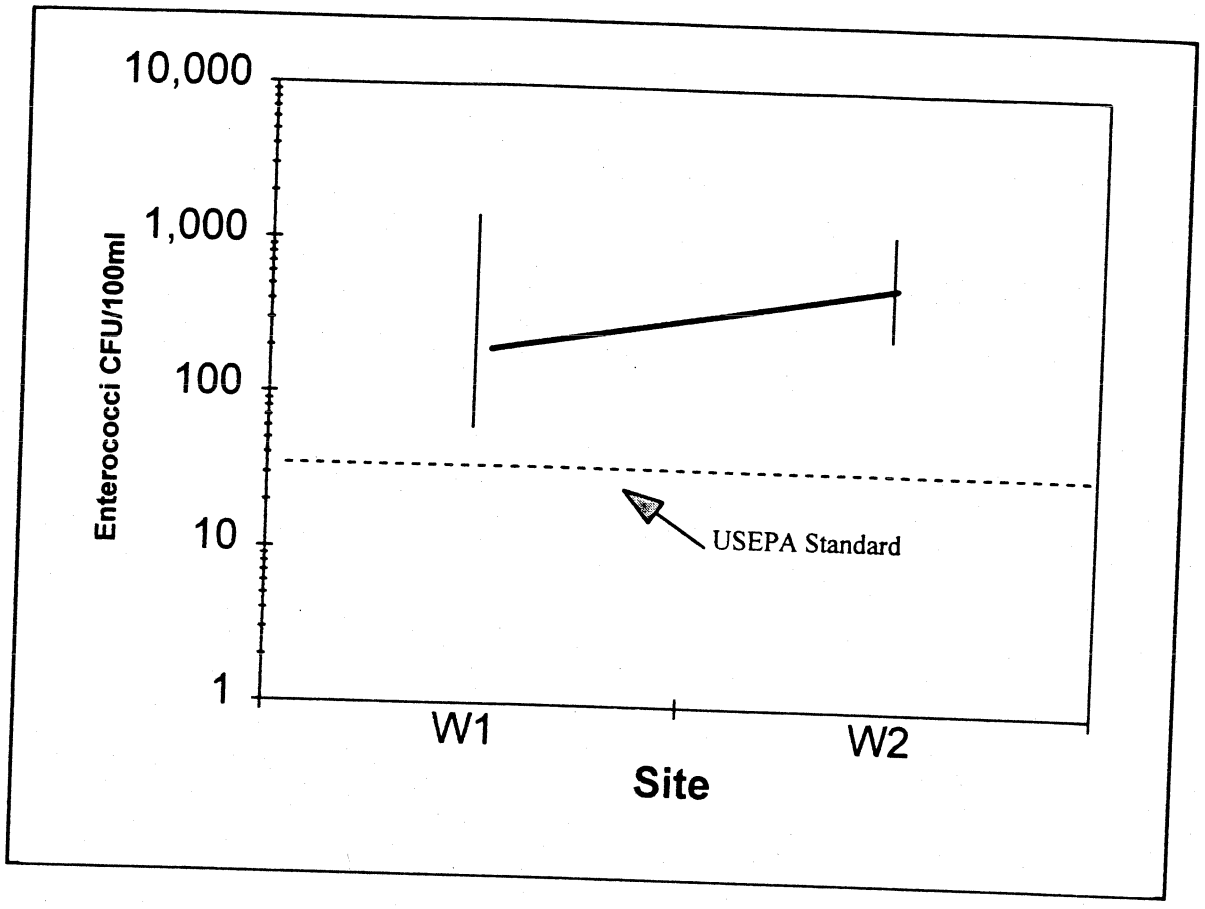

Figure 4. Enterococci densities at sites W1 and W2 for four samples collected between 9 and 27 June 1994. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The federal recreational water quality standard for fresh waters is 33 CFU enterococci per 100 ml or 126 CFU *E. coli* per 100 ml.

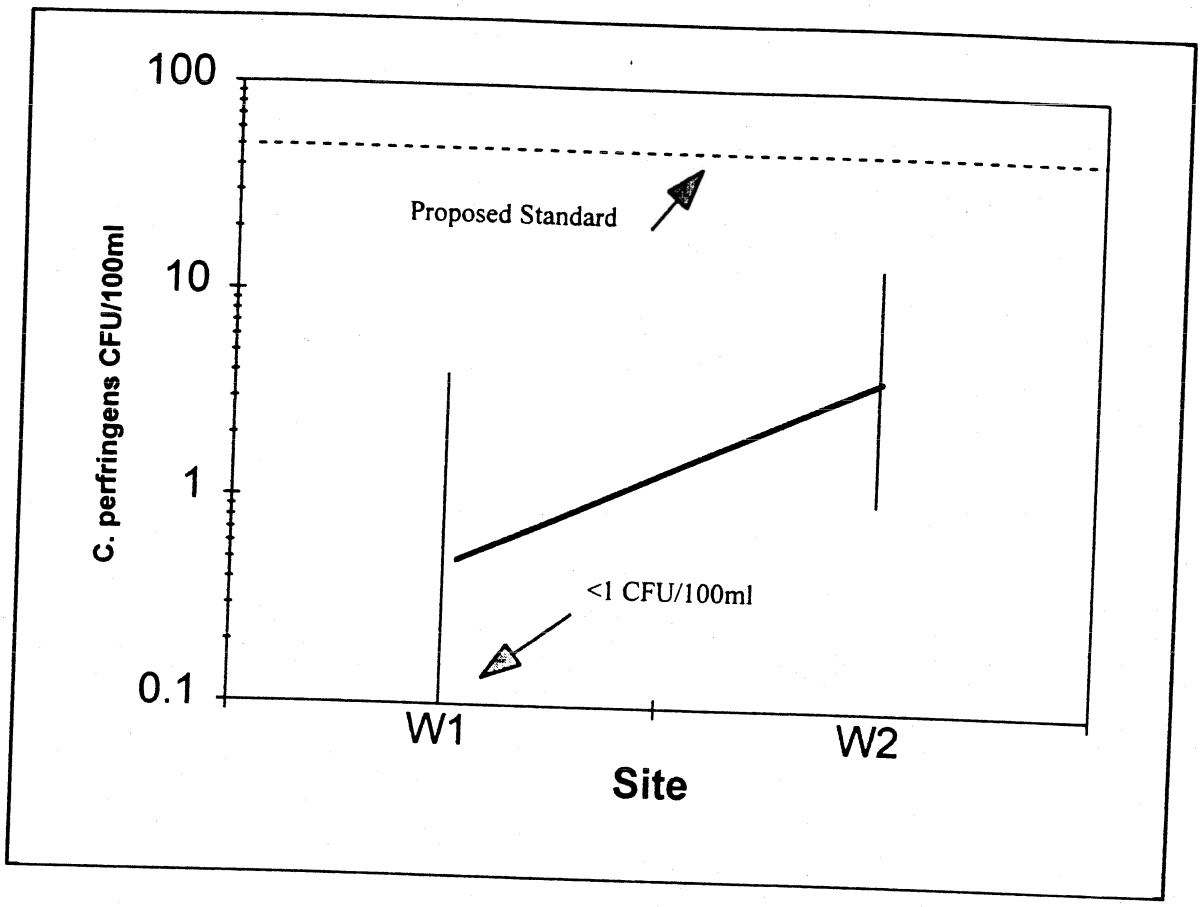

Figure 5. *C. perfringens* densities at sites W1 and W2 for four samples collected between 9 and 27 June 1994. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. A proposed recreational water quality standard for fresh waters is 50 CFU *C. perfringens* per 100ml (Fujioka 1983).

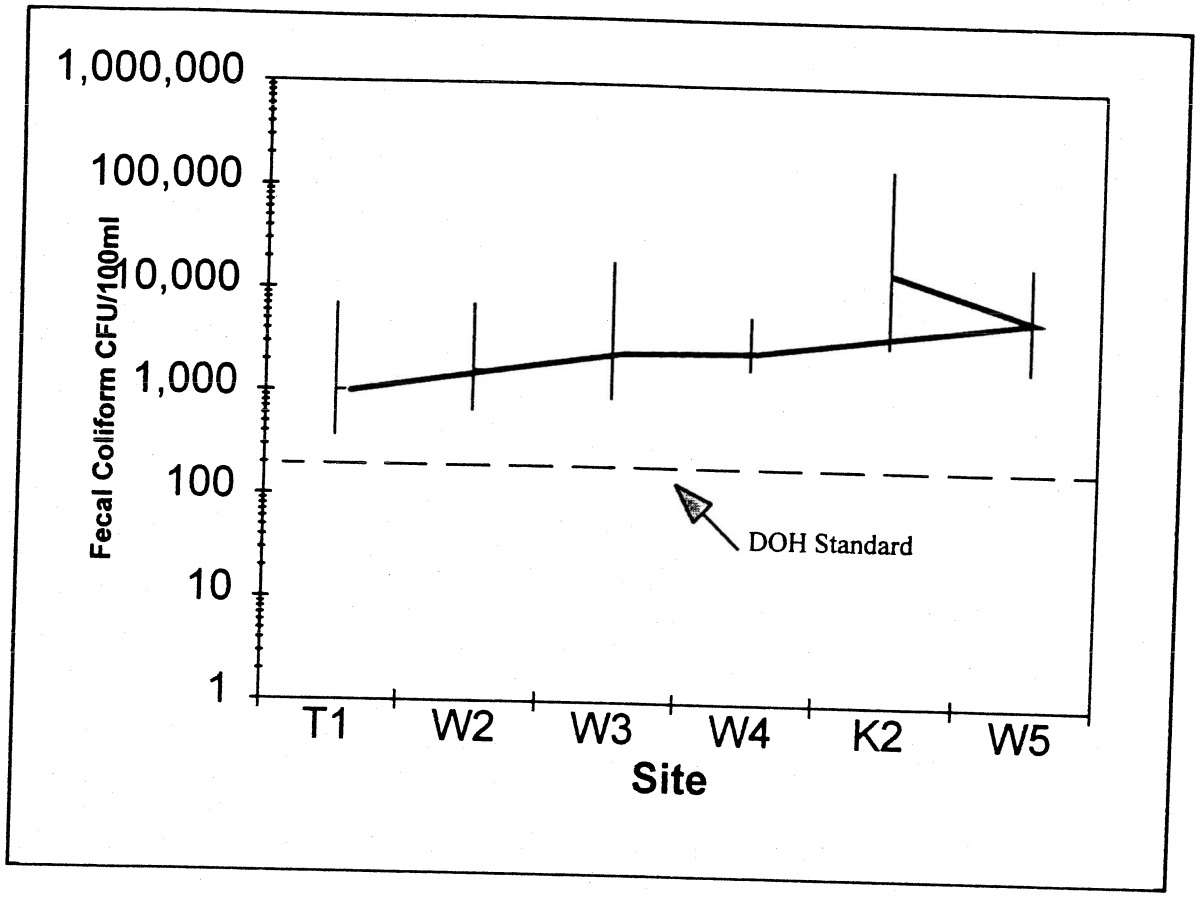

Figure 6. Fecal coliform densities at sites T1, W2, W3, W4, and K2 for eleven samples collected between 19 July and 20 October 1993; and at site W5 for six samples collected between 18 August and 20 October 1993. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The state recreational water quality standard for fresh waters is 200 CFU fecal coliforms per 100ml.

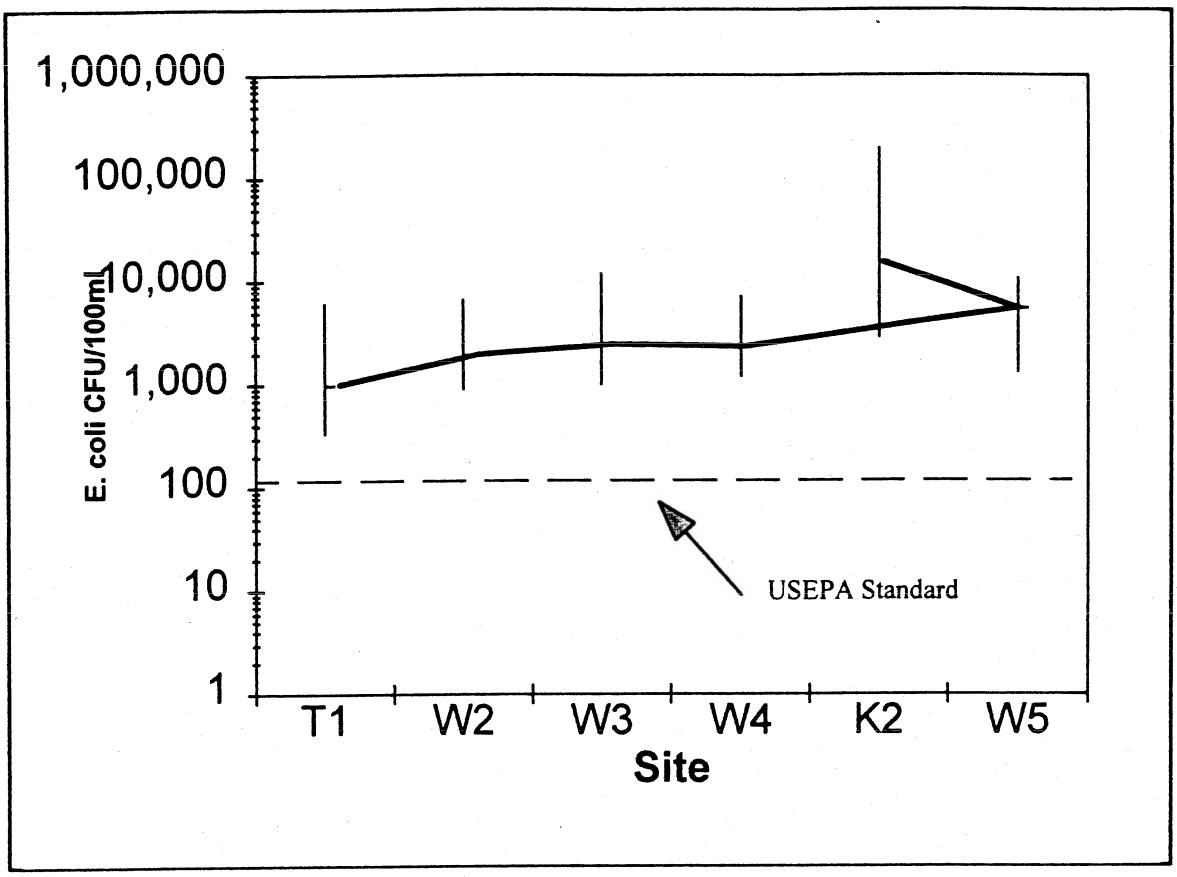

Figure 7. *E. coli* densities at sites T1, W2, W3, W4, and K2 for eleven samples collected between 19 July and 20 October 1993; and at site W5 for six samples collected between 18 August and 20 October 1993. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The federal recreational water quality standard for fresh waters is 33 CFU enterococci per 100 ml or 126 CFU *E. coli* per 100 ml.

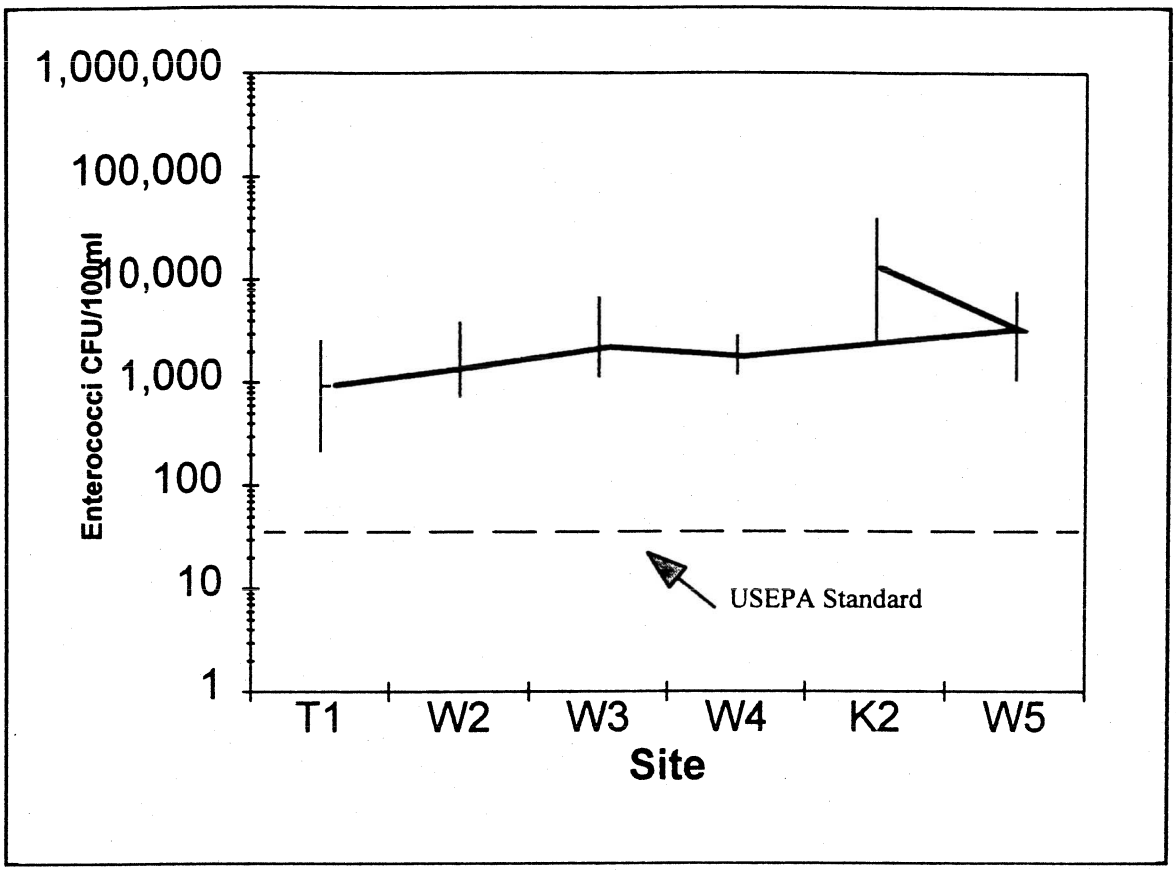

Figure 8. Enterococci densities at sites T1, W2, W3, W4, and K2 for eleven samples collected between 19 July and 20 October 1993; and at site W5 for six samples collected between 18 August and 20 October 1993. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The federal recreational water quality standard for fresh waters is 33 CFU enterococci per 100 ml or 126 CFU *E. coli* per 100 ml.

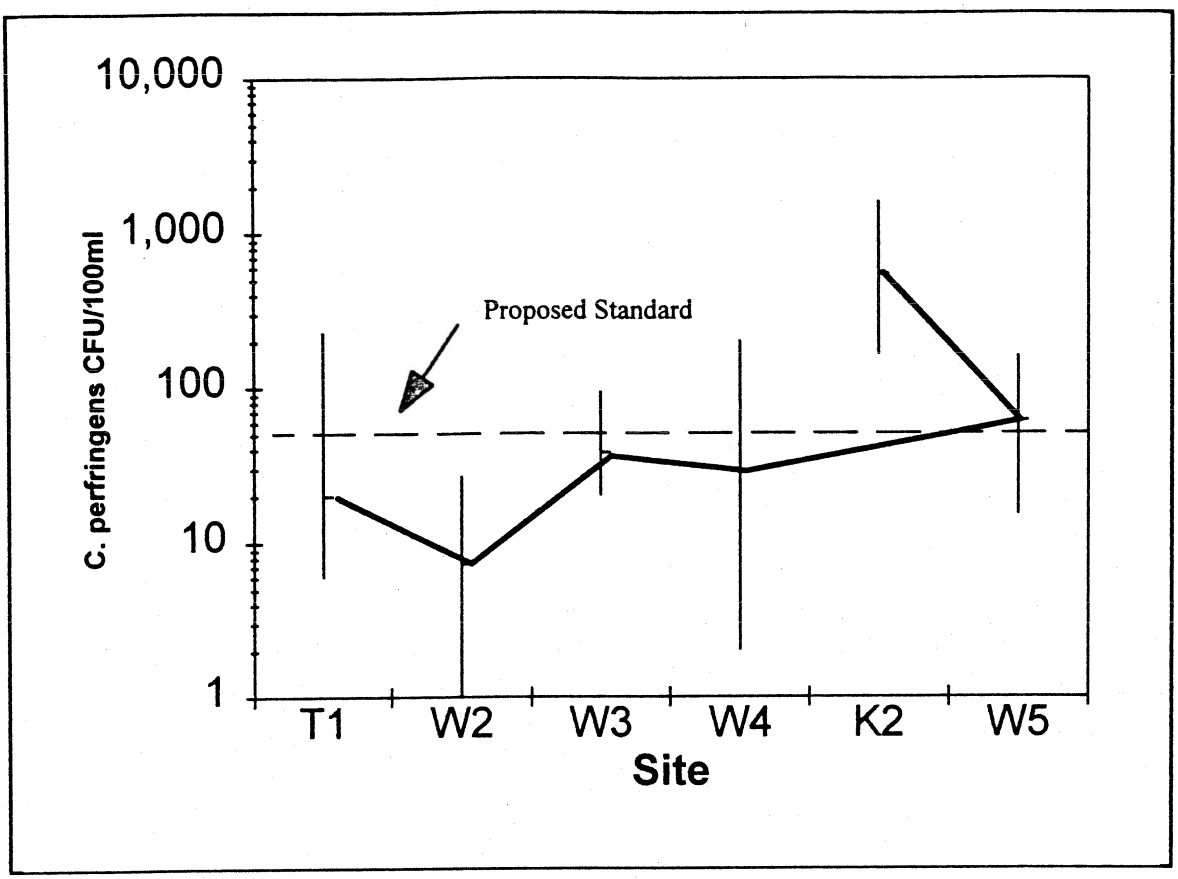

Figure 9. *C. perfringens* densities at sites T1, W2, W3, W4, and K2 for eleven samples collected between 19 July and 20 October 1993; and at site W5 for six samples collected between 18 August and 20 October 1993. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. A proposed recreational water quality standard for fresh waters is 50 CFU *C. perfringens* per 100ml (Fujioka 1983).

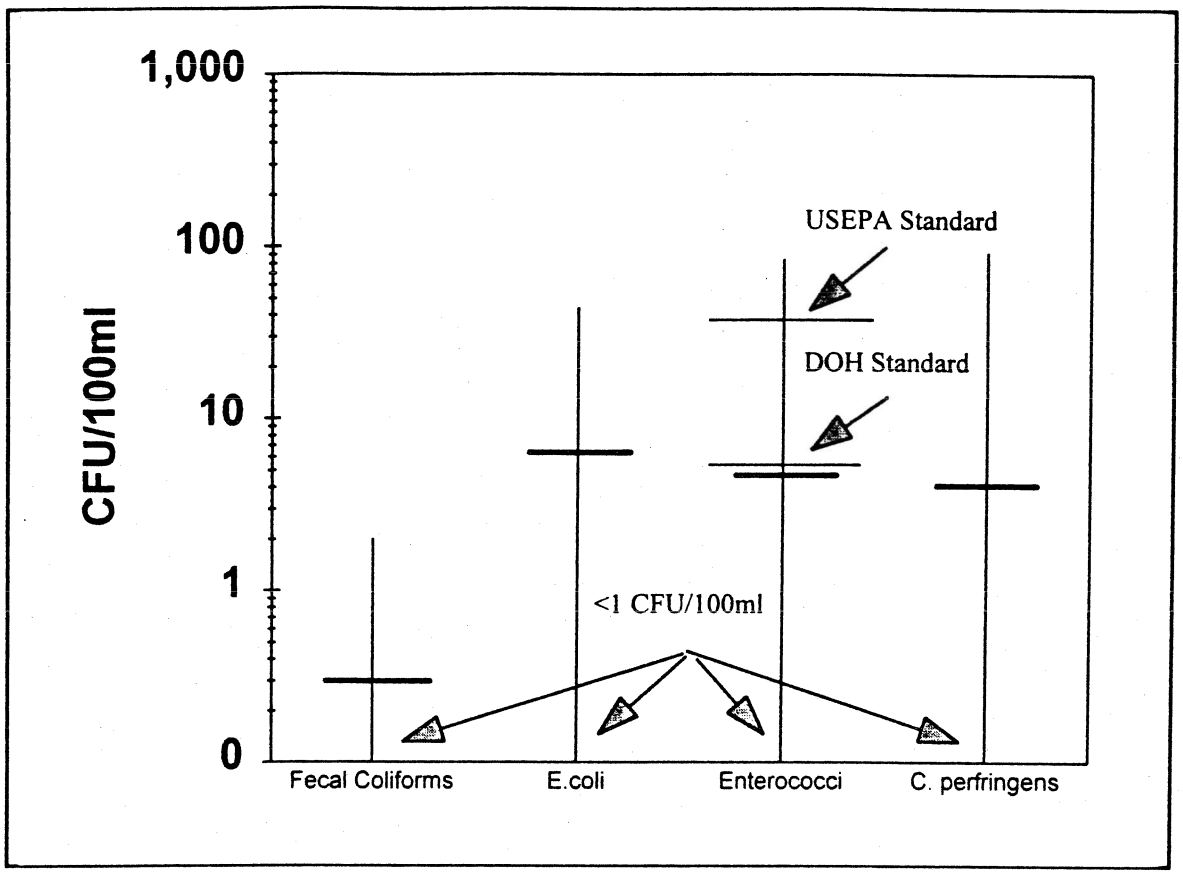

Figure 10. Indicator bacteria densities at site B1, Waimanalo Bay at Bellows AFS, for seven samples collected between 18 August and 20 October 1993. The vertical bars indicate the maximum and minimum concentrations. The dark line connects the geometric mean concentrations. The federal recreational water quality standard for marine waters is 35 CFU enterococci per 100 ml or 126 CFU *E. coli* per 100 ml.

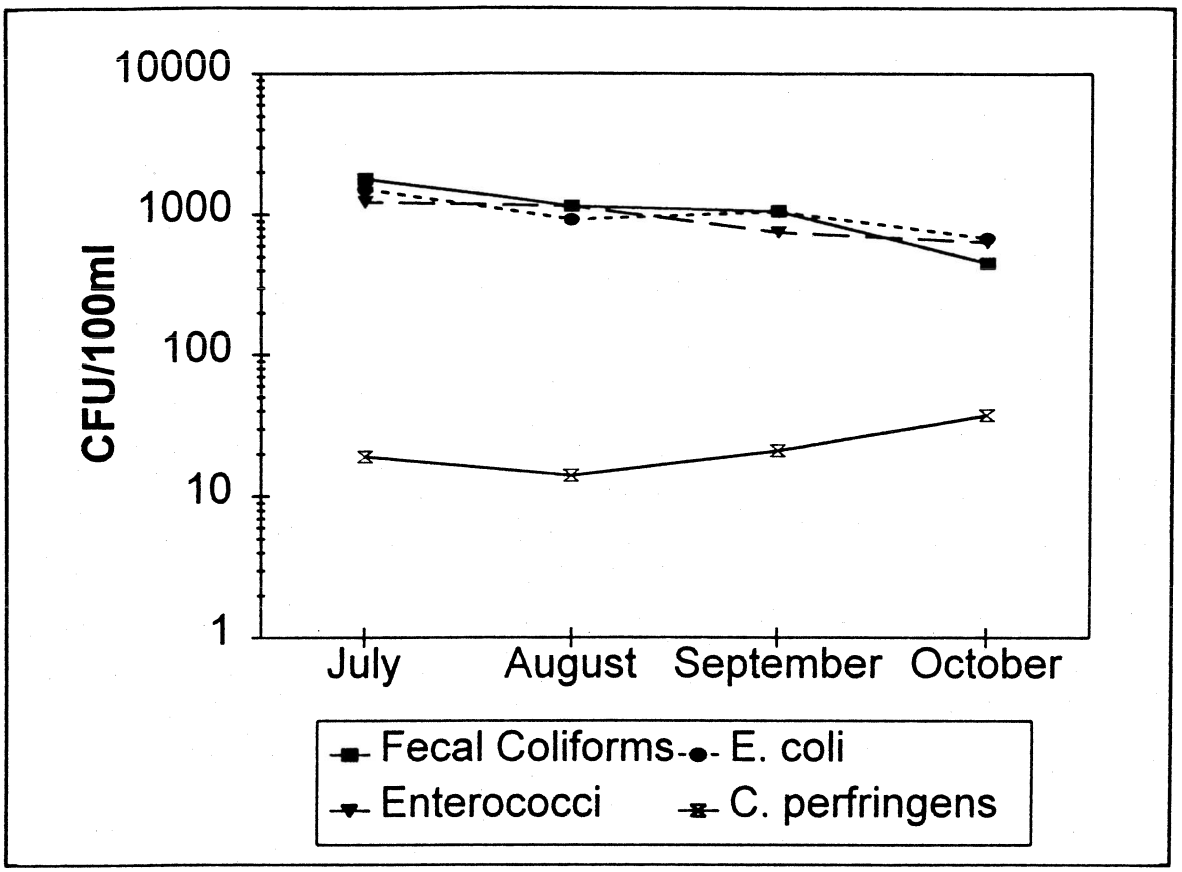

Figure 11. Monthly geometric mean concentrations for fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at site T1.

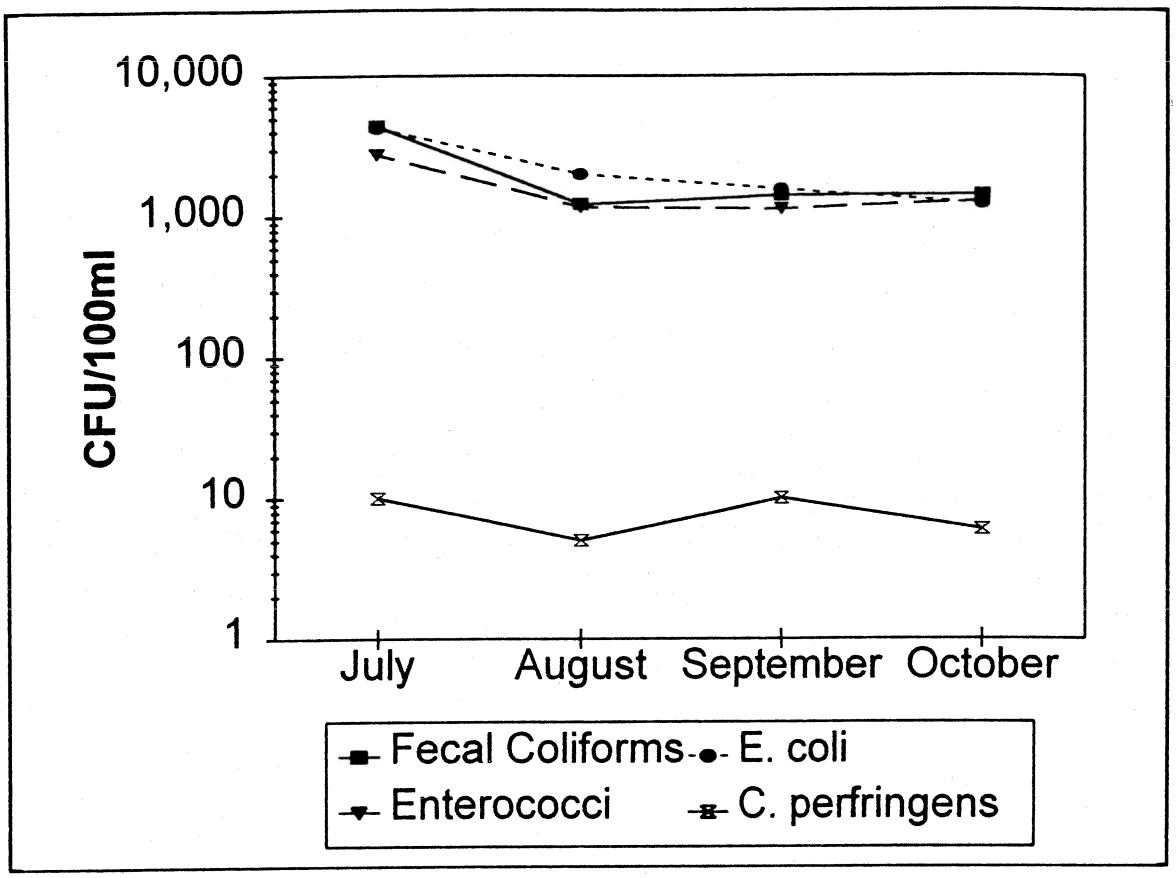

Figure 12. Monthly geometric mean concentrations for fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at site W2.

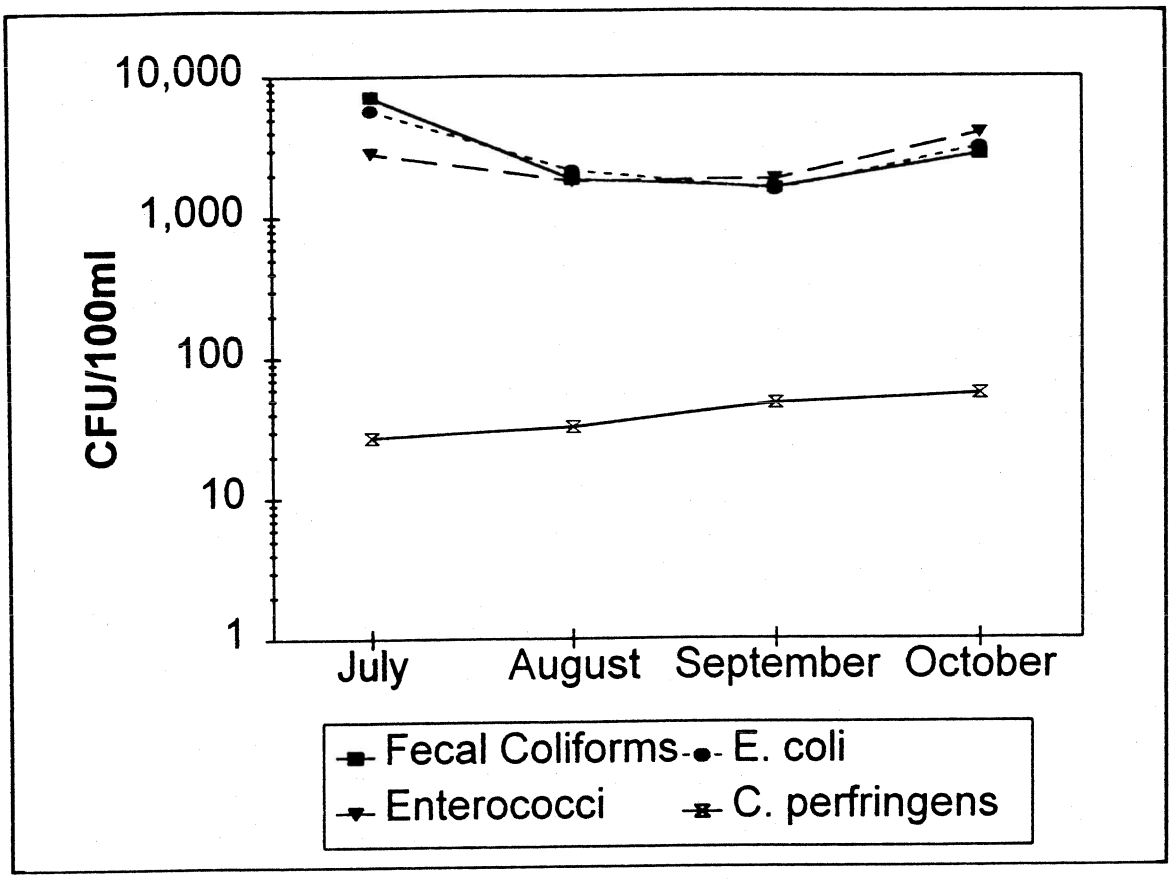

Figure 13. Monthly geometric mean concentrations for fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at site W3.

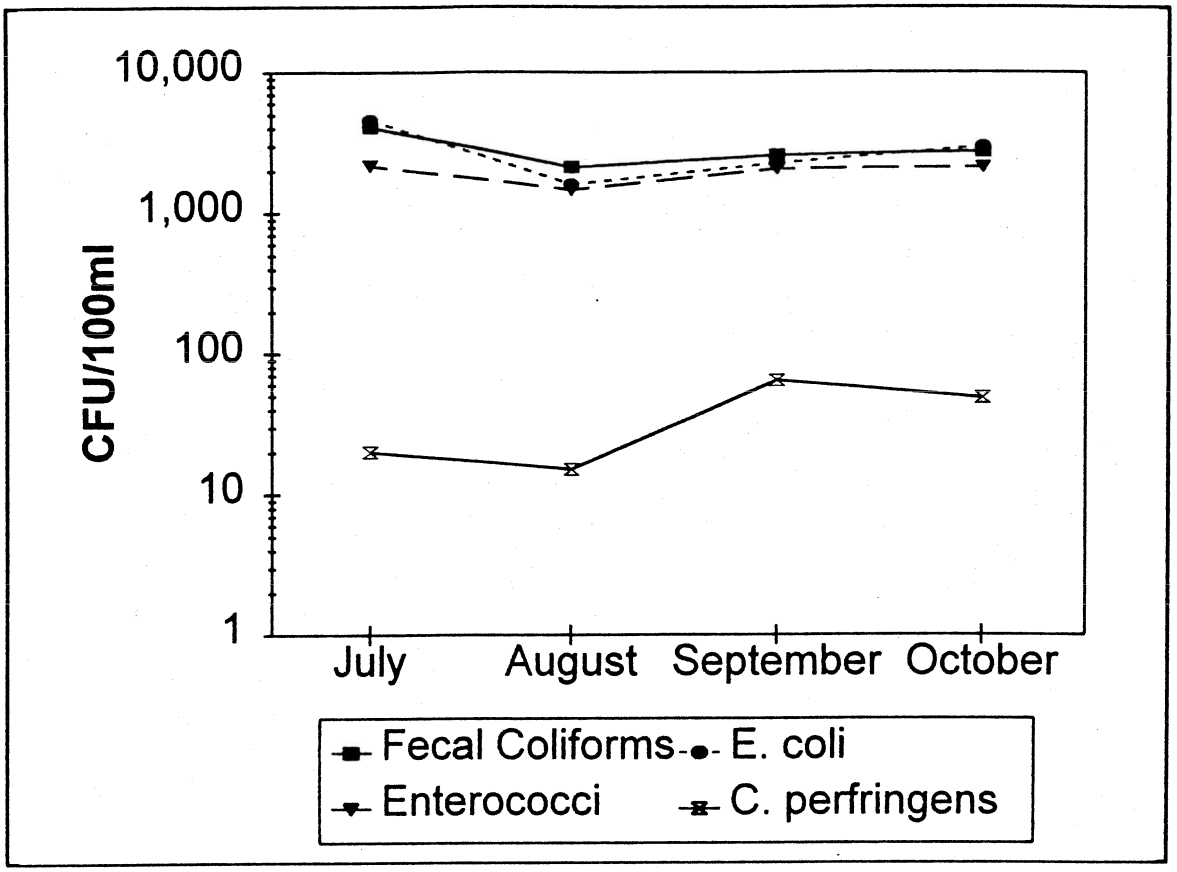

Figure 14. Monthly geometric mean concentrations for fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at site W4.

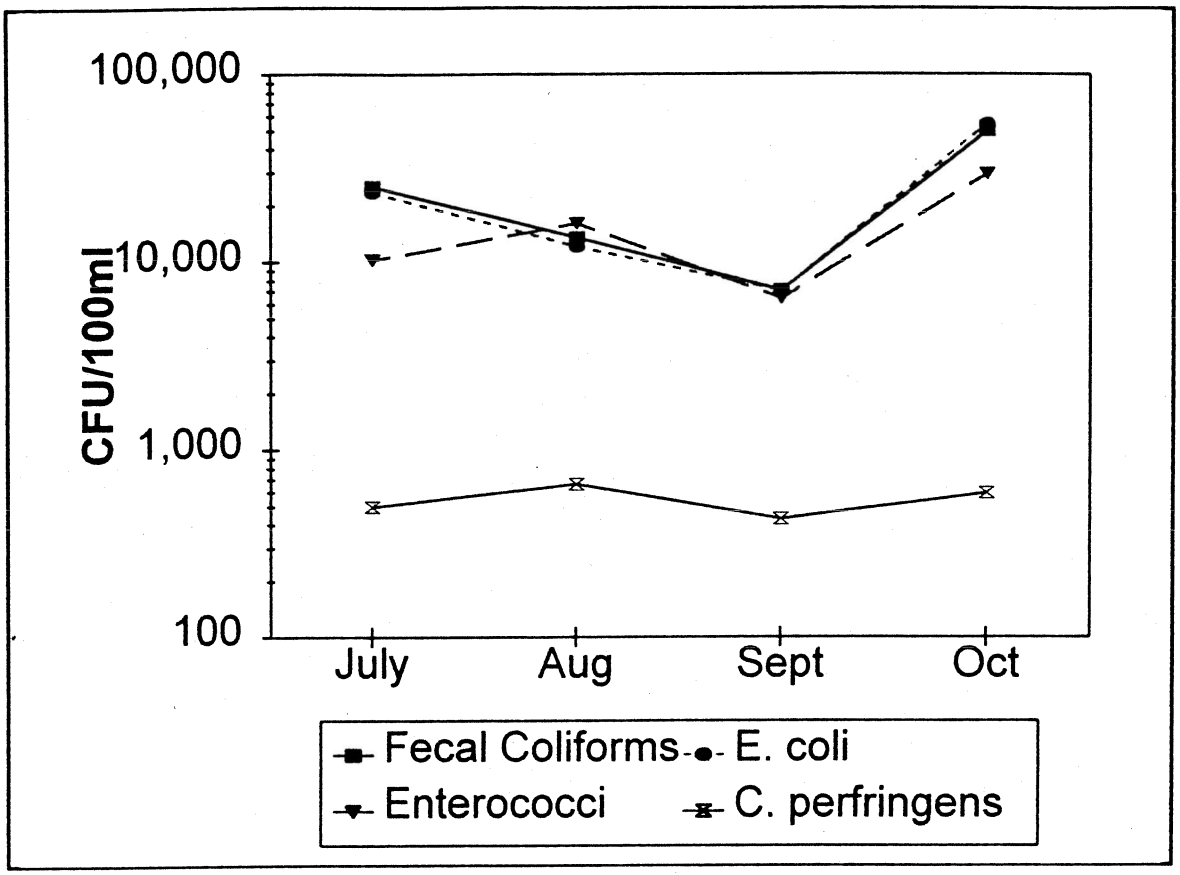

Figure 15. Monthly geometric mean concentrations for fecal coliforms, *E. coli*, enterococci, and *C. perfringens* at site K2.

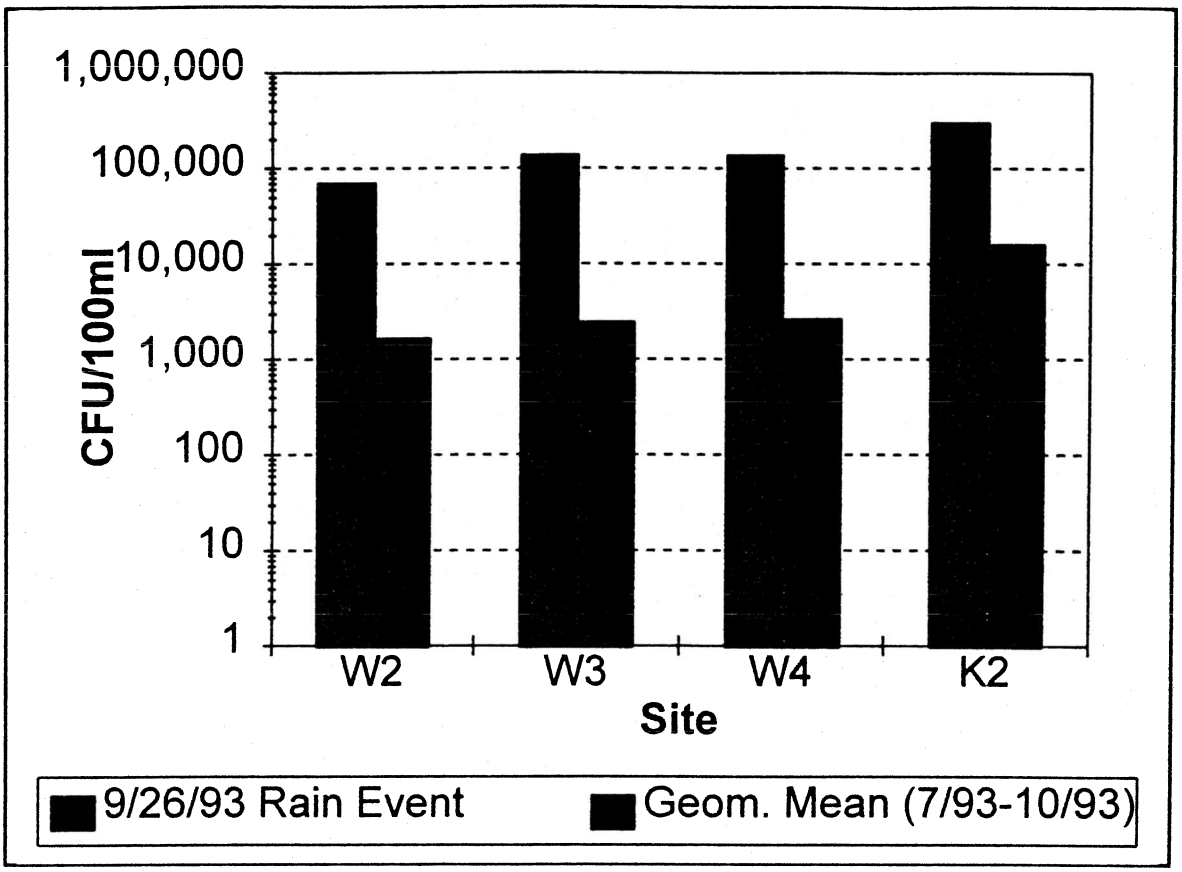

Figure 16. Fecal coliforms concentrations at sites W2, W3, W4, and K2 during a rain event of 26 September 1993, contrasted with the geometric mean concentrations of eleven samples collected between 19 July and 20 October 1993.

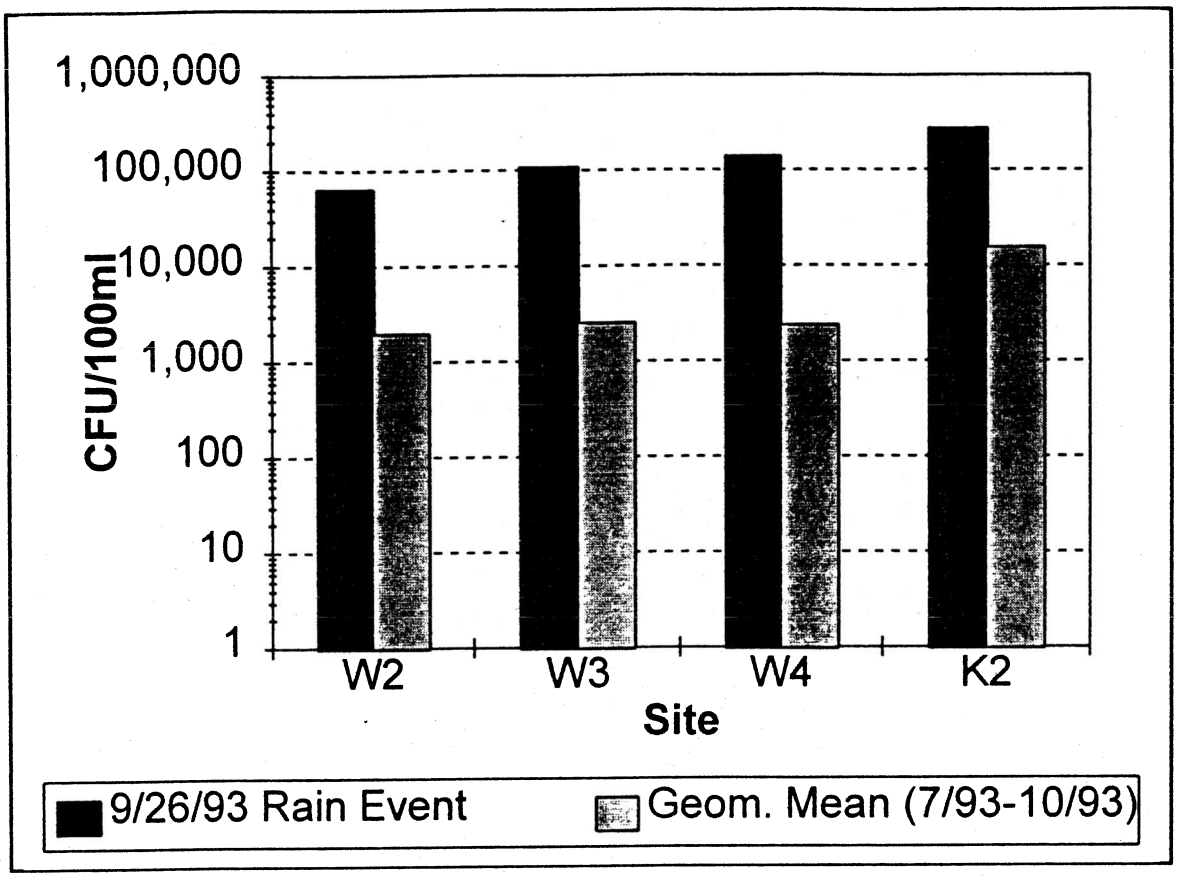

Figure 17. *E.coli* concentrations at sites W2, W3, W4, and K2 during a rain event of 26 September 1993, contrasted with the geometric mean concentrations of eleven samples collected between 19 July and 20 October 1993.

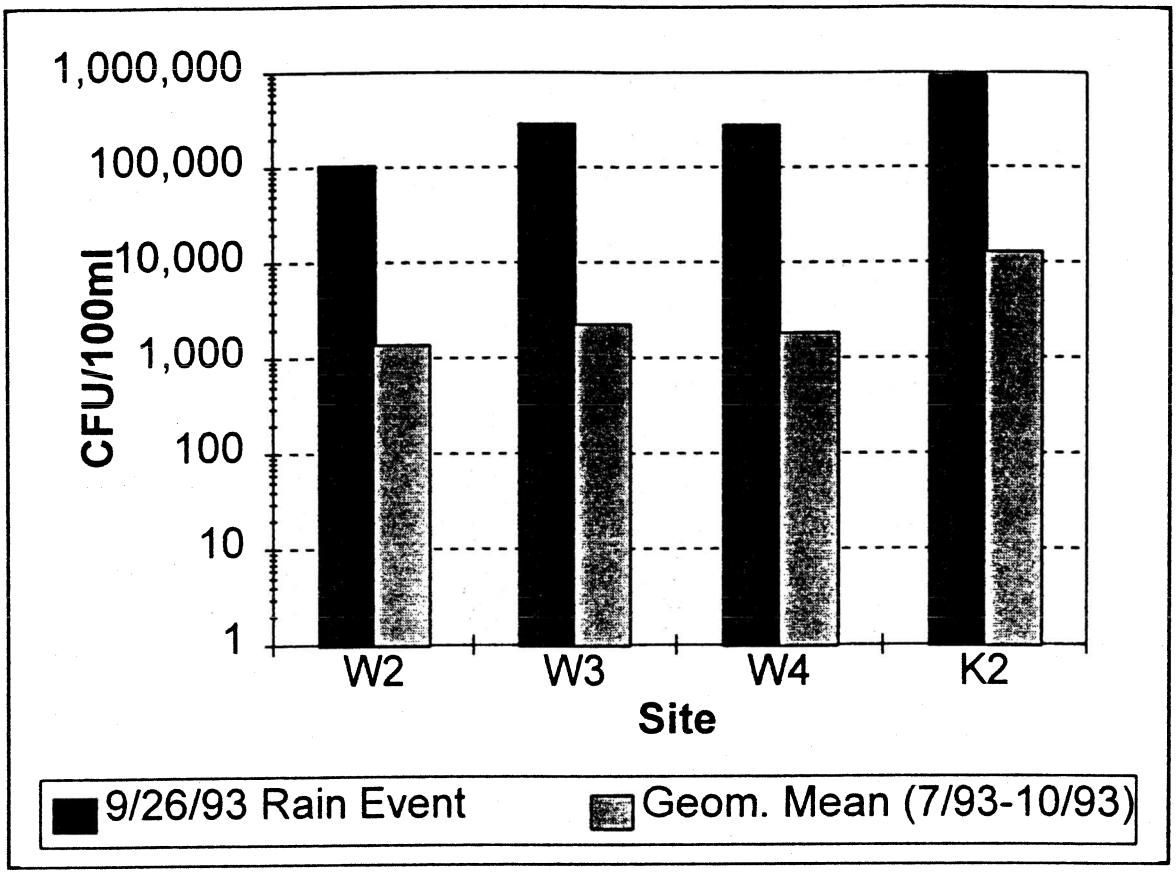

Figure 18. Enterococci concentrations at sites W2, W3, W4, and K2 during a rain event of 26 September 1993, contrasted with the geometric mean concentrations of eleven samples collected between 19 July and 20 October 1993.

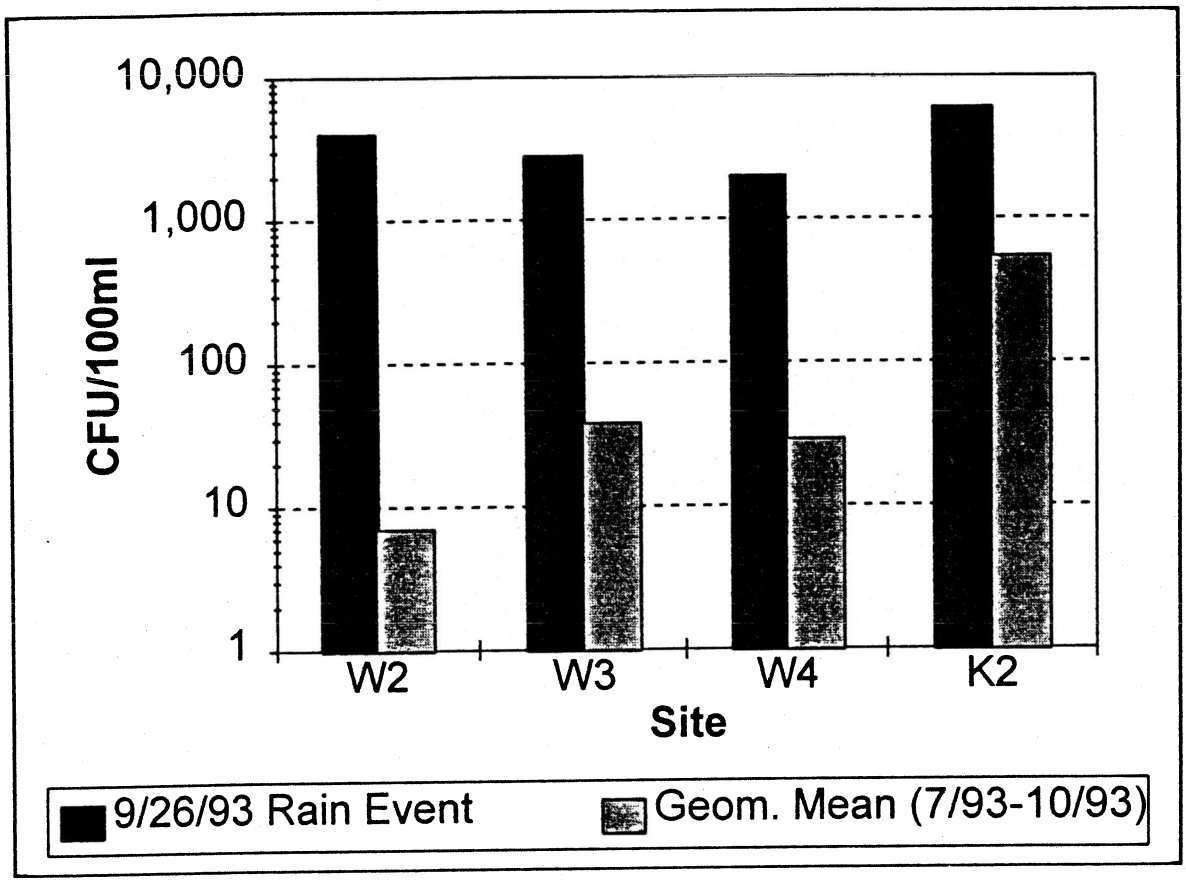

Figure 19. *C. perfringens* concentrations at sites W2, W3, W4, and K2 during a rain event of 26 September 1993, contrasted with the geometric mean concentrations of eleven samples collected between 19 July and 20 October 1993.

PART IV. DISCUSSION

A. SOURCES OF FECAL INDICATOR BACTERIA

Ideally, the source of fecal indicator bacteria should be from human effluent only. Unfortunately, the bacterial indicators and techniques currently employed do not have such specificity. Animal wastes are one probable source of indicator bacteria. As Table 4 shows, animal wastes can contain very high levels of indicator bacteria. Feral animals like mongoose; farm animals such as cows, horses, and pigs; poultry; and domestic pets such as cats and dogs - which are all fairly common in Waimanalo - may be sources of indicator bacteria in Waimanalo Stream.

It is not likely, however, that animal wastes are the sole sources of indicator bacteria in Waimanalo Stream. As Fujioka (1988, 629) observes, a stream known to be contaminated with sewage typically has high levels of nutrients. The low nutrient levels that characterize most Hawaiian streams do not provide evidence of the extensive fecal contamination necessary for the amounts of fecal indicator bacteria detected throughout Hawai'i. Indeed, as Figure 20 shows, there was very little rainfall over Waimanalo over the course of this study. Overland runoff into Waimanalo Stream due to rainfall was probably not the most significant direct contributor of indicator bacteria levels. A likelier source of bacteria in streams in Hawai'i, suggested by Fujioka (1988, 630), is from the soil. Indicator bacteria, perhaps initially seeded by animal wastes, have been shown to survive and replicate in soils in Hawai'i (Hardina and Fujioka 1991).

Table 4. Concentrations of fecal indicator bacteria found in animal and human feces.

	Average density per gram				
Animal Group	Fecal Coliforms	*Escherichia coli*	Enterococci	*Clostridium perfringens*	Sources
Wild Animals					
Rats	100,000	100,000	100,000,000	-	Fujioka, C., 1989
Birds	1,000,000,000	1,000,000,000	10,000,000	-	Fujioka, C., 1989
Mongoose	1,000,000,000	100,000,000	10,000,000	-	Fujioka, C., 1989
Pigeon	100,000,000	100,000,000	100,000	-	Fujioka, C., 1989
Duck	760,000	1,600,000	1,400,000	290,000	Roll, 1992
Farm Animals					
Cow	4,000,000	-	-	80	Sorenson, 1989
Pig	3,300,000	-	-	3,980	Geldreich, 1977
Sheep	-	-	-	70	Sorenson, 1989
Horse	12,600	-	-	<1	Geldreich, 1977
Duck	33,000,000	-	-	-	Geldreich, 1977
Chicken	1,300,000	-	-	250	Geldreich, 1977
Turkey	290,000	-	-	-	Geldreich, 1977
Pets					
Mouse	100,000	100,000	100,000,000	-	Fujioka, C., 1989
Dog	10,000,000	10,000,000	1,000,000	-	Fujioka, C., 1989
Cat	<4	<4	10,000	-	Fujioka, C., 1989
Guinea pig	100,000	100,000	1,000	-	Fujioka, C., 1989
Rabbit	<4	<4	<4	-	Fujioka, C., 1989
Human	13,000,000	-	-	1,580	Geldreich, 1977

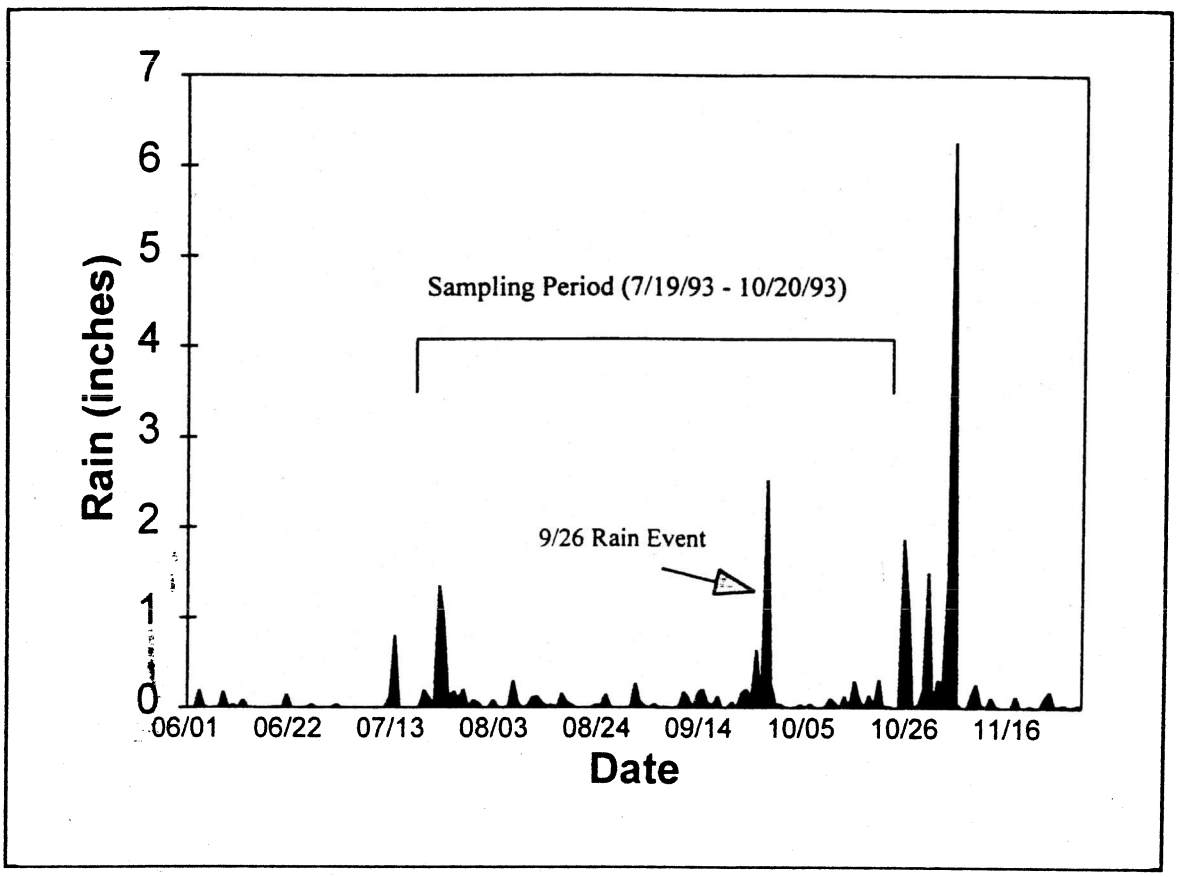

Figure 20. Rainfall measured at the University of Hawai'i Waimanalo Experimental Farm. (Source: Fujii, DLNR 1994)

How long can fecal indicator bacteria survive once it is introduced into the environment? Microbial survival and growth are highly dependent on environmental conditions. Most bacteria can survive and multiply only within a narrow range of temperatures (Tortora *et al* 1992, 142). Fecal indicator bacteria, whose original habitat is in the intestinal tracts of humans and animals, are accustomed to temperatures between 30°C and 40°C. The water temperature of streams in Hawai'i can range between 18°C and 37°C (Hathaway 1978, 31), well within the tolerances of most fecal indicator bacteria (Fujioka 1988, 629).

Bacteria are 80% to 90% water and dependent on soluble nutrients in the surrounding waters for their survival (Tortora et al 1992, 144). Many types of bacteria are highly susceptible to desiccation and may not grow or reproduce when dry (Tortora 1992, 174). Moist soils (Hardina and Fujioka 1991), stream bottom sediments (Hunter *et al* 1992, Doyle *et al* 1992), and storm drain sediments (Marino and Gannon 1991, Kebabjian 1994), appear to provide ideal environments for microbial growth. These studies have shown that it is possible for fecal indicator bacteria to survive and multiply in a warm, wet, and nutrient-rich, environment.

B. TRANSPORT OF FECAL INDICATOR BACTERIA INTO WAIMANALO STREAM

There is only one major point source in the Waimanalo watershed controlled and regulated by the State of Hawai'i Department of Health through the Federally mandated National Pollutant Discharge Elimination System (NPDES) permit program, the Waimanalo Dairy (Honolulu C&C, 1990). The Waimanalo Dairy discharges its agricultural and feedlot wastes into Inoa'ole Stream. Inoa'ole Stream was not regularly sampled in this study because it is an intermittent stream. There are no major point sources regulated by the NPDES permit program discharging into

Waimanalo Stream . The major source of fecal indicator bacteria in Waimanalo stream - like many other streams in Hawai'i (Fujioka *et al* 1988) - are probably predominantly from nonpoint sources.

There are three major components to nonpoint source pollution: surface runoff, interflow, and ground-water runoff (Novotny and Olem 1994, 103). Surface runoff is the residual flow after all losses, such as infiltration, evaporation, ponding, and transpiration by vegetation, are accounted for. Precipitation is the main source of surface runoff. However, agricultural practices like irrigation, and urban runoff from road cleaning, can also be considered surface runoff. Surface runoff carries the highest load of particulate pollutants (Novotny and Olem 1994, 103). Hunter *et al* found that Overland flow contributed the greatest bacterial load into a stream (1992, 1874). Hunter *et al* also found a strong positive correlation between stream gauge height and bacterial density, suggesting a relationship between the catchment land store and indicator bacteria concentrations in the stream. As shown in Figures 16 through 19 during the storm event of 26 September 1993, indicator bacteria concentrations increased by over one hundred times over ambient conditions. This storm event was also the first significant rainfall over Waimanalo in over four months, as illustrated in Figure 20. Thus, a sizable land store of fecal indicator bacteria may have accumulated during these four months of drought.

Interflow is the subsurface water movement in the horizontal direction. Over irrigation is the most common cause of interflow pollution, usually with salts and pesticides (Novotny and Olem 1992, 171). Hunter *et al* found that the soil matrix appeared to filter out most bacteria before they reached the stream (1992, 1872).

Groundwater runoff is the part of the runoff whose source is from springs and wells

(Novotny and Olem 1992, 103). The infiltration of sewers in urban areas into streams is also considered groundwater runoff (Novotny and Olem 1992, 103), though this possible source of pollution was not investigated in this study. Since Waimanalo Stream is a perennial stream, its sources at the base of the Ko'olau's are ultimately derived from groundwater (Hawaii, DLNR 1990, 5-6).

Among other sources of water into Waimanalo stream is the Waimanalo Irrigation System. Kahawai stream also receives inputs from the new reservoir located above Mahailua Street (Respicio 1993). These inputs from the Waimanalo Irrigation System may increase the fecal bacterial concentrations in Waimanalo and Kahawai Streams. A study has shown that the release of reservoir water during rain free periods created peaks in fecal indicator bacteria by stirring up the stored stream bottom sediments (Kay and McDonald 1983).

C. LAND USE AND INDICATOR BACTERIA DENSITIES IN THE WAIMANALO WATERSHED

1. The Upper Watershed.

The upper watershed appears quite pristine. Human influences are limited to horseback riders, the occasional hiker, and overflow from the Waimanalo irrigation system. Water is transferred from Maunawili Valley to Waimanalo through the Anianinui tunnel for the Waimanalo Irrigation system. The water is transported to Anianinui Tunnel over several miles of open ditches in Maunawili Valley. Most of the water from the tunnel is screened into a 16-inch pipe that leads to the reservoir at the end of Mahailua Street (USDA-SCS 1981, 47). The overflow from the screening is channeled down to Waimanalo Stream, just downstream of Site W1.

Because of the very limited impact of human activity, the indicator bacteria levels at this reach of Waimanalo Stream were the lowest of all fresh water sampling sites (Figures 2 through 9). The indicator bacteria measured at Sites W1 and W2 probably occur naturally in the environment *C. perfringens* densities were very low at these sites, particularly at Site W1, the most pristine sampling location. The *C. perfringens* densities at T1 occasionally exceeded the proposed standard of 50 CFU *C. perfringens* per 100 ml (Fujioka 1983), possibly because the waters at T1, at the end of Anianinui tunnel, have traveled through several miles of open ditches in Maunawili Valley before reaching Anianinui tunnel. This confirms Fujioka and Shizumura's data on other O'ahu streams that pristine streams are expected to have less than 10 CFU *C. perfringens* per 100ml (1985).

2. Middle Watershed.

The middle watershed is influenced by both urban and agricultural activities. Sites W3 and W4 are located along Waimanalo Stream. The middle reaches of Waimanalo stream passes through an agricultural area, mainly truck crops and nurseries. Site K2, located on a tributary of Waimanalo Stream called Kahawai Stream, is in the center of residential Waimanalo. Figures 6 through 9 show that while indicator bacteria concentrations at Sites W3 and W4 rose slightly from Sites T1 and W2 (a two to three fold increase), Site K2, with geometric means of fecal coliforms, *E. coli*, and enterococci concentrations well over 10,000 CFU per 100 ml, and C. perfringens over 500 CFU per 100 ml, is much higher (a ten fold increase) than all other sampling sites.

Although these fecal indicator bacteria concentrations in Waimanalo Stream appear to be very high, the levels measured along sampling stations W1 through W6 appears comparable to

densities measured on other streams on O'ahu (Table 5.) Indicator bacteria densities in Kahawai stream are much higher than in other streams on O'ahu.

Table 5. *E. coli* densities in various streams on O'ahu.

Stream	CFU per 100ml
Ahuimanu	1380
Kahana	1087
Kalihi	4502
Manoa	4320
Nuuanu	995
Palolo	3006
Waikele	3055

Source: (Oshiro 1989, 89)

Possible sources of indicator bacteria at Sites W3 and W4 on Waimanalo Stream are runoff of soil and animal wastes from agricultural activities; for Site K2, on Kahawai Stream, it may be urban runoff. Kahawai Stream passes through much more agricultural and urban development than Waimanalo Stream; the fecal indicator bacteria densities seem to reflect that trend. Generally, grazing animals such as cattle and horses have low concentrations of *C. perfringens* (Sorenson *et al* 1989). Since K2 also has high concentrations of *C. perfringens*, animals other than grazing animals may be the source of indicator bacteria at Site K2.

These results compare with studies conducted elsewhere. Niemi and Niemi (1991) found in Finland that diffuse bacterial loading from agricultural areas is a significant source of fecal pollution in stream waters. They found concentrations of fecal coliforms and fecal streptococci in

agricultural areas generally exceeding 100 CFU per 100 ml, and occasionally exceeding 1000 CFU per 100 ml, significantly higher than levels found in pristine areas.

3. Lower Watershed

The lower watershed is located in Bellows AFS and is closed to the public. The human impact at this reach of Waimanalo Stream is limited to occasional military exercises. Site W5 is located a few hundred yards downstream of the confluence of Kahawai Stream and Waimanalo Stream, and next to the confluence of a stream flowing from Olomana Golf Course. Site W5 is at the beginning of the Bellows AFS Secondary Wetlands Site and is under tidal influence, with the salinity ranging from 0 to 6 parts per thousands (ppt).

The decrease in indicator bacteria densities from Site K2 to Site W5 may be attributed to dilution, salinity, and sunlight. The high concentrations of bacterial indicators associated with the water of Kahawai Stream at Site K2 are first diluted by Waimanalo Stream, then by a tributary flowing from Olomana Golf course, and finally by water coming up from the ocean.

Bacteria are sensitive to changes in the osmotic pressure of the surrounding water. High osmotic pressure from the addition of salts may draw water outside the cell. Conversely, unusually low osmotic pressure, such as in distilled water, may cause water to enter the cell (Tortora 1992, 144-5). The survival of fecal indicator bacteria in brackish water and seawater may be a factor of the salinity. Hanes and Fragala (1967) observed an increase in the death rates of *E. coli* and enterococci corresponding with an increase in the percentage of seawater.

Radiation is another key factor in the survival of fecal indicator bacteria in the environment. In particular, ultraviolet (UV) radiation damages the DNA of the cell (Tortora 1992, 175-6). Exposure to UV radiation has been shown to decrease the concentrations of

various indicator organisms (Fujioka *et al* 1981, Barcina *et al* 1990, Davies-Colley *et al* 1994). The presence of UV radiation also appears to increase the decay rates of bacteria in seawater as compared to freshwater (Davies and Evison 1991). Waimanalo Stream at Bellows AFS is channelized, wide and flowing slowly, and fully exposed to sunshine.

Table 6. Enterococci densities at various beaches on O'ahu.

Beach	CFU per 100ml
Ala Moana	2.8
Barber's Point	0
Hauula	0.8
Kahana Bay	35.4
Kailua	11
Kalama	1
Lanikai	0
Magic Island	2.2
Waikiki	10.5

Source: (Oshiro 1989, 84)

It is possibly this combination of dilution, salinity, and UV radiation that reduced the fecal indicator concentrations from over 1000 CFU per 100ml at Sites K2 and W4, to a level below State and Federal water quality standards at site B1 on Waimanalo Bay. The indicator bacteria densities at Site B1 are comparable to those measured at other beaches on O'ahu as shown in Table 6. There are no obvious sources of fecal indicator bacteria in Waimanalo Bay other than Waimanalo Stream. Data collected during regular monitoring by the Air Force at Bellows AFS, shown in Figure 21, appear to point to Waimanalo Stream as the source of bacteria. The enterococci concentrations decreased as they sampled further from the stream mouth.

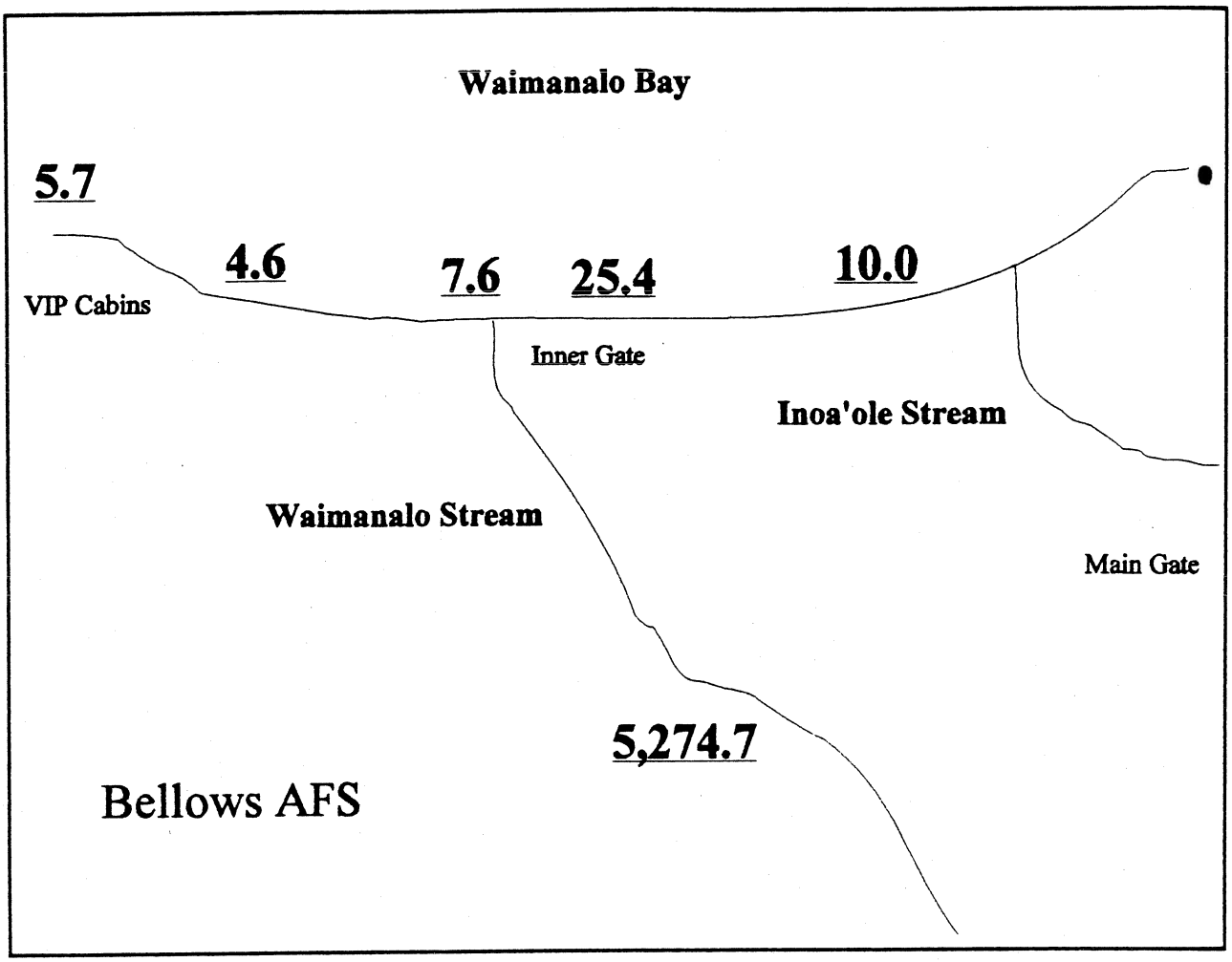

Figure 21. Enterococci densities at Bellows AFS. 5-day geometric mean enterococci concentrations (underlined numbers) as CFU per 100ml taken over a 30-day time period (28 October 1992 to 22 November 1992). (Source: Whitehouse, 15 MG/SGPB, 1993)

D. STATISTICS

The distribution of microorganisms from a single sampling point varies log-normally. Thus, arithmetic averages of bacterial counts would skew the description of central tendency. The accepted method of describing the distribution of microorganisms is the geometric mean. (Pike 1993, 106)

Table 7 shows the $\log_{10}$ standard deviation of fecal indicator bacteria concentrations measured during this study. Typical values for $\log_{10}$ standard deviations of fecal indicator bacteria concentrations range between 0.4 and 0.7; these values, however, vary from site to site (Pike 1993, 106-7). The $\log_{10}$ standard deviations appear quite consistent for the stream water samples, but varied for the beach station, Site B1. This may be because B1 is located near a stream mouth and thus subject to greater variances such as ocean currents, stream flows, and tides.

Table 7. Log_{10} standard deviations of fecal indicator bacteria concentrations.

Site	Number of Samples	Fecal Coliforms	*Escherichia coli*	Enterococci	*Clostridium perfringens*
T1	11	0.54	0.50	0.34	0.44
W2	11	0.28	0.28	0.22	0.39
W3	11	0.40	0.34	0.26	0.23
W4	11	0.16	0.23	0.14	0.57
K2	11	0.47	0.51	0.40	0.34
W6	6	0.41	0.35	0.32	0.37
B1	7	0.88	0.89	0.82	0.00

The potential variability in microbiological samples is very large. Tillet (1991) found a 400-fold variation in range in the 95% confidence interval in bacteria counts in river water due to

natural variation, and a 4-fold variation due to laboratory methods. In this study, replicate water samples were occasionally to reduce the uncertainty of laboratory errors masked by the natural variation in microbial counts. The variance of replicate analysis was tested using the Cochran's dispersion test as described by Havelaar et al (1993, 6-7), as follows:

$$T_i = \sum_{i=1}^{n} \sum_{j=1}^{m} [(y_{ij} - \bar{y}_i)^2 / \bar{y}_i]$$

Where:

T_i	=	test statistic
y_{ij}	=	single count from one plate
y_i	=	mean of replicate counts
m	=	number of replicates per tube
j	=	rank number of replicate count (j=1,2,...m)
n	=	number of sets of replicate counts (i=1,2,...n)

Table 8. Results of the Cochran's dispersion test for replicate variation

Media	N	T_i	χ^2	Comment
mFC	20	20.90	60-70%	Not Significant
mTEC	21	17.10	20-30%	Not Significant
mE	21	14.40	10-20%	Not Significant
mCP	21	35.00	95-97.5%	Overdispersion

N=number of replicate samples
T_i=test statistic
χ^2=chi-square distribution

The results of the Cochran's dispersion test for replicate variation are shown in Table 8. If the value of the T-statistic, T_i, is significantly greater than the upper 5% of the χ^2 distribution, there is overdispersion in the replicate variation. This means that there is a significant difference

between the two replicate sets. If the value of the T statistic, T_i, is significantly smaller than the lower 5% of the χ^2 distribution, there is under dispersion in the replicate variation. This means that the replicate variation is unnaturally small, which may be due to biased plate counts, overcrowding of plates, and other counting errors. Table 8 indicates that there was overdispersion in the mCP replicates. This is probably due to the low plate counts inherent in the enumeration of *C. perfringens*. This problem may be corrected by filtering a greater volume of water to obtain higher plate counts.

PART V. CONCLUSIONS

1. Waimanalo Stream exceeds both the USEPA water quality standard of 33 CFUs enterococci per 100ml or 126 CFUs *E. coli* per 100ml and the State of Hawai'i stream water quality standards of 200 CFUs fecal coliform per 100ml at all sampling sites.

2. Waimanalo Bay at the sampling site near the mouth of Waimanalo Stream met both the USEPA standard for marine waters at 35 CFUs enterococci per 100 ml, and the State of Hawai'i standard of 7 CFUs enterococci per 100ml.

3. The bacterial densities along Waimanalo increased from the upper watershed to the lower watershed. The indicator densities ranged from a 200 to 8000 CFUs per 100ml for fecal coliforms, *E. coli*, and enterococci, and from 1 to 120 CFUs per 100 ml *C. perfringens* in the upper reaches; to levels exceeding 30,000 CFUs per 100 ml for fecal coliforms, *E. coli*, and enterococci, and 1000 CFUs per 100 ml *C. perfringens* in the lower reaches.

4. A storm event raised levels of indicator bacteria over two orders of magnitude.

5. Possible sources for the indicator bacteria were not determined. Past research suggests both point sources like agricultural animal wastes; and from nonpoint sources like storm drains, street runoff, and agricultural wastes, as possible contributors of indicator bacteria in Waimanalo Stream.

PART VI. APPENDIX

Bacteriological, pH, Turbidity, and Salinity Results

Table 9. Site T1. Anianinui Tunnel, Waimanalo side of Anianinui Ridge.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/19/93	6,520	5,200	2,200	11	7.78	3.6	0
07/28/93	488	440	680	36	7.88	13	0
08/04/93	504	544	640	8	7.81	5.5	0
08/11/93	7,120	5,720	2,600	23	7.59	16	0
08/18/93	444	328	680	11	7.83	5	0
08/25/93	1,080	704	1,520	22	7.29	22	0
09/01/93	6,380	6,240	2,380	36	7.44	33	0
09/08/93	500	480	212	26	7.64	16	0
09/22/93	360	380	800	10	7.43	7.2	0
10/06/93	540	880	1,000	230	7.47	7.25	0
10/20/93	372	516	400	6	7.37	4.9	0

Table 10. Site W1. Waimanalo Stream 0.25 miles upstream of Olomana Ranch

Date	FC	EC	ENT	CP	pH	Turb	Salinity
06/09/94	920	1,040	60	4	ND	ND	ND
06/15/94	2,160	2,240	1,440	<1	ND	ND	ND
06/21/94	320	680	208	<1	ND	ND	ND
06/27/94	256	344	80	<1	ND	ND	ND

FC	Fecal Coliforms (CFU/100ml)	EC	*E. coli* (CFU/100ml)
ENT	Enterococci (CFU/100ml)	CP	*C. perfringens* (CFU/100ml)
Turb	Turbidity (NTU)		
Salinity	parts per 1000 (ppt)		
ND	Not done		

Table 11. Site W2. Waimanalo Stream at Waikupanaha St, near Olomana Ranch.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/19/93	7,200	6,800	3,880	9	7.71	3.9	0
07/28/93	2,680	2,680	1,960	11	7.78	7.7	0
08/04/93	656	5,240	720	1	7.72	4	0
08/11/93	2,200	2,440	2,000	27	7.6	7.6	0
08/18/93	920	880	1,040	4	7.66	1.6	0
08/25/93	1,680	1,400	1,240	8	7.64	3.7	0
09/01/93	2,160	1,980	1,900	18	7.72	11	0
09/08/93	900	1,040	780	11	7.7	5.4	0
09/22/93	1,440	1,800	960	6	7.57	4.4	0
09/26/93	69,600	64,400	104,000	4,000	7.37	320	0
10/20/93	1,420	1,240	1,580	3	7.72	2.4	0
06/09/94	1,600	1,280	280	1	ND	ND	ND
06/15/94	2,360	2,200	1,200	5	ND	ND	ND
06/21/94	680	680	252	4	ND	ND	ND
06/27/94	840	1,440	1,000	14	ND	ND	ND

Table 12. Site W3. Waimanalo Stream at Kumuhao St, 1 mile from Kalanianaole Hwy.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/19/93	19,200	12,000	4,000	31	7.46	1.7	0
07/28/93	2,680	2,720	2,000	23	7.32	2.2	0
08/04/93	880	1,680	1,240	20	7.46	2	0
08/11/93	1,640	1,680	1,640	28	7.32	2.7	0
08/18/93	1,320	1,200	1,200	20	7.35	3.4	0
08/25/93	6,040	6,080	4,140	94	7.54	5.6	0
09/01/93	3,693	3,280	3,560	33	7.47	4.8	0
09/08/93	1,093	1,133	1,120	55	7.48	3.4	0
09/22/93	1,000	987	1,547	57	7.39	3.25	0
09/26/93	136,000	108,000	288,000	2,800	7.65	120	0
10/06/93	1,853	2,227	2,253	73	7.49	4.75	0
10/20/93	4,200	4,440	6,800	42	7.46	4	0

FC	Fecal Coliforms (CFU/100ml)	EC	*E. coli* (CFU/100ml)
ENT	Enterococci (CFU/100ml)	CP	*C. perfringens* (CFU/100ml)
Turb	Turbidity (NTU)	Salinity	parts per 1000 (ppt)
ND	Not done		

Table 13. Site W4. Waimanalo Stream at Kalanianaole Hwy near Flamingo St.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/19/93	5,880	7,200	2,640	200	9.00	4.3	0
07/28/93	2,800	2,920	1,760	2	9.35	2.9	0
08/04/93	2,000	1,160	1,160	6	8.39	0.56	0
08/11/93	2,080	1,800	1,160	12	8.98	2.3	0
08/18/93	2,040	1,440	2,360	34	9.23	1.5	0
08/25/93	2,320	2,120	1,390	19	9.33	3	0
09/01/93	4,580	4,100	2,860	46	9.35	3.9	0
09/08/93	1,760	1,520	1,500	47	9.09	12	0
09/22/93	2,080	1,820	2,020	124	8.77	2.8	0
09/26/93	136,000	140,000	280,000	2,000	8.07	270	0
10/06/93	3,680	2,860	1,960	50	8.89	3	0
10/20/93	2,760	3,040	2,253	46	9.05	6	0

Table 14. Site W5. Waimanalo Stream at Tinker Road, Bellows AFS

Date	FC	EC	ENT	CP	pH	Turb	Salinity
08/18/93	1,840	1,280	2,480	52	7.5	13	4
09/01/93	3,400	8,000	6,400	160	7.7	9.7	0
09/08/93	2,680	3,600	1,040	68	7.82	13	0
09/22/93	20,000	9,200	2,400	44	7.89	8.9	4
09/26/93	7,200	6,600	3,000	136	8	18	2
10/20/93	13,600	10,800	7,600	15	7.75	5.2	6

Table 15. Site W6. Waimanalo Stream about 100 yards from Waimanalo Stream mouth

Date	FC	EC	ENT	CP	pH	Turb	Salinity
08/18/93	920	1,080	440	7	7.81	4.8	15
08/25/93	456	800	248	9	8.01	4.6	26

FC	Fecal Coliforms (CFU/100ml)	EC	*E. coli* (CFU/100ml)
ENT	Enterococci (CFU/100ml)	CP	*C. perfringens* (CFU/100ml)
Turb	Turbidity (NTU)	Salinity	parts per 1000 (ppt)
ND	Not done		

Table 16. Site K1. Waimanalo Stream at Mahailua St near Kakaina St.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
10/20/93	40	80	480	<1	7.58	6.1	0

Table 17. Site K2. Kahawai Stream at Kalanianaole Hwy near Frankie's Drive In.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/19/93	38,800	46,000	26,400	1,440	7.27	6.2	0
07/28/93	16,400	12,000	3,960	170	7.41	4.8	0
08/04/93	14,800	13,200	14,800	250	7.29	3.5	0
08/11/93	3,080	4,280	8,000	720	6.55	1.5	0
08/18/93	33,200	28,400	30,800	1,600	7.37	7.2	0
08/25/93	22,000	13,200	18,000	640	8.06	7.1	0
09/01/93	11,600	20,000	22,000	520	7.6	16	0
09/08/93	5,040	2,800	5,200	162	7.19	2.8	0
09/22/93	6,000	6,000	2,280	920	7.23	3.5	0
09/26/93	300,000	272,000	920,000	6,000	7.92	9.8	0
10/06/93	164,000	196,000	39,200	400	8.02	4.8	0
10/20/93	15,200	15,200	22,000	860	7.66	19	0

Table 18. Site B1. Waimanalo Bay about 50 yards south of Waimanalo Stream mouth.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
08/18/93	10	4	10	2	8.1	15	34
08/25/93	3	3	1	<1	8.14	6.4	34
09/01/93	44	44	33	<1	8.25	4.6	34
09/08/93	<1	<1	1	<1	8.15	4.4	34
09/22/93	<1	<1	18	<1	8.12	3.25	34
10/06/93	<1	<1	<1	<1	8	3	34
10/20/93	84	92	44	1	8.19	3.4	33

FC	Fecal Coliforms (CFU/100ml)	EC	*E. coli* (CFU/100ml)
ENT	Enterococci (CFU/100ml)	CP	*C. perfringens* (CFU/100ml)
Turb	Turbidity (NTU)	Salinity	parts per 1000 (ppt)
ND	Not done		

Table 19. Site I1. Inoa'ole Stream at Hihimanu St.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
07/28/93	144	108	32	8	7.91	6.9	0

Table 20. Site I2. Inoa'ole Stream at Kalanianaole Hwy.

Date	FC	EC	ENT	CP	pH	Turb	Salinity
08/18/93	23,200	14,000	27,200	56	7.64	14	0
10/20/93	1040	560	4400	3	7.77	1.8	0

FC	Fecal Coliforms (CFU/100ml)	EC	*E. coli* (CFU/100ml)
ENT	Enterococci (CFU/100ml)	CP	*C. perfringens* (CFU/100ml)
Turb	Turbidity (NTU)	Salinity	parts per 1000 (ppt)
ND	Not done		

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