APPENDIX C

MAMALA BAY STUDY SUMMARY

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The Sierra Club and Hawaii's Thousand Friends filed suit against the City and County of Honolulu (CITY) in 1990, alleging violations of the Clean Water Act (CWA). The suit asserted that the City had not met secondary treatment discharge limits on or before July 1, 1998, despite submitting an application for a waiver permit and obtaining preliminary approval of a waiver permit. At issue were the water quality of Mamala Bay, and the lack of a factual perspective to make a determination. Given this, parties arrived at an agreement to settle on four concepts: (1) the City agrees to install effluent screens, (2) re-install dissolved air floatation (DAF), (3) conduct a pretreatment study before the 301(h) permit becomes effective; and (4) to appoint a Mamala Bay Commission and conduct the the Mamala Bay Study (STUDY). On November 19, 1993, the court approved the consent decree. The consent decree directed the Mamala Bay Commission:

"That the parties shall establish and the City shall fund a Mamala Bay Study Commission ("the Commission") whose purpose shall be:

a) to study the point and non-point sources of pollution discharges into Mamala Bay;
b) to analyze the effects of these sources on the environment and public health (including recreation); and
c) to make any appropriate recommendations on how to reduce the pollution levels and improve the water quality of Mamala Bay."

The court further stated that the study shall address:

a) the environmental effects of the discharges from the City's sewage treatment plants into Mamala Bay;
b) the surfacing of the plants' sewage plumes, the transport regime in the waters located near the plants' outfall sites, and any consequent effects on public health; and
c) the potential public health impacts from the viable but non-culturable pathogen phenomenon."

The court ordered the City to fund the study to the amount of $8,000,000. Later, as part of a separate legal issue regarding the City's Honouliuli Wastewater Treatment Plant (38 mgd), which also discharges primary treated effluent into Mamala Bay via the Barbers Point Deep Ocean Outfall, the court included an additional $1,000,000 to include a study of the impacts from the discharges from the Honouliuli Wastewater Treatment Plant in the Mamala Bay Study.

The court ordered that the Mamala Bay Study Commission shall consist of three individuals, having scientific and technical backgrounds. The task of the

Commissioners was to design and direct the Mamala Bay Study, and report, to explore the issues cited above. The commission consisted of: Dr. Rita R. Colwell; Dr. Gerald T. Orlob; and Dr. Jerry R. Schubel.

The Mamala Bay Commission, in addition to the court prescribed issues, believing other issues would need to be studied, defined supplementary issues:

(a) Define the ocean circulation patterns within Mamala Bay, including the effects of the Trade and Kona winds and other factors impacting the fate of pollutant transport, and characterize the sewage plumes from the outfalls,

(b) Quantify point and non-point sources of pollution and their relative impacts in terms of loading, frequency in extreme events and proximity to sensitive areas of exposure to humans and aquatic ecosystems,

(c) Characterize the fate of indicator organisms and pathogens originating from point and non-point sources and to determine the detectability and survivability of these organisms in the marine environment,

(d) Assess the risks to public health from exposure to waters contaminated by point and non-point sources of pollution to Mamala Bay,

(f) Identify and quantify the effects on ecosystems of point and non-point sources of pollution of Mamala Bay, and

(g) Identify and evaluate practical and implementable alternatives for the control of pollution of Mamala Bay.

Mamala Bay was defined as ocean areas from Diamond Head to Barbers Point, Oahu, extending offshore to a distance that could be directly impacted by point and nonpoint discharges and extending sufficiently inshore to include significant non-point sources that could affect the quality of near-shore waters. These included areas such as Ala Wai Canal and Pearl Harbor.

The Mamala Bay Study consisted of 27 projects and special investigations, all of which support the goals of the project, culminating in a final report, with recommendations. The projects and project titles are:

1. MB-2: Mamala Database
2. MB-3: Pollutant Source Identification
3. MB-4: Plume Modeling
4. MB-5: Modeling Transport and Fate of Pathogenic Organism in Mamala Bay
5. MB-6: Ocean Current Measurements
6. MB-7: Characterization of the Microbiological Quality of Water in Mamala Bay
7. MB-7: Overall Impact of Sand Island Outfall on the Incidence of Pathogens in Mamala Bay
8. MB-7: Molecular Investigation of the Effect of Pollution on Pathogenic and Indigenous Bacteria in Mamala Bay

9. MB-7: Microbial Aspects of Point and Non-point Sources
10. MB-7: Coliphage and Indigenous Phage in Mamala Bay
11. MB-7: Viability of Cryptosporidium parvum Oocysts in Marine Waters
12. MB-9: Definition of Indicator Species for Pollution Monitoring in Mamala Bay, Oahu, Hawaii
13. MB-9: Impact of Point and Non-Point Source Pollution on Coral Reef Ecosystems in Mamala Bay
14. MB-9: Shallow Marine Community Response to Point and Non-Point Sources of Pollution in Mamala Bay, Oahu. Part A: Fish and Coral Communities
15. MB-9: Shallow Marine Community Response to Point and Non-Point Sources of Pollution in Mamala Bay, Oahu. Part B: Micromolluscan Assemblages and Algal Biomas
16. MB-9: Effects of Sewage Discharges and Stream Runoff on Phytoplankton Communities and Water Quality in Mamala Bay
17. MB-9: Temporal Variability in Macrobenthic Community Structure and the Effect of Freshwater Runoff
18. MB-9: Recruitment Patterns of Marine Benthic Invertebrates in Mamala Bay; A Process-Oriented Measure of Ecosystem Response to Pollution
19. MB-10: Management Alternatives and Management Measures for Waste Discharges to the Mamala Bay Ecosystem
20. MB-10: Identification of Stressors of Concern in the Mamala Bay Ecosystem
21. MB-10: Effects of Effluent from the Barbers Point and Sand Island Outfalls on the Mamala Bay Ecosystem
22. MB-10: Proposed Monitoring Plan to Assess the Efficacy of Waste Treatment Alternatives Applied in the Mamala Bay Watershed
23. MB-10: Infectious Disease Public Health Risk Assessment for Mamala Bay
24. MB-11: Water Quality Management in Mamala Bay
25. MB-11A: Wastewater Management Strategies in an Integrated Coastal Management Plan for Mamala Bay
26. MB-12: Mamala Bay Study Report
27. MB-SP1: Point Source Characterization and Control Options for Mamala Bay (Reported in MB-11A, Appendix 8.2)
28. MB-SP2: Plume Dynamics and Dispersion in Mamala Bay, Hawaii
29. MB-SP3: Ala Wai Canal Dye Study (reported in MB-5)
30. MB-SP4: Molecular Detection of Staphylococcus aureus in waters of Mamala Bay, Hawaii

The Commission's findings are as follows (sometimes taken verbatim from the study, City comments or responses will be in italics):

A good starting point is to describe the major pollutant sources. One of the first objectives was to characterize wastewater plumes from the City's outfalls, including the extent of rise due to buoyancy, degree of dilution achieved and frequency of plume surfacing. Unfortunately, however, sufficient rigor was not focused on the third, albeit not as significant a source as the City's outfalls, marine discharge from the Fort Kamehameha Wastewater Treatment Plant, discharging at the mouth of Pearl Harbor.

MODELING THE FATE OF WASTEWATER

Project MB-4, Near Field Modeling, applied the EPA approved model RSB (Roberts-Snyder-Baumgartner) to simulate the transport, dispersion and dilution behavior of the plumes discharged from the Sand Island and Barbers Point marine outfalls in the vicinity of the diffusers, i.e., "initial mixing region." Using effluent data and oceanographic measurements, to simulate waste field characteristics in the "near field," including the rise height, degree of dilution and frequency of plume surfacing. Twenty thousand simulations were analyzed statistically to determine the surfacing frequencies and the degrees of dilution of the wastewater discharge under varying oceanographic conditions. The results from this effort were used for modeling of the "far field" fate and transport models in Project MB-5.

Comparison between the near field model results and field observations from of natural tracer study (Project MB-SP2) were done. Although there were general agreement between field observations and model results, it was concluded that better correlation was not achieved due to the unique oceanographic and meteorological conditions at the time of the field observations.

Complex oceanographic conditions impacted the plume trapping depth and dilution. Strong semi-diurnal tidal currents and low frequency drift combined to produce peak currents of about 50 centimeters per second at the Sand Island outfall and 30 centimeters per second at the Barbers Point outfall. Principal current components were oriented approximately parallel to the local bathymetry and to the diffusers. Model simulations used oceanographic and outfall discharge data for June 5, 1994 to April 18, 1995. Results of some 20,000 simulations, analyzed statistically, showed a high degree of seasonal variation in plume surfacing and dilution. The simulations, i.e., currents along local isobaths paralleling the shoreline, confirmed the general orientation of the mean circulation.

Based on near-field model results, the annual average dilutions were predicted to be very high within the initial mixing regions for both outfalls, but showed significant variations (and thus wide variation in dilutions) with the seasons, depending on the magnitude of water column stratification. For a submerged plume at Sand Island outfall dilutions varied from 87 to more than 3700 with a mean of 627. For a surfacing plume, dilutions ranged from 600 to 5400, with a mean of 1353.

During winter months temperature variations (and thus a weaker water column stratification) resulted in higher frequencies of surfacing, subsequently higher initial dilutions than in summer months. Over the 10.5 month simulation period, the Sand Island outfall plume surfaced an average of about 22 percent of the time, with a large month-to-month variation. Monthly plume surfacing averages ranged from a low of 5 percent in September, with an average rise height of about 23 meters, to a surfacing frequency of 62 percent in December, and with an average rise height of 46 meters. The outfall diffuser at Sand Island has an average depth of about 70 meters.

Several fundamental conclusions concerning the performance of the Sand Island and Honouliuli outfalls were derived from the results of the near field modeling effort. First, it is apparent that the outfalls and their diffuser systems are well designed, achieving high dilutions within the initial mixing regions and trapping the plumes below the surface for a high proportion of the time. Even when the plumes are observed and predicted to surface, both the Sand Island and Honouliuli plumes are highly dilute, with average dilution factors of 600 to 1000, or more. Associated risks to public health, although present, are accordingly reduced because of the dilution. On the other hand, the high degree of seasonal variation in plume submergence and rise height, coupled with the large variability in current and stratification regimes, can convey contaminants beyond the immediate vicinity of the outfalls, particularly into offshore waters. The potential for contamination of offshore waters is greatest under unstratified conditions when the plumes surface. Again, however, these episodes are accompanied by the largest dilutions.

Because currents transport pollutants that could affect public health, a portion of the effort was to study the oceanic circulation around the outfalls and in the near-shore regions. To adequately define properties of the Mamala Bay circulation, the effects of Trade and Kona winds must be considered.

OCEANOGRAPHIC STUDIES

Direct field observations of oceanographic and meteorological variables were made in Project MB-6 to describe the three-dimensional current structure in Mamala Bay over a 1.5-year duration to include Kona and Trade wind conditions. These observations included measurements of temperature, density profiles, tides, water levels and surface winds. State-of-the-art oceanographic instrumentation, including bottom anchored Acoustic Doppler Current Profilers (ADCPs), taught wire vector current meters, thermistor strings, and pressure sensors were deployed at various depths and locations throughout Mamala Bay to obtain spatial and temporal descriptions of current structure during the study period. These instruments were principally located along four transects perpendicular to the shoreline. Data gathered were used in other projects to analyze the transport and fate of contaminants discharged to Mamala Bay from point and non-point sources to determine appropriate microbiological sampling sites and to support special field studies, including tracking of the discharge plume from the Sand Island outfall.

Monitoring transects at Barbers Point and Diamond Head extended to depths of 500 meters and those in the interior portion of the bay extended to 250 meters depth close to the alignment of the outfalls. The diffusers are located at depths ranging from 67 to 72 meters at Sand Island and 61 to 63 meters at Honouliuli. Oceanographic parameters were also measured in relatively shallow depths near the mouth of the Ala Wai Canal, considered to be a principal source of shore-based contaminant discharge to the bay. Field observations made by Federal agencies were used to augment meteorological and oceanographic records at other on-shore or near-shore stations around Oahu.

Oceanographic records consisted primarily of time series of current velocities and directions, tidal oscillations, salinity and thermal structure at monitoring sites.

These were reduced to form the data files necessary to drive the near-field and far-field hydrodynamic and water quality models.

Physically-based oceanographic processes that influence the circulation in Mamala Bay can be divided into the following categories: those caused by surface tides (semi-diurnal, with a period of 12.4 hours, and diurnal, with a period of 24.8 hours) and those that resulted from other factors including wind forcing, propagation of long period waves and circulation in deep offshore coastal waters.

The semi-diurnal tide, moving in a southwesterly direction in the Pacific Ocean appears to split near the North Shore of Oahu, creating two progressive tide waves, one propagating along the east side of the island and the other along the west side. Coastal trapping causes these two waves to curve around the headlands at Barbers Point and Diamond Head and to merge within Mamala Bay before continuing toward the southwest. As a result, strong tidal velocities measured at Barbers Point and Diamond Head were then oriented parallel to the depth contours and directed towards the middle of the bay. Weak currents resulted where the flows merged from opposite directions. Converging flows at flood tide caused a downwelling (downward flow) at the center of the bay, which reversed with the tidal cycle at ebb tide. Consequently, large changes in stratification occurred over the tidal cycles with the water column often becoming homogeneous at different sites, a critical factor in predicting the transport and fate behavior of the discharged effluent plume.

Diurnal tides were observed to be relatively uniform in amplitude throughout the bay and propagated principally from west to east. Consequently, the combination of semi-diurnal and diurnal tides varied significantly at different sites in the bay, with semidiurnal tides dominating at Barbers Point and Diamond Head, and diurnal tides dominating in the center of the bay. Both tidal components were generally directed parallel to the depth contours.

Analyses of sea level and currents revealed relatively weak local correlation with wind at sampling sites in the center of the bay. A general weakening of the westward flows was observed with weakening of the Trade Winds from the northwest. There was little or no evidence of direct wind forcing effects in shallow near-shore areas. Instead, analysis of temperature fluctuations revealed a strong dependence of circulation within the bay on large-scale oceanographic processes in the ocean surrounding the island. During the first year of the monitoring, a branching of onshore flow can be seen just east of Sand Island, resulting in eastward mean flow along the shore towards Diamond Head. It should be understood that these patterns were derived from a 1-year record of investigation that, although representative of the general conditions during the Mamala Bay Study, may not include all phenomena that can affect circulation in the bay over a longer period.

In a study off the mouth of the Ala Wai Canal current measurements showed a mean eastward flow along Waikiki Beach towards Diamond Head. Several outflow events of one to two days duration that had been preceded by periods of heavy precipitation, sometimes coincident with a Kona wind event, were monitored between October 1994 and January 1995. These intermittent events provided significant discharges from the Ala Wai Canal into Mamala Bay, that due to the general eastward flowing currents transported contamination from the canal along the eastern beaches; e.g., Waikiki.

POINT AND NON-POINT SOURCE LOADINGS

The next object was to quantify the primary point and non-point sources of pollution and to assess the relative impacts of various treatment options on risks to public health and sensitive aquatic ecosystems.

Pollutant loadings to Mamala Bay were classified into two principal categories: "point sources," or those sources that are discrete and identifiable (i.e., the three ocean outfalls that discharge directly to Mamala Bay), and "non-point sources," or those sources that represent aggregations of discharges from several, less readily identified, or unknown, sources (i.e., the outflow from the Ala Wai Canal). These two types of sources may differ greatly in the concentrations and types of pollutants discharged, in classification, reporting and availability of descriptive information, volume discharged, and in methods of analysis. Pollutant information was required for the purposes of modeling the transport and fate of contaminants throughout the bay, for estimating public health risk and ecosystem exposure, and for developing water quality control measures. All data sets developed in Project MB-3, "Pollution Source Identification," were entered into the Study's data base, Project MB-2, and made available to all project participants.

Major point source discharges to Mamala Bay are those from the Sand Island, Honouliuli, and Fort Kamehameha Wastewater Treatment Plants (WWTPs). Minor point source discharges are those from approximately thirty industrial and agricultural sources, whose discharges are self-monitored and reported under the National Pollutant Discharge Elimination System (NPDES) program administered by the State of Hawaii.

Point source loadings were determined from data on historic water quality and flows provided by the operators of the WWTPs discharging to Mamala Bay as required under the NPDES.

Non-point sources include uncontrolled dispersed surface flows, such as those tributary to the Ala Wai Canal, stormwater surface runoff, and ground water accretions which enter the bay from many different locations along the shoreline. In the Mamala Bay Study certain of these sources, not uniquely measurable, are assumed to be aggregated at discrete locations along the periphery of the bay, e.g., the mouth of the Ala Wai Canal, the entrance to Pearl Harbor, Keehi Lagoon, etc., where their loads may be imposed on the bay.

Non-point source loadings were estimated using a watershed model, WMM, to develop seasonal and annual loads together with the surface runoff model HEC-STORM to represent hourly event-based time series. Annual loadings were based on long-term average rainfall data for the Mamala Bay watershed.

A significant gap was identified in the information available on the quality of water discharged from the Ala Wai Canal. Field sampling was conducted to evaluate concentrations of pollutants discharged from the canal, particularly after storm events. A special dye tracer study (Project MB- SP3) was conducted on the canal to evaluate the effect of a storm event on the potential for non-point source contamination of adjacent water use areas.

Approximately one third of the annual volume flowing into Mamala Bay is attributed to point sources with the rest originating from non-point sources. Non-point source discharges, the chief sources of sediment, copper and zinc, may enter via the sub-embayments bordering Mamala Bay, namely, Pearl Harbor, Keehi Lagoon - Honolulu Harbor, Kewalo Basin and the Ala Wai Canal. Point source discharges are the primary sources of conventional pollutants, including biochemical oxygen demand (BOD), total suspended solids (TSS), together with nutrients, indicator bacteria, pathogenic microorganisms, and some metals, with the greatest contribution originating with the Sand Island and Honouliuli WWTPs.

On an annualized basis, non-point source discharges of indicator bacteria are a very small proportion, from 0.1 to 5 percent of the loading from point sources. However, during or following intense storm events, field observations indicated that non-point source bacterial loads could be a much higher proportion of the total. For example, enterococci loading rates under such conditions were found to be equivalent to the combined loading rate of all point sources during the same time period.

Because most of the non-point source discharges first pass through smaller sub-embayments before entering Mamala Bay, some of the suspended sediment load, bacteria, and other dissolved and suspended contaminants may bind to sediment, settle, or be transformed into other constituents. Flow, deposition and resuspension of contaminants within these water bodies depend on factors such as residence time, flowrates from non-point source discharges, volume of material carried and its form (i.e., bound to sediment, dissolved or particulate, particle size). Depending on the quality of non-point source contributions, water and sediment quality in the sub-embayments may at times be in violation of State water quality standards for different constituents.

Field sampling programs conducted at the Ala Wai Canal and at beaches along the eastern Mamala Bay shoreline during storm events showed that the canal contributed large concentrations of fecal coliforms to the bay, particularly at eastern beaches such as Waikiki, and were confirmed in simulations using the contaminant fate model in Project MB-5. Concentrations of *Salmonella* and *Cryptosporidium* at eastern beaches and in offshore waters can also be attributed in part to discharges from the Ala Wai Canal. Model simulations were performed to compare the effects of elimination of discharges from three shoreline non-point sources: Keehi Lagoon, Pearl Harbor and the Ala Wai Canal. Analyses of model results indicated that elimination of Keehi Lagoon and Pearl Harbor discharges would have little effect within the bay, but substantial improvements would result by elimination of the Ala Wai Canal as a source. Similarly, model simulations showed that bacterial concentrations at Ala Moana and Tavern beaches are likely to be more closely correlated with non-point sources than with point sources. Sampled concentrations and simulation estimates were found to be lower in the summer months at the beaches and at Ala Moana Bridge, when precipitation was lowest, but point source loads were highest suggesting that point source discharges were not impacting beaches during summers months having low precipitation. The general seasonal pattern for levels of indicator bacteria at the eastern beaches was consistent with findings at Ala Moana Bridge, i.e., that indicator bacterial levels were correlated with seasonal time-averaged precipitation patterns for high rainfall events and discharges from Ala Wai during the period studied.

MODELING THE TRANSPORT AND FATE OF POLLUTANTS

Modeling of the transport and fate of pollutants was used as a mechanism to compare the effects of loadings from selected point and non-point sources, and combinations of these on contamination of the bay. The three-dimensional hydrodynamic model developed in Project MB-5 was initially calibrated for the observed oceanographic conditions of the period April 15, 1994 through April 15, 1995. It was then used to drive the transport and fate model to simulate the effects of physical, chemical and biological processes on the distribution and incidence of indicator bacteria and pathogens for the same period under the estimated actual loadings from point and non-point sources, i.e., for "current conditions". Scenarios developed in Project MB-10 defining alternative measures for enhancing the quality of Mamala Bay were then simulated with the model to determine the changes in quality that might be anticipated. Options chosen for simulation included treatment upgrades and disinfection alternatives at both Sand Island and Honouliuli WWTPs, as well as elimination of contaminant contributions from non-point sources like the Ala Wai Canal, Pearl Harbor and Keehi Lagoon. Results obtained for the different scenarios were then compared to simulation results obtained under '"current conditions." Organisms modeled included fecal coliforms, enterococci, *Clostridium perfringens, Salmonella,* enterovirus, *Giardia* and *Cryptosporidium.*

Analysis of hydrodynamic model simulations showed that circulation patterns in the bay conformed to conditions actually observed during the oceanographic monitoring program. The time series of model results included periods typical of Trade and Kona wind conditions. It was determined that circulation conditions most likely to result in pathogen transport onto the beaches occurred during the winter months when weak water column stratification and Kona winds allowed the outfall plumes to surface. (Incidentally, this is also the period of greatest initial dilution within the initial mixing region around the outfall diffusers.) Under Trade wind conditions, results did indicate some occasions when an initially-trapped outfall plume could surface, depending on stratification of the water column and physical oceanographic processes.

Estimates of contaminant concentrations obtained from the near-field plume model in Project MB-4, together with the flow field simulated with the hydrodynamic model, were used in the contaminant fate model to estimate concentrations of pollutants throughout Mamala Bay over the simulation period. The incidence and frequencies of occurrence of indicators and pathogens were determined by statistical analysis of simulation time series for selected sampling locations. Based on the results of these simulations for "current conditions," it was determined that at all beaches, average fecal coliform levels were dominated by point source contributions. Average enterococci and ***Clostridium*** levels were mainly attributed to point sources at beaches along the western side of the bay and by non-point sources along the eastern side. Model results showed that contamination originating with the Sand Island plume could be transported throughout the bay, although at contaminant concentrations that varied widely, both spatially and temporally. It was found that fecal coliform bacteria counts could range from virtually non-detectable levels, i.e., from less than 1 colony forming unit (cfu) per 100 milliliters to more than 200 colony forming units per 100 milliliters. Exceedance of the marine standard for fecal coliform was found to occur on five days at six beaches and was attributed to point sources. Enterococci could vary from undetectable levels to over 7 colony forming units per 100 milliliters, exceeding marine standards more frequently than fecal coliform. Of the concentrations predicted in near-shore areas, 80 percent were attributed to non-point sources and 20 percent to point sources. Concentrations were highly variable depending on stratification conditions and variations in tidal and low frequency currents. Loadings of pathogenic microorganisms, while significant at point sources, were so reduced by dilution that concentrations were far below detectable levels except near the outfalls.

The Honouliuli wastewater treatment plant outfall was found to contribute measurable concentrations of indicator organisms only at Oneula Beach, with transport being predominantly westward from the outfall. The Honouliuli effluent plume was predicted to have no detectable impact along most of the Mamala Bay shoreline. Specific water quality impacts of point and non-point sources are discussed in greater detail in a later section, "Water Quality Management Alternatives".

At the beaches there was no conclusive evidence that swimmers contributed significantly to elevation of indicator organism concentrations, although one sampling series conducted during the study period suggested a possible correlation between fecal coliform counts and the number of swimmers. Shedding of bacteria by swimmers, although a potential source, remains uncertain for Mamala Bay.

MICROBIAL CONTAMINANTS

With the major sources of pollutants identified and the ocean current regime characterized, the fates of indicator organisms and viable pathogens originating from point or non-point sources of pollution and the detectability and survivability of these organisms in the marine environment need to be determined. Standard methods of analysis and state-of-the-art molecular biological techniques were successfully applied in identification of indicator organisms in Mamala Bay. Results of field sampling programs indicated that both point and non-point sources contributed measurable concentrations of standard fecal indicators (fecal coliforms, *E. coli*, enterococci) and alternative fecal indicators (C. *perfringens* and FRNA phage) to waters of the bay. On the other hand, non-point sources, notably the Ala Wai Canal and Keehi Lagoon, appeared to be major contributors to contamination of adjacent bathing beaches.

Contributions from these sources increased greatly during heavy rains.

Among indicator organisms C. *perfringens* and FRNA phage were determined to be more stable in marine waters than poliovirus and therefore better indicators of the possible presence of pathogens. *C. perfringens* may be preferred because it is not found in high concentrations in soil and survives longer in marine waters than do pathogens. Detection of this organism is simple and reliable. Another important finding of the Study was that *Shigella spp.* and enterotoxigenic *E. coli* (ETEC) are more valuable field indicators of contamination of human origin that the traditionally used *Escherichia coli.*

The relative contributions of the outfalls and shore-based sources to the incidence of the three common indicator organisms (i.e., fecal coliforms, enterococci, and *Clostridium)* on six different Mamala Bay beaches were identified. It is significant to note that fecal coliforms are most closely identified with the Sand Island WWTP, except at Oneula Beach which is very near the Barbers Point outfall; that enterococci are derived primarily from shore-based sources; and that *Clostridium* originates with both the Sand Island outfall and shore-based sources, the latter being of equal or greater significance at the eastern beaches.

Bacterial viruses (bacteriophages) tend most often to be identified with eutrophic environments, that is, they may flourish where there are sufficient nutrients, i.e., other bacteria. They tend to be prevalent in coastal areas following storm events that produce land runoff, i.e., contributions from non-point sources. In this sense they can be useful indicators of non-point source runoff. They were recovered in this study along the transect through the Sand Island outfall, in Pearl Harbor, the Ala Wai Canal, Keehi Lagoon, Manoa Stream, Hanauma Bay and at the control station off Diamond Head. In this study they were never found at Waikiki Beach or at offshore sites.

State-of-the-art methodologies, including cultural, molecular PCR-based (polymerase chain reaction) and immunofluorescent techniques, were used to isolate and identify specific pathogens from both point and non-point sources of contamination of Mamala Bay. Pathogens detected in point sources were enteroviruses, the bacterial species *Salmonella spp., Shigella spp.*, enterotoxigenic *E. coll, Campylobacter jejuni* and Cholera Toxin CT-positive vibrios, and the protozoans *Giardia* and *Cryptosporidium.* Bacterial, viral and protozoan pathogens were also isolated in marine waters offshore, in bathing waters, and in other sources like the Ala Wai Canal and Manoa Stream. Culturable *Shigella spp.* were detected by gene probe techniques in samples from Waikiki and Hanauma Bay, although the origins of these bacteria could not be determined in the Study.

The incidence of the pathogens *Giardia* and *Cryptosporidium* at beaches and close inshore areas was low, less than about 1 in 15,000 to 20,000 of these organisms found in the Sand Island discharges in most cases sampled during the study period. Pathogens detected on Sand Island Beach were several orders of magnitude less than in primary sewage, possibly a consequence of dilution of the discharge from the Sand Island outfall. There was no direct evidence from the study that the outfall contributed measurably to pathogen microbiological contamination of more remote bathing beaches. The Ala Wai Canal and Manoa Stream in close proximity to bathing areas were more contaminated with pathogens than offshore marine waters, a factor that could account for beach contamination, as suggested also by results of indicator organism samplings.

Survival experiments showed that *V. cholerae, Shigella spp.* and enterotoxigenic *E. coli* remained culturable for extended periods under optimum conditions, but that under typical conditions in Mamala Bay they are likely to become non-culturable in less than one day. Experiments indicated that culturable forms of these organisms are unlikely to be detectable in environmental samples.

Staphylococcus aureus, although not directly linked with sewage discharges, is an apparent cause of skin infections among bathers, especially those preferring intensively used recreational waters. In a special investigation carried out in the Mamala Bay Study (Project MB-SP4) culturable S. *aureus* was isolated from Waikiki Beach samples and other sites in Mamala Bay using a PCR technique. The technique appeared to produce positive results where conventional methods tended more often to be negative. Because concentrations were low, near the margin of detectability, it was not possible to determine the source of *S. aureus* contamination. There was insufficient evidence to attribute contamination by *S. aureus* to either point or non-point sources or to bathers using the affected waters.

C. perfringens was found to be a preferred indicator of sewage pollution due to its stability in the marine environment. The presence of indicator organisms, especially enterococci and *Clostridium perfringens,* suggests that non-point sources of contamination were more likely than point sources to affect the quality of near-shore waters. Fecal coliforms proved to be useful indicators of the influence of point source discharges from the Sand Island and Honouliuli WWTPs.

New microbiological techniques used revealed the presence of specific pathogens, e.g., bacteria, viruses, and protozoans, in Mamala Bay waters, in sewage, and in non-point sources. Concentrations in marine waters were very low, in some cases below detectability except in very large samples after concentration. Non-point source locations such as the Ala Wai Canal were more contaminated than offshore waters. Pathogens such as *V. cholerae, Shigella spp.* and enterotoxigenic *E. coli* were found to be viable but non-culturable after as little as one day's exposure to marine waters. *Staphylococcus aureus* was identified in near-shore but was not directly linked to sewage discharges.

With the major point and non-point sources identified and ocean currents defined and indicators determined, the risk to public health from exposure to contaminated water will be quantified.

The quality of natural waters is defined in terms of its physical, chemical and biological characteristics. From the viewpoint of public health, the microbiological content of water is of prime importance, especially with respect to microscopic agents of disease, the pathogens. These may include in rough order of their sizes, pathogenic viruses, bacteria, and protozoa, some of which may be found in discharges from both point and non-point discharges into the waters of Mamala Bay and within the bay itself. However, since human pathogens are generally fewer in number and more difficult to detect than non-pathogenic forms also identified with contamination of water by humans, it has been customary in control of water borne diseases to rely on indicator organisms to suggest the potential presence of pathogens. Typical indicator organisms (fecal coliforms and enterococci) are known to be present in domestic sewage. Standards of water quality are often based on concentrations of indicators, assuming that pathogenic forms are so much less in concentration that adherence to a standard level of the indicator assures a safe water. This may not always be the case, hence the need for advanced techniques for direct detection of pathogens and improved methods to relate the presence of pathogens to the more easily detected indicators.

VIRUSES

Viruses of concern in water pollution are found in the human intestinal tract. Ingestion of waters polluted with these viruses that are associated with fecal contamination, may result in eye or respiratory infections, fever, rash, and diarrhea.

INDICATOR BACTERIA

Coliform bacteria, as typified by *Escherichia coli,* and enterococci, both reside in the intes tinal tract and are present in large numbers in feces of humans and other warm blooded animals. Because of their relatively larger concentrations in polluted waters and comparatively easier means for their detection and enumeration, the presence of coliform bacteria is considered to be indicative of the presence of fecal pollution, and by inference of the possible presence of pathogens of sewage origin. Ingestion of some strains of these bacteria are also known to cause gastrointestinal disease. It should be noted that some bacteria in the coliform group are also found in non-fecal contaminated environments, hence the need for more specific identification of coliforms of fecal origin.

PROTOZOA

Protozoa are single-cell organisms of which several species are parasitic, although most are free-living. One member of the parasitic group, *Giardia lamblia,* is of concern in drinking water. The resulting disease, giardiasis, is contracted from ingestion of water contaminated with fecal matter from human or animal sources. Symptoms associated with this gastrointestinal disease vary, depending on the individual and the 'amount' of exposure, but can include nausea, indigestion, diarrhea, loss of appetite, bloating, fatigue, and weight loss. Although this disease is generally not life-threatening in the United States and can commonly be treated within the period of a few days to several weeks, it can recur or persist for a long time if left untreated. Throughout the United States, hikers drinking untreated water from mountain streams most commonly acquire the disease. In the case of Mamala Bay waters, exposure to the microorganisms may occur due to ingestion of water contaminated during recreational use of the bay. Other pathogens that were considered in this study and that are causes of gastrointestinal diseases include enterotoxigenic E. *coli, Salmonella,* enteroviruses and *Cryptosporidium.*

Some of the new methods applied in this Study revealed the presence of pathogens such as enteroviruses and infectious protozoans *(Giardia* and *Cryptosporidium)* in the waters of Mamala Bay, although concentrations were often near the limits of detection, requiring very large samples for analysis. For example, although *Giardia* was detected at Waikiki and Queens Surf beaches on at least ten occasions, the maximum concentration was 0.005 cysts per liter, or about one protozoan in 2000 liters of water. In contrast the mean abundance of this organism in the Ala Wai Canal was 0.017 cysts per liter and in Sand Island's discharge it was 2300 cysts per liter. The investigations in this Study were designed to determine the presence or absence of certain microbiological organisms in Mamala Bay waters and where suitable analytical methods existed, to determine their concentrations.

Water quality is often assessed in terms of standards that have been prescribed by State and Federal agencies. Depending on the uses of the water, different standards will apply. The most stringent standards apply to drinking waters, followed by waters used for recreation. They may include specifications for the maximum concentrations of different types of microorganisms and other water quality parameters such as dissolved and suspended solids, dissolved oxygen, temperature, algae, organic substances and toxic compounds. Microbiological standards for marine recreational waters have been States Environmental Protection Agency (USEPA). In the absence of specific marine standards, those that apply to inland waters were used as reference values in this Study. The standards are given in Table 3.1 in terms of the geometric mean.

TABLE 3.1
STANDARDS FOR ASSESSMENT OF MICROBIOLOGICAL QUALITY OF MAMALA bAY

Microbiological Organism	Standard (geometric mean)
Enterococci	7 enterococci / 100 ml
Fecal Coliform	200 coliform / 100 ml (for inland waters)
Escherichia coli	126 E. coli / 100 ml
Clostridium perfringens	5 CPU / 100 ml (proposed for recreational ocean waters) 2 CPU / 100 ml (proposed for open ocean waters use)

It is implicit in the concept of risk to public health from exposure to pollution in Mamala Bay that there are many uncertain factors that in combination determine the likelihood of an individual or a population of individuals contracting a disease. Among these are the kind of pathogen and disease it may produce, its strength at the point of entry into the bay, its fate between the source and receptor, its concentration in the water at the location of contact, the dose received by the exposed individual(s), and the resistance of the individual(s) to disease. All of these are uncertain quantities in the real world, hence the risk to public health becomes a matter of determining the probability a disease will actually occur.

In those cases where there is no established statistical pattern or incidence of a disease evidenced by epidemiological surveys, as in the case of Mamala Bay, risk to public health must be inferred from the statistics of the potentially causative agents. In the present instance there are at least three ways to estimate risk:

1. Frequency Analysis of Contamination

The frequency of exceedance of a standardized threshold (e.g., the State of Hawaii's enterococci standard of geometric mean 7 colony forming units per 100 milliliters of sea water) may be used as a relative measure of risk that can be determined by statistical analysis of field data or output from the fate and transport model developed in Project MB-5. There is an implied risk associated with the setting of the standard that is presumed to be acceptable to the general public and enforceable by responsible regulatory authority. However, since the actual risk is seldom known, exceedances of the standard value, or any other level of concentration, are only useful in comparative analysis. In this Study comparisons of probability distributions of concentrations predicted by the hydrodynamic and transport models are based on this concept.

Examples of this approach to assessment of risk are the comparisons of probability distributions of fecal coliform concentrations at four Mamala Bay beaches: Ewa, Sand Island, Ala Moana, and Tavern. For example, at Ala Moana Beach both field observations and model results indicate that the probability of not exceeding the fecal coliform standard of 200 colony forming units per 100 milliliters is about 98 percent, i.e., 2 percent of the time the standard would be exceeded.

In evaluation of alternative management options the models can reveal, in considerable detail, the relative number of occasions, i.e., the frequency, at which a particular standard is exceeded, a measure of the relative risk, or effectiveness of the alternative. Such a comparison shows the number of days on which the 7 colony forming units per 100 milliliters standard for enterococci was exceeded in one year at offshore and beach locations for six different management scenarios. The analysis shows that off Waikiki the number of violations of the enterococci standard of 7 colony forming units per 100 milliliters would be reduced to about one-third by elimination the Ala Wai Canal as a source, i.e., the risk is reduced by one-third by this option. By contrast, elimination of the other sources would have comparatively little effect on exceedance of the enterococci standard at this location.

2. Individual Dose Response Model

This approach, developed in Project MB-7, considers the dose, exposure, and response characteristics for an individual susceptible to disease, for instance a swimmer exposed by actually ingesting contaminated seawater. It is assumed that the risk to the individual depends upon the concentration of the pathogen in contaminated water, the amount of water that might be accidentally ingested, and the likelihood that once ingested the pathogen will actually produce clinical symptoms in the individual. The risk is the product of the individual probabilities of the pathogen concentration, the amount of water ingested, and the individual's susceptibility to disease. It may also depend on the etiology of the organism, i.e., its viability at the time of ingestion, among other environmental factors. This approach utilizes information from the transport and fate model to determine the probable concentrations of pathogens at specific exposure locations. The models used to evaluate public health risks in Mamala Bay were previously applied in development of appropriate standards for the Safe Drinking Water Act by the Environmental Protection Agency.

3. Population Response Model

This approach, developed in Project MB-10, extends the individual risk notion to consider characteristics of a population exposed. Thus, such factors as the numbers of individuals exposed at a given site, the age composition of the group, multiple sources of the same disease agent, and immune characteristics of the population are considered in formulating a statistical model in which the state variables are described by random functions. Because of the large number of variables involved and their combined uncertainties, a Monte Carlo technique that assumes random variations of model variables about mean values is employed to estimate the prevalence (number of individuals per 100,000 of the general population) contracting the disease. Results are presented as the mean prevalence plus a variance about the mean. Again, transport and fate model results may be used to assess alternative pollution control strategies in terms of the relative risks to public health of exposure to predicted concentrations of microorganisms.

Analysis of estimated mean concentrations of an indicator organism combined with the frequency of exceedance of a threshold value, i.e., a standard, provides a means for comparison of the relative effects of different point and non-point source treatment options, although actual concentrations may not exactly correspond to those at a given location on a given day. Simulation results for mean fecal coliforms at beaches and offshore locations for four treatment levels (existing, CEPT, secondary, and elimination) at Sand Island were conducted. In this example the transport and fate model indicates that mean concentrations of fecal coliforms vary widely with location and degree of treatment provided at Sand Island. Lowest concentrations occur at Waikiki Beach, less than about 1 colony forming unit per 100 milliliters. (Hawaii's standard is 200 colony forming units per 100 milliliters.) The highest concentrations occur in offshore waters nearest to the outfalls. Off Waikiki under present conditions mean fecal coliform counts are about 9 times greater than at the beach.

Among the four treatment levels considered, chemically enhanced primary treatment (CEPT) provides a reduction in mean fecal coliforms at Waikiki Beach of about 20 percent, while secondary treatment would reduce counts by about 50 percent. Disinfection was considered to reduce counts in the outfall by 99.9+ percent. In these simulations the number of days on which a fecal coliform counts exceeded 50 colony forming units per 100 milliliters was estimated to be approximately 14 at Sand Island Beach closest to the outfall, but less than 2 at any of the eastern beaches, like Waikiki. During the one-year simulation with the model there were only five days on which fecal coliform counts exceeded the 200 colony forming units per 100 milliliters standard at any of the following beaches: Queens Surf, Waikiki, Ala Moana, Sand Island, Ewa and Oneula. On all five occasions the contamination was attributed to outfall sources. While there were 80 days when the enterococci standard of 7 colony forming units per 100 milliliters was exceeded, only 20 percent were from outfall discharges, the remainder were from shoreline (non-point) sources. Outfall impacts on beaches and offshore waters are almost all related to Sand Island, except near the Barbers Point outfall and the nearby Oneula Beach. Barbers Point outfall had no appreciable influence on eastern beaches and their offshore waters.

Results obtained for mean enterococci, through computer simulation, are similar, except that enterococci counts are less affected by treatment, both at the beaches and offshore. At Waikiki and Queens Surf beaches mean enterococci counts were generally below the 7 colony forming units per 100 milliliters and were more strongly influenced by upgrades in treatment at Sand Island than were fecal coliforms. However, non-point sources were the major contributors of high enterococci counts at the eastern beaches where high fecal coliform counts were more closely identified with the Sand Island outfall. At the eastern beaches non-point sources, especially the Ala Wai Canal, tended to dominate the higher counts of both indicators.

SOURCE MODELING

The models were used to assess the incidence of pathogens, principally with respect to the eastern beaches for which field data were available. Evaluation of pathogen sources indicated that the Sand Island outfall was a major source of *Giardia, Cryptosporidium,* enterovirus, *and Salmonella.* However, with respect to the eastern beaches the Ala Wai Canal was found to play a major role also in observed contamination events, especially during periods of extreme runoff. The Ala Wai Canal was the dominant source of *Salmonella* on the beaches, while the Sand Island outfall accounted for the greater proportion of the other pathogen concentrations predicted by simulation. The maximum detected level of *Giardia* at Waikiki and Queens Surf beaches was 0.005 cysts per liter, i.e., 1 cyst in 2000 liters. This concentration level was confirmed by the transport and fate model for loading conditions determined by direct sampling of the principal sources.

RISK ASSESSMENT

Risks of acquiring a viral or protozoan infection were estimated for recreational users of Mamala Bay waters based on a 7-day exposure period for enteroviruses, adenoviruses, *Cryptosporidium* and *Giardia.* Average estimates of pathogen concentrations were obtained from field observations at four beaches and results of the pathogen fate modeling studies.

The risk of acquiring a viral infection due to exposure to Mamala Bay waters was found to range from a low of 1 individual in 1000 at Waikiki Beach to a high of 5 individuals in 1000 at Queens Surf Beach. The risks were compared to those associated with acquiring a viral infection by mechanisms other than by aquatic exposure, for example, by person-to-person contact, or contact with contaminated food or surfaces. Risks associated with aquatic exposure were found to be 2 to 10 times lower in the summer, but equivalent to or greater than background levels during the fall and spring seasons.

The risk of acquiring an infection due to exposure to protozoa (e.g., *Giardia)* in Mamala Bay waters was found to range from a low of 2 individuals per 100,000 at Hanauma Bay (assumed to be a "control" site not affected by effluent from Sand Island or Barbers Point outfalls) to a high of 9 individuals per 100,000 at Waikiki Beach. The risk of acquiring a protozoan infection due to recreational use of the beaches was found to be approximately 4.5 times greater than background levels. Overall, the potential for a protozoan infection was estimated to be approximately 100 times less than the risk of acquiring a viral infection.

A public health risk assessment model developed in Project MB-10 was applied to Waikiki and Ala Moana beaches to examine the risk of diseases associated with exposure to *Giardia, Cryptosporidium, Salmonella* and enteroviruses in Mamala Bay waters. Contaminant concentration estimates obtained from the transport and fate modeling were used to compare estimates of the modeled average daily prevalence (proportion of population that exhibits symptoms of disease, averaged over the simulation period) over background prevalence (the proportion of population that exhibits symptoms of disease resulting from methods other than aquatic exposure) obtained from published literature values.

Simulations were performed to test the effects of pathogen contributions from swimmers ("shedding"), pathogens from sources other than shedding, and order of magnitude increases or decreases in pathogens contributed from the other sources ("non-shedding"). Analysis of results showed that for the four microorganisms tested at two beach sites, Ala Moana and Waikiki, there was very little statistical variation in the results among the scenarios tested as compared to the background prevalence in the population. However, there were significant differences in the background prevalence for the different diseases. For example, background values for the prevalence of *Giardia* had a mean of 1.5 per 100,000 population per day and a variance of 1.9. For *Cryptosporidium,* the mean value was estimated to be 0.6 per 100,000 per day with a variance of 0.3, and for *Salmonella,* the values were 0.4 per 100,000 per day and 0.1 variance, respectively.

Increasing or decreasing the contribution from non-shedding sources by an order of magnitude did not appear to significantly increase the disease prevalence in the population above background. The models were most sensitive to changes in the background disease transmission rate and to variations in the fraction of the population that moves from infectious and symptomatic conditions to non-infectious and asymptomatic conditions in a given day.

Because the modes of disease transmission, immune status of human beings and other factors can change over time, and given the uncertainties in physical, biological, and population data, use of a statistical approach was appropriate. Simulation results provide a statistical basis for evaluation of risks, such that results should only be analyzed on a probabilistic basis for a population, rather than considering the results of each simulation individually.

The analyses described above indicate that the risks of contracting an infection by bathing, swimming, surfing, or fishing in Mamala Bay waters are low. At the principal beaches the risk of acquiring an illness from ingestion of contaminated water at the concentrations actually observed in the Study, for example, was found to be little different from the risk for the general population not exposed to Mamala Bay waters. This conclusion appears to be substantiated, incidentally, by the very low incidence of reported cases of disease among both the resident and recreational populations that use the waters of Mamala Bay.

However, despite the lack of epidemiological evidence, the actual presence of pathogenic microorganisms in near-shore and recreational waters confirmed in the Study warrants consideration of reductions in sources of contamination. There is evidence in the results of modeling studies that offshore waters that are likely to be frequented by surfers and fishermen are contaminated at levels of indicator organisms (fecal coliforms and enterococci) that occasionally exceed Hawaii's standards. Exceedance of the fecal coliform standard of 200 colony forming units per 100 milliliters is rare offshore of the eastern beaches, but near the outfalls during periods when the plumes are likely to surface (primarily during winter months) the standard may often be violated. In the case of the comparatively stringent enterococci standard of 7 colony forming units per 100 milliliters exceedance of the standard may be even more frequent. Therefore, while it is not possible to precisely determine the risks to public health, there is an apparent need to assure that the values and uses of Mamala Bay, as they are defined in the ICM concept, are preserved.

ECOSYSTEM EFFECTS STUDY

The other aspect of the study focused on the identification and quantification of the effects of point and non-point sources of pollution on the indigenous ecosystems of Mamala Bay.

Assessment of ecosystem responses to pollution of Mamala Bay was carried out by a University of Hawaii team in a series of discrete investigations within Project MB-9 that were concerned with the effects of pollution on phytoplankton communities, benthic invertebrates, fish, coral and reef systems, macro-benthic communities, and indicator species.

These studies generally revealed that the effects of sewage discharges on Mamala Bay ecosystems, although potentially biostimulatory due to increased nutrient availability, are actually slight and localized. Near outfall locations there was evidence that increased phytoplankton production was correlated to elevated concentrations of ammonium and silicate identified with sewage discharges, although there were strong indications that non-point sources were more important nutrient contributors. Discharge from the Fort Kamehameha Wastewater Treatment Plant into relatively shallow water offshore was found to have a greater impact on local water quality than either the Sand Island or Barbers Point outfalls. Poor water quality at Ewa Beach and other western beaches was attributed primarily to ground water seepage and cesspool drainage, i.e., to non-point sources. Overall, the impact of nutrient discharges on Mamala Bay was small from either point or non-point sources. Most variations in communities and populations of organisms were found to be more related to substrate composition, current fluctuations, and seasonality.

Shallow reef communities shoreward of the outfalls appeared to be little affected by the discharges. Coral production was not found to be significantly affected by the presence of the outfalls over the period since the recovery of coral stands following the installation of the deep water outfalls. Lack of substrate in Mamala Bay favorable to coral recruitment and the recent devastation of coral stands by severe storm events tend to make interpretation of effects of the outfalls somewhat uncertain, but data on species abundance and growth rates seem to indicate normal recovery is not compromised by sewage discharges.

Recruitment of tunicates and sea squirts to suitable substrates apparently occurs only at the outfalls since the outfall structures themselves provide attachment surfaces. Deposition of organic particulates near the outfalls appears to have little effect on the composition of sediments in the vicinity of the diffusers. One indicator species, *Ophyrotrocha sp.* was found in significant numbers only at the deep Sand Island outfall site. Other indicator organisms, often identified with pollution impacts, were found to be distributed widely in Mamala Bay, independent of proximity to outfall locations.

Overall, point sources appeared to have little influence on near-shore communities of benthic fauna, while non-point sources, such as those identified with the Ala Wai Canal, Keehi Lagoon, and Pearl Harbor, significantly affected bottom dwelling organisms. Recruitment of some benthic organisms was found to be reduced in the vicinity of Pearl Harbor and near the mouth of the Ala Wai Canal.

Point sources of pollution of Mamala Bay have comparatively minor quantitative effects on phytoplankton and benthic communities. There is conclusive evidence that nutrient enrichment in shoreline areas is closely related to non-point sources, e.g., cesspool and ground water drainage, or to localized discharges, such as those from the Fort Kamehameha outfall and the Ala Wai Canal. A Mamala Bay monitoring program should include periodic samplings of benthic chemistry, sediment characteristics and benthic communities, including coral stands, in areas adjacent to the Sand Island outfall and offshore of principal sources of non-point source accretions, i.e., the Ala Wai Canal, Pearl Harbor, and Keehi Lagoon. Comprehensive analyses of the environmental impacts of pollutants discharged to Mamala Bay and development of effective environmental quality control solutions must be based on factual evidence of such effects. Storage of data in electronic format will facilitate synthesis of information gathered in related studies and evaluation of historical trends, and will prevent duplication of efforts. Upon conclusion of the Study, the Mamala Bay data base will be made accessible to the public as a site on the Internet, where these data can be stored and retrieved. Instructions for accessing the database are provided in the Study report.

POLLUTION CONTROL ALTERNATIVES EVALUATION

Having characterized the potential problem, the next step was to identify and evaluate practical and implementable alternatives for the control of pollution of Mamala Bay.

The presence in Mamala Bay waters of indicator organisms and pathogens that originate with both point and non-point sources is evident in results of field monitoring and supported by transport modeling results. Analysis of field data and model results indicates that there are locations within the bay where water uses may be adversely affected by the present levels of loads imposed upon the bay and its ecosystem and where risks to public health may be significant. In some locations water quality as measured by traditional indicator microorganisms does not comply at all times with Hawaii's standards. Moreover, results of monitoring have indicated the presence of pathogenic viruses, bacteria and protozoans in significant concentrations in discharges to the bay, and in small, but measurable, concentrations in waters used for swimming, surfing, fishing and other water related recreation.

While it has not been possible to determine precisely the risks imposed on Mamala Bay's values and uses by discharges from point and non-point sources, it is apparent that there is a need to provide additional assurance that they will be preserved, even enhanced. Accordingly, and consistent with the direction of the consent decree and the concept of Integrated Coastal Management, a range of alternative scenarios for control of point and non-point sources of pollution of Mamala Bay were developed and examined. The major goal of this effort, implemented in Projects MB-10 and 11 A, was to devise a preferred plan for management of water quality in the bay with emphasis on reducing the incidence of indicator organisms and pathogens.

Sand Island and Honouliuli WWTPs are basically primary treatment plants that have been marginally effective in recent years in meeting their goals for removal of total suspended solids (TSS) and biochemical oxygen demand (BOD). Efforts have been made to enhance removal efficiency at the Sand Island WWTP using dissolved air flotation, with limited success. Moreover, neither plant has been able to provide an acceptable degree of disinfection. Both have facilities for disinfection of the effluent using chlorine; however, the equipment is presently inoperable through disuse. Because chlorination was not in effect at either plant during the study (the Commission specifically requested that chlorination not be reinstituted until after the Study was completed), the potential exists for reducing contamination of future discharges by appropriate disinfection procedures. Modeling results show that a disinfection process that reduces the microbiological concentration at the outfall by as much as 99.9 percent will produce a corresponding reduction at offshore locations affected primarily by the outfalls. Possibilities for disinfection are either chlorination/dechlorination or ultraviolet light. Achieving effective and economical disinfection by whatever method will require improvement of the efficacy of wastewater treatment, i.e., obtaining a decrease in the concentration of suspended solids that inhibit disinfection of the effluent. Because the performances of both the Sand Island and Honouliuli WWTPs are presently marginal with respect to the State and Federal standards for removal of solids, it is apparent that treatment upgrades will be needed in any event and that these should enhance disinfection. Further, both field and modeling studies point to the need to reduce concentrations of both indicators and pathogens in the effluents. Alternatives for upgrading treatment at the two WWTPs, including appropriate disinfection, include the following:

1: No Action

This alternative is essentially that existing during the period of the Study, i.e., simple primary treatment without any disinfection. It constitutes a "base", or "no action" alternative, one that is only marginally in compliance with water quality standards for Mamala Bay, and against which other options for upgrading wastewater treatment may be compared.

2: Meet Water Quality Standards

The City and County of Honolulu have made considerable effort to study ways of bringing existing facilities into compliance with the requirement for 30 percent BOD removal and 30 percent reduction in BOD effluent loading. At Sand Island these have included reinstitution of dissolved air flotation (DAF) as an alternative to gravity settling, but not used routinely since the plant was built. Chemically enhanced primary treatment (CEPT) facilities have recently been installed at Sand Island and full plant tests of DAF and CEPT have been made. City and County consultants have recommended DAF to meet the 30 percent BOD removal requirement. Tests at Sand Island WWTP showed that DAF increased BOD removal but decreased suspended solids removal, while CEPT increased both BOD and solids removal. Limited testing of chemical treatment conducted at the Honouliuli WWTP have also shown improvements in BOD and suspended solids removal. It remains to be demonstrated that these measures will result in performance in compliance with standards.

3: Chemically Enhanced Primary Treatment (CEPT)

Chemically Enhanced Primary Treatment involves addition of flocculating agents, polymers or metal salts, to wastewater during the treatment cycle to enhance flocculation of fine suspended and colloidal solids, thereby increasing particle settling rates. This option, proposed by the MB-11A team for both treatment plants, implies optimizing chemical treatment to achieve maximum removal of total suspended solids (TSS) and greater flexibility among disinfection options, as well as increasing BOD removal. MB-11A studies indicate the importance of testing additional additives at both pilot plant and full plant scales, and implementing measures to improve polymer aging, dilution and mixing. Costs for CEPT are in addition to those for primary treatment, including capital and operating costs of chemicals, mixing equipment, and sludge handling and disposal.

4: CEPT + Disinfection
CEPT, with effective solids removal, is considered to be the minimum level of treatment upgrade that will allow effective ultraviolet (UV) disinfection as an alternative to chlorination. If chlorination is reinstalled it would probably be necessary to provide for dechlorination at additional cost. The ultraviolet disinfection option which leaves no residual should be studied on a pilot plant scale. A comparison of UV versus chlorination/dechlorination is provided in the Study report. Added costs over CEPT alone would include facilities for disinfection and, in the case of UV, for the disposal of spent lamps.

5: Secondary Biological Treatment
In secondary biological treatment, residual dissolved organic matter is converted to suspended solids and removed from the wastewater, usually by sedimentation. As a result, removals of both BOD and TSS are increased and concentrations of microorganisms in the effluent are reduced. Costs of secondary treatment are higher than for CEPT plus disinfection.

6: Secondary Treatment + Disinfection
Because of reduced solids beyond levels obtained with primary treatment, disinfection efficiency is enhanced. UV disinfection is recommended for use with secondary treatment.

7: Waste Water Reuse at Honouliuli
Plans are under way for reducing ocean wastewater discharge at Honouliuli by providing secondary treatment and appropriate disinfection for a portion of the flow that could be reused on land. The remaining flow would be treated by CEPT. Disinfection would not be provided for that portion discharged through the Barbers Point outfall.

The relative effectiveness of these point source control options was evaluated using the Mamala Bay models and estimated loadings of indicator organisms imposed at the Sand Island and Barbers Point outfalls and by non-point sources. It should be noted that in these cases, although the load at the outfalls was adjusted from the current condition according to the proposed level of treatment, e.g., CEPT, secondary, and CEPT plus disinfection, no adjustments were made in non-point sources of contamination. Thus, the results reflect the changes due to improvement in treatment only at the wastewater treatment plants. Results were compared to those obtained under 'current' conditions, i.e., conventional primary treatment without disinfection.

Effects of the different wastewater treatment options on reductions in fecal coliform, enterococci and *Clostridium* levels were compared at a large number of locations in Mamala Bay: at popular public bathing beaches, inshore of the outfalls, at selected sites offshore in surfing areas and at locations offshore of the outfalls. Treatment options evaluated with the models included chemically enhanced primary treatment (CEPT) and secondary treatment, each with and without disinfection at Sand Island and Honouliuli treatment plants. Also, a series of runs included options where the effects of the point source discharges were omitted to illustrate the influence of point sources relative to non-point sources. As a result of the various treatment options, the greatest reductions in indicator bacteria levels were predicted at the western beaches, including Ewa Beach and Oneula Beach, closest to the outfalls. Significant, but lesser, reductions were predicted for the eastern beaches, Waikiki, Ala Moana, etc. due in major part to the larger impact of non-point sources on these beaches. However, at all beaches affected by contamination from point sources, all treatment options generally resulted in decreases in levels of indicator organisms.

Upgrading of the Sand Island treatment plant to CEPT resulted in an approximately 50 percent reduction in fecal coliform counts throughout the bay. With either secondary treatment or disinfection of Sand Island effluent, model results showed a factor of three reduction in mean coliform counts at the eastern beaches. CEPT was found to be less effective in reducing enterococci counts (reductions of 20 percent at Ewa Beach and 10 percent at all other beaches) because of the high contribution of enterococci from shore-based sources, but reductions in counts were predicted at offshore locations and at the western beaches less affected by non-point sources. With either secondary treatment or disinfection, enterococci levels in the vicinity of the Sand Island outfall were reduced, but at the other locations examined, only minor improvements were observed over the levels achieved with CEPT. Comparisons of predicted mean fecal coliform and enterococci concentrations at Mamala Bay beaches under different treatment options were shown for near-shore (beach) and offshore locations. While CEPT was not found to reduce *Clostridium* counts, disinfection was predicted to reduce counts by approximately 80 percent at western beaches and 30 percent to 50 percent at eastern beaches.

Considering near-shore areas, upgrading of the Honouliuli treatment plant primarily influenced levels of bacteria only at Oneula Beach. Fecal coliform levels were reduced by 50 percent at this location with implementation of CEPT and by an additional 30 percent with disinfection or secondary treatment. Enterococci and *Clostridium* levels were affected to a lesser degree due to the high levels of these organisms contributed from Sand Island and shore-based sources. Model results also indicated that upgrading treatment resulted in reduction of contamination in offshore areas of the bay near the Barbers Point outfall, areas that may be used for surfing and fishing activities. For example, fecal coliform counts at stations in the vicinity of the outfall were reduced by approximately 50 percent and 90 percent as a result of CEPT and secondary, respectively. Enterococci levels were reduced by about 40 percent with CEPT and 60 percent with secondary treatment. Due to the dominance of Sand Island outfall in observed levels of disinfection at Honouliuli, with no effect observed in eastern bay locations.

Non-point sources are the primary concern with respect to near-shore areas, specifically bathing beaches. In general, by their very nature as dispersed sources of pollution, specific control measures are difficult to implement. Some of the major contributors of non-point source pollution were identified during the Mamala Bay Study, and included the Ala Wai Canal, Manoa Stream, Keehi Lagoon and Honolulu Harbor.

1. ALA WAI CANAL

A possible candidate for effective control is the Ala Wai Canal, which is a major source of contamination of the near-shore environment near its mouth, especially during high runoff events. The Ala Wai has been the subject of much investigation in the past because of its high level of contamination, both bacterial and of nutrients. A special study was conducted to evaluate the effects of discharge from the Ala Wai Canal on the water quality at nearby beaches during a storm episode. Results indicated that during high runoff events alongshore currents toward Diamond Head convey runoff from the Ala Wai Canal to Waikiki Beach. Hydrodynamic and water quality models confirmed field observations.

Several alternatives have been suggested for potential improvement in the quality of the Ala Wai discharges including flushing, construction of a saltwater barrier, in-canal treatment, dredging and source control of discharges in the watershed. They are discussed in the following sections.

Problems within the Ala Wai watershed include erosion, excessive use of fertilizers and pesticides, urban runoff, improper disposal of toxicants, wastes and litter, and possible leakage from underground storage tanks and disturbed sewer pipes. Possible remediation and management measures include development of source reduction and control programs (through actions such as enforcement of ordinances, implementation of measures to control erosion, public outreach and education regarding impacts of discharging pollutants within the watershed) and containment or remedial actions. Manoa Stream, which receives diffuse inflow and discharges into the Ala Wai Canal, is a prime candidate for control of illicit accretions in upstream drainage basins. Management of water quality in the Ala Wai Canal watershed should include active participation by the City and County of Honolulu on controlling leakage from sewers and combined sewer outflows.

2. OTHER NON-POINT SOURCES

Other watersheds such as the Kewalo Basin, Pearl Harbor, Keehi Lagoon, Honolulu Harbor, and Ewa Plain which are significant contributors of uncontrolled runoff and contamination by non-point sources can also benefit from implementation of a community-based water quality management plan. Development of such a plan should be a high priority item on the agenda of an Integrated Coastal Management Forum that will address water quality issues of Mamala Bay and its tributary watersheds.

The Mamala Bay Study report presents a comprehensive assemblage of new data and information on ocean circulation and water quality. It describes state-of-the-art techniques for acquiring these data and for applying them in assessment of risks to public health and the marine ecosystem. It evaluates an array of alternatives designed to improve water quality in Mamala Bay. This summary of the study has outlined principal tasks of the Study, analyzed results of the individual investigations, and presented specific recommendations for the creation of a practical Integrated Coastal Management Plan. The stage is now set for implementation of such a plan, one that will meet the expectations of environmental leaders, public officials and an informed public in assuring the future health of Mamala Bay.

According to the Mamala Bay Commission, the most significant findings of the Study are:

a) Through computer simulation and field measurement, ocean circulation in Mamala Bay is extremely complex, driven largely by tidal fluctuations with major components paralleling the shoreline, but influenced seasonally by thermal stratification and Trade and Kona winds.

b) Through computer simulation and field measurement, sewage plumes from the City's outfalls are greatly diluted within the zone of the diffusers. Plumes are retained below the ocean surface during periods of greatest stratification, usually in the summer. The greatest frequency of plume surfacing and highest dilutions occur in the winter.

c) Through computer simulation, contamination in discharges through the Sand Island WWTP outfall can reach most beaches and offshore areas of Mamala Bay at the present level of wastewater treatment. Contamination originating from the Honouliuli WWTP only reaches the western beaches at detectable levels.

d) Through computer simulation and field measurements, non-point sources are most responsible for contamination of the eastern beaches of Mamala Bay, such as Waikiki, Ala Moana, Queens Surf beaches, especially during high runoff storm events. About two-thirds of the annual flow into Mamala Bay originates from uncontrolled non-point sources. Runoff from the Ala Wai Canal is a major source of contamination of Waikiki Beach.

e) Pathogens and bacteria of fecal origin were isolated from the waters of Mamala Bay and from both point and non-point sources of pollution. New techniques for isolation of pathogens from ocean water indicate that some may remain viable for periods of a day or more, but not culturable by conventional methods.

f) Present levels of wastewater treatment at the City's WWTPs are not sufficient to meet regulatory standards. Increased removals of biochemical oxygen demand (BOD) are needed and reductions in suspended solids in plant effluents are necessary to ensure effective disinfection.

Based on factual findings and interpretation of results of scientific investigations conducted during the course of the Study, the Mamala Bay Study Commission presents the following recommendations:

1) that the data base developed by the Study be maintained by an appropriate agency of the City and County of Honolulu or the State of Hawaii for the beneficial use of all who may wish to access it.

2) that regular water quality monitoring be continued at sites identified during the Study and coordinated with water quality sampling programs of the City and County and other appropriate agencies and that data developed in these programs be entered into the data base.

3) that monitoring of ocean circulation and the driving forces that govern circulation within the bay be continued by an appropriate scientific agency.

4) that a Mamala Bay ecosystem monitoring program be instituted to include periodic samplings of benthic communities, including coral stands, in areas adjacent to the Sand Island outfall and offshore of principal sources of non-point accretions, e.g., the Ala Wai Canal, Pearl Harbor, and Keehi Lagoon.

5) that the mathematical models developed in the Mamala Bay Study be maintained by an agency of the City and County of Honolulu or the State of Hawaii capable of implementing them as needed to evaluate the effectiveness of measures or facilities proposed to improve the water quality of Mamala Bay.

6) that the level of wastewater treatment practiced at the Sand Island and Honouliuli WWPTs be upgraded at least to the level of efficiency of chemically enhanced primary treatment (CEPT) to increase removal of suspended solids and BOD and to facilitate effective disinfection.

7) that provision be made at the Sand Island and Honouliuli WWTPs to evaluate the performance of CEPT, including assessing the effectiveness of alternative chemical enhancement additives and their proper aging and mixing.

8) that appropriate disinfection be provided for the ocean outfall discharge at the Sand Island WWTP.

9) that ultraviolet irradiation as a means of disinfection be investigated by means of pilot plant studies as an alternative to chlorination/dechlorination at the Sand Island WWTP.

10) that effective and responsible methods of disposal of sewage sludge, chemical precipitates, UV lamps (in the event of UV disinfection) and other treatment by products be developed and applied at Sand Island and Honouliuli WWTPs.

11) that a feasibility study be undertaken by the City and County of Honolulu to evaluate the effectiveness of alternative measures to control non-point sources of contamination of Mamala Bay including the Ala Wai Canal, particularly during and immediately following intense storm events, and to implement the measures found to be most feasible.

12) that an Integrated Coastal Management Forum be created to bring together scientists, managers and representatives of stakeholder groups with the objective of providing a sustained environment within which the products of the Mamala Bay Study will be applied and the recommendations of the Study implemented for the benefit of all interests.