MAMALA BAY STUDY

WATER QUALITY MANAGEMENT FOR MAMALA BAY

PROJECT MB-11

Mamala Bay Study Commissioners:

Rita R. Colwell
Maryland Biotechnology Institute
University of Maryland
College Park, MD   20740

Gerald T. Orlob
Department of Civil and Environmental Engineering
University of California
Davis, CA   95616

Jerry R. Schubel
New England Aquarium
Central Wharf
Boston, MA   02110-3399

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1 INTEGRATED COASTAL MANAGEMENT

1.1 Systems Analysis Approach

A goal of Integrated Coastal Management in the context of the Mamala Bay Study was to achieve an implementable plan for control of pollution of the bay that reduced the risks to public health and damage to the environment to levels acceptable to the affected society. Because of the inherent complexity of the Mamala Bay system, the wide range of possible measures that might be invoked to control pollutant impacts, and the uncertain responses of the bay to specific alternative water quality management options, the Commission decided upon a systems analysis approach to identify the relative merits of proposed alternatives.

Using data from the natural environmental system, the mathematical models could simulate the system's behavior under conditions of both actual and hypothetical pollutant loadings. It provided investigators with the means to assess quantitatively the system's response to specific changes in environmental parameters, pollutant loadings, and operational or structural measures. The models aided in determining the relative risks to public health caused by the incidence of pathogenic organisms originating from an array of point and non-point sources, or from a single source under different operational scenarios, such as upgrading wastewater treatment processes to new levels. Findings from the model simulations were used together with field observations and laboratory results to evaluate and compare alternatives with the objective of finding the unique alternative, or combination of alternative measures, to best satisfy the objectives of an Integrated Coastal Management Plan.

1.2 Study Formulation

In formulation of the Mamala Bay Study Plan, the Commission envisioned using mathematical models together with the results of field monitoring programs to assess the risks imposed on public health and the Mamala Bay ecosystem by point and non-point source contaminant discharges to the bay. A "near field" model would be used to represent the ocean hydrodynamic conditions in the immediate vicinity of the outfalls, a "far field" hydrodynamic model to represent the larger scale oceanic circulations in Mamala Bay that could potentially transport pollutants from both point and non-point sources to sensitive locations in the bay, and a water quality model to characterize the fate of indicator microorganisms, specific pathogenic organisms, or other polluting substances as they are

transported in the ocean environment. Estimates of contaminant concentrations obtained from the transport and fate analyses would be used to evaluate risks to human health associated with exposure to contaminants at concentrations estimated at various locations in Mamala Bay.

1.3 Development of Basic Data

Construction of the Mamala Bay models required development of basic information about the real systems being represented and the loadings imposed on them, in sufficient detail to calibrate the models and to provide the boundary conditions and loadings by point and non-point sources necessary for simulation of alternative pollution control options. Detailed descriptions of point and non-point sources of pollution were obtained by analysis of historical records and by field sampling programs conducted during the Study. The data included rates of flow, loadings of organic and toxic substances, and concentrations of indicator organisms and pathogens. Key inputs to the water quality model were concentrations of microbiological indicator and pathogenic organisms originating from point and non-point sources.

Because of the seasonal variability of atmospheric and oceanic conditions and the complexity of the Mamala Bay environment, the Commission determined that a field program of at least 1.5 years duration would be necessary to obtain the data on currents, tides, wind and water quality characteristics needed for calibration of the far-field hydrodynamic model and for definition of boundary conditions that would drive the model. Instrumentation used to obtain spatial and temporal descriptions of current and thermal structures during the study period included bottom-anchored Acoustic Doppler Current Profilers (ADCPs), taught wire vector current meters, thermistor strings, and pressure sensors at various depths and locations throughout Mamala Bay. Located along transects perpendicular to the shoreline, these instruments provided data needed to assess the performance of the outfalls' diffuser systems, i.e., the dilution and height of rise of the sewage plumes, using the near-field model. They also provided measurements of the three-dimensional current, salinity and density structures necessary to perform contaminant transport and fate simulations.

Other Study components contributing to data and information used by the models included field programs designed to detect and where possible, quantify concentrations and viability of microbiological contamination originating from point and non-point sources, a natural tracer study to measure the size and rise height of the effluent plume discharged at

the Sand Island outfall, and a dye-tracer study performed at the outlet of the Ala Wai Canal to Mamala Bay to examine the transport of discharges from the canal under dry and wet weather conditions.

1.4   Calibration of Models

Implementation of the systems approach using the models developed for Mamala Bay was a multi-step process. It required first that the models be calibrated against representative sets of field observations, that is, adjusted so that they reproduced to a reasonable (usually statistically specified) degree the key responses measured in the real system. In the case of Mamala Bay hydrodynamic adjustments were made in friction, diffusivity, viscosity, and heat flux coefficients and water quality adjustments were made in settling rates, light penetration coefficients, phototoxicity, decay and other calibration parameters until, under a known set of boundary forcing functions, the primary variables calculated by the models were in agreement with prototype observations. Once the models were calibrated they were operated with the same set of coefficients, but with a new set of forcing functions and pollutant loadings. Examples for Mamala Bay included new wind stress conditions, e.g., Kona vs. Trade wind, unique tidal oscillations, wastewater discharge and treatment alternatives, elimination of non-point source contributions, or any combinations of these. In the case of Mamala Bay the goal of calibration was to achieve agreement between the models and the real system using concentrations of microbiological organisms observed at locations in near-shore and offshore areas as indicators of risk to public health.

1.5   Application to Management Scenarios

The most important part of the systems analysis approach is the actual application of the model(s) to a selected set of scenarios of alternatives to find that which best satisfies the goals of Integrated Coastal Management. In the Mamala Bay Study definition and selection of alternatives was a team effort involving all principal investigators and commissioners.

Information on the present performance characteristics of the Sand Island and Honouliuli wastewater treatment plants and the efficacy of alternatives to upgrade performance of these plants were considered. Different alternatives for control of point and non-point source contaminant discharges to the bay and their effects on public health were evaluated.

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2 FINDINGS OF THE STUDY

The Mamala Bay Study is unique among water quality management projects. For the first time anywhere all aspects of point and non-point sources of pollution of coastal waters and the response of the marine environment have been integrated within a single coordinated investigation. It is unique also in the opportunity it has provided to utilize state-of-the-art ocean monitoring equipment, advanced mathematical modeling methods, and newly developed molecular microbiological techniques as tools to describe quantitatively the risks imposed on the public health and the aquatic environment of Mamala Bay. In addition to answering specific questions raised in the consent decree, the Study has provided new insights into potential for pollution of the bay and the most effective means of controlling risks within acceptable limits.

Detailed descriptions of the investigations that comprise the Mamala Bay Study are presented in the final Study report, a compilation of individual reports prepared by the principal investigators of twenty seven projects and special studies contracted by the Commission. The separate project reports address specific issues identified in the Study Plan or as developed during the course of the Study, although due to interaction between projects during the Study, as explicitly required by the ICM approach, there was a concerted effort to achieve a comprehensive and fully integrated result. The important findings of the Study are briefly summarized as follows.

2.1 Ocean Circulation

Ocean circulation in Mamala Bay is extremely complex, dominated by inhomogeneous tidal currents that cause large internal tidal fluctuations. Physically-based oceanographic processes that had significant effects on 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 wave, 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 semi-diurnal 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 on the shelf 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. General seasonal variations in mean flow patterns in the bay during the first year of the Study revealed a branching of onshore flow east of Sand Island, resulting in eastward mean flow along the shore towards Diamond Head.

Current measurements off the mouth of the Ala Wai Canal 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.

2.2 Outfall Plume Characteristics

At the Sand Island and Honouliuli outfalls oceanographic variability strongly influenced dilution and height of plume rise. Strong semi-diurnal tidal currents combined with low frequency drift to produce peak currents of about 50 centimeters per second at the

Sand Island outfall and 30 centimeters per second at the Honouliuli outfall. Principal current components were oriented approximately parallel to the local bathymetry and to the diffusers. Results of model simulations using oceanographic and outfall discharge data for the 10.5 month period from June 5, 1994 to April 18, 1995 showed a high degree of seasonal variation in plume surfacing and dilution.

Based on near-field model results, average dilutions over the year were predicted to be very high within the initial mixing regions at both outfalls, but showed significant variations with the season, depending on the degree of stratification of the water column. Dilution factors (the ratio of wastewater concentration at the discharge point to the concentration at the maximum height of plume rise) varied widely. 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 weaker stratification conditions resulted in higher frequencies of surfacing and higher initial dilutions than in summer months when the water column was stratified, due primarily to higher surface temperatures during the summer. Over the 10.5 month simulation period, the plume from the Sand Island outfall, discharged at an average depth of about 70 meters, 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, with an average rise height of 46 meters.

Results of analyses performed for the Honouliuli outfall and discharge plume also showed a high degree of seasonal variability, with the highest dilution and most frequent surfacing achieved during winter months. Compared to the frequency of surfacing at the Sand Island outfall, the plume discharged at the Honouliuli outfall surfaced less frequently, approximately 18.5 percent for the 10.5 month period, and achieved higher dilutions due to its lower flow rate per unit diffuser length. The average diffuser depth at the Honouliuli outfall is about 62 meters.

Some general conclusions concerning the performance of the Sand Island and Honouliuli outfalls may be derived from the results of the near field modeling project. 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

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surface, most likely in the winter months, both the Sand Island and Honouliuli plumes are highly dilute, on the average at dilution factors of 600 to 1000, or more. However, 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 destratification conditions when the plumes surface, but this is accompanied by increased dilutions.

2.3 Point and Non-point Sources

Approximately one third of the annual volume flow to 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 subembayments 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 monitored during the Study, 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.

Scenarios developed in Projects MB-10 and MB-11A defining alternative measures to enhance the quality of Mamala Bay waters were simulated with the three-dimensional hydrodynamic transport and fate models developed in Project MB-5 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 the major contributors of non-point source contamination along the shoreline. 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*.

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. Field observations were confirmed in simulations using the contaminant fate model developed in Project MB-5. Concentrations of *Salmonella* and *Cryptosporidium* at eastern beaches and in offshore waters could also be attributed in part to discharges from the Ala Wai Canal. Model simulations performed to compare the effects of elimination of discharges from three shoreline non-point sources, Keehi Lagoon, Pearl Harbor and the Ala Wai Canal, indicated that substantial improvements would result from elimination of the Ala Wai Canal as a source and that elimination of Keehi Lagoon and Pearl Harbor discharges would have a lesser effect within the bay.

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. 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 during the period studied.

Analysis of hydrodynamic model simulations showed 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.

Based on the results of 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 to 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, but 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 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.

2.4 Fates of Indicator Organisms and Pathogens

Standard methods of analysis and state-of-the-art molecular biological techniques were successfully applied in identification of indicator organisms and bacterial, viral, and protozoan pathogens 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 and near-shore waters. Contributions from these sources increased greatly during heavy rains. 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.

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*.

In comparing relative contributions of the outfalls and shore-based sources to the incidence of the three common indicator organisms, fecal coliforms, enterococci, and *Clostridium* on six different Mamala Bay beaches, model results indicated that fecal coliforms were most closely identified with the Sand Island WWTP, except at Oneula Beach near the Honouliuli outfall. Enterococci originated primarily from shore-based sources and *Clostridium* originated with both the Sand Island outfall and shore-based sources, the latter being of equal or greater significance at the eastern beaches.

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. coli, 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 locations including 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 near-shore areas within Mamala Bay was low; less than about 1 in 15,000 to 20,000 of these organisms found in the Sand Island discharges. Pathogens detected on Sand Island Beach close to the outfall were several orders of magnitude less than in primary sewage, possibly a consequence of dilution of the discharge from the Sand Island outfall. 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.

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Culturable *Staphylococcus aureus* was isolated from Waikiki Beach samples and other sites in Mamala Bay using a PCR technique used in Project MB-SP4. 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.

2.5   Risks to Public Health

Three unique approaches for assessment of risk to public health were applied in the Mamala Bay Study: (1) determining the frequency of threshold exceedance and probability distributions of indicator organisms and pathogens at specific locations, as a means for comparing relative effects of different point and non-point source treatment options; (2) considering the dose, exposure, and response characteristics for an individual susceptible to disease, for instance a swimmer exposed by actually ingesting contaminated sea water; and (3) applying empirical exposure-dose-response models to examine the risk to a population based on 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.

Simulation results produced by Project MB-5 for mean fecal coliforms at beaches and offshore locations for four treatment levels at Sand Island indicated 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. Under present conditions mean fecal coliform counts offshore from Waikiki Beach are about 9 times greater than at the beach. Among the four treatment levels considered, chemically enhanced primary treatment (CEPT) provided a reduction in mean fecal coliforms at Waikiki Beach of about 20 percent, while secondary treatment reduced counts by about 50 percent. Disinfection was considered to reduce counts in the outfall by 99.9+ percent. During the one-year simulation period 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

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milliliters was exceeded, only 20 percent were from outfall discharges, the remainder were from shoreline (non-point) sources. At Waikiki and Queens Surf beaches mean enterococci counts were generally below the standard 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. Outfall impacts on beaches and offshore waters are almost all related to Sand Island, except near the Honouliuli outfall and the nearby Oneula Beach. Honouliuli outfall had no appreciable influence on eastern beaches and their offshore waters. Non-point sources, especially the Ala Wai Canal, tended to dominate the higher counts of enterococci at eastern Mamala Bay beaches.

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.

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

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Honouliuli 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 population 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. The results 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.

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.

There is evidence in the results of modeling studies that offshore waters that are likely to be used for surfing and fishing activities are contaminated at levels of indicator organisms that occasionally exceed Hawaii's standards. Results showed that the fecal coliform standard of 200 colony forming units per 100 milliliters may often be violated near the outfalls during periods when the plumes are likely to surface (primarily during winter months) and that exceedance of the enterococci standard of 7 colony forming units per 100 milliliters may be even more frequent. Therefore, 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.

2.6 Effects on the Mamala Bay Ecosystem

Studies performed to evaluate the effects of pollution on phytoplankton communities, benthic invertebrates, fish, coral and reef systems, macro-benthic communities, and indicator species 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 WWTP into relatively shallow water offshore was found to have a greater impact on local water quality than either the Sand Island or Honouliuli 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 from either point or non-point sources was small. 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

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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.

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, affect bottom dwelling organisms. Recruitment of some benthic organisms is reduced in the vicinity of Pearl Harbor and near the mouth of the Ala Wai Canal.

2.7 Water Quality Management Alternatives

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. 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.

2.7.1 Point Source Control Alternatives

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 to enhance removal efficiency at the Sand Island WWTP using dissolved air flotation have had limited success. Moreover, neither plant has been able to provide an acceptable degree of

disinfection. Both have facilities for disinfection of the effluents 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.

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. 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., 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 higher 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 for Project MB-11A. 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 Honouliuli outfall.

Effects of the different wastewater treatment options on reductions in fecal coliform, enterococci and *Clostridium* levels were compared at different locations in Mamala Bay: at popular public bathing beaches, inshore of the outfalls, at selected sites offshore of beaches and at offshore locations near the outfalls. Treatment options evaluated with the models included CEPT and secondary treatment, each with and without disinfection at Sand Island and Honouliuli treatment plants. Also, a series of model 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. 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 Honouliuli 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 *Clostridium*, only minor reductions were obtained at western beaches as a result of disinfection at Honouliuli, with no effect observed in eastern bay locations.

2.7.2   Non-Point Source Control Alternatives

Non-point sources are the primary concern with respect to near-shore areas, specifically bathing beaches. 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.

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 Canal has been the subject of much investigation in the past because of its high level of contamination, both bacterial and of nutrients. Results of a field program conducted to evaluate the effects of discharge from the Ala Wai Canal on the water quality at nearby beaches indicated that during high runoff events alongshore currents toward Diamond Head convey runoff from the canal to Waikiki Beach.

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. Several alternatives have been suggested in Project MB-11A for potential improvement in the quality of Ala Wai Canal discharges. They include flushing, construction of a saltwater barrier, in-canal treatment, dredging and source control of discharges in the watershed.

Of the alternatives suggested, reduction in the sources of pollutants may be the one most likely to have long-term success for elimination of contaminants from the Ala Wai Canal. The framework for implementation of a comprehensive community-based plan which identifies possible problems and sources of pollutants, abatement methods and research needs, such as that presented in the **Ala Wai Watershed Management Plan**, developed in 1992 by the State of Hawaii, Department of Land and Natural Resources, should include involvement by local stakeholders, including government, local businesses, residents and non-profit organizations who would benefit from the improved conditions. 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.

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.

3 CONCLUSIONS

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 executive summary of the study report 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.

In conclusion, it is appropriate to identify some of the most significant findings of the Mamala Bay Study :

a) 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) 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) 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) 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.

4 RECOMMENDATIONS

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.