Internal Wave Measurements in Mamala Bay
Oahu, Hawaii

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Abstract. Oceanit Laboratories, Inc. (Oceanit) investigated the influence of internal waves and their impacts on the performance of the municipal wastewater outfall in Mamala Bay, Oahu. Disposal of municipal wastewater through deep ocean outfalls is environmentally acceptable if there is adequate density stratification to keep the wastewater plume from surfacing. Trapped below the surface, the wastewater plume disperses and moves out of the disposal area without adversely impacting surface or coastal waters. However, density stratification variability causes undesirable environmental and public health impacts from wastewater plumes that reach the surface and move to the shore under onshore current and wind conditions. Two major wastewater outfalls discharge close to 100 million gallons per day (mgd) of primary treated wastewater into Mamala Bay on Oahu, Hawaii, through outfalls at depths of around 200 feet. In order to investigate density stratification variability and the effect on the wastewater plume from internal waves, Oceanit conducted current and temperature profile measurements close to the Sand Island outfall in Mamala Bay. Horizontal and vertical components of currents, as well as temperature profiles, were measured at one-minute intervals for a period of 12 months. An acoustic Doppler current profiler (ADCP) and an Applied Microsystems thermistor string were used for the measurements. Conductivity, temperature, and depth (CTD) profiles were measured monthly to supplement data. Current and temperature data were analyzed to investigate high frequency variability of parameters that impact wastewater dilution and dispersion. High-passed data were analyzed to identify high frequency variability and possible internal wave influence. Results showed increasing high-frequency energy in both current and temperature signals with increasing depth. Results also indicated the presence of variance peaks that were related to the semidiurnal tidal period. High-energy peaks were observed in the water column at a period of approximately 40 minutes.

Introduction

Domestic and industrial wastewater from communities is typically collected and treated before disposal into receiving waters such as lakes, rivers or the ocean. All wastewaters, regardless of treatment received, contain substances that pose potential pollution threats to the environment and risk to public health. Wastewater outfalls are designed to operate in about 100 to 200 feet of water. The most important component is the diffuser, which is a few thousand feet in length and directs wastewater flow through a series of holes spaced along the sides of the outfall pipe.

When wastewater enters the marine environment from the diffuser, it is buoyant and tends to rise. This effluent, initially travelling horizontally after leaving the holes in the diffuser, gradually ascends on a vertical path. Throughout this path, the effluent mixes with the ambient seawater by entrainment. The highly concentrated wastewater becomes progressively more and more diluted with increasing distance from the outfall. This stage of mixing is called initial dilution, and it ceases when the mixed effluent stream reaches vertical equilibrium. In a homogeneous water column, the initial dilution phase ends when the plume reaches the water surface. In a stratified water column, the initial dilution phase ends when the plume reaches vertical equilibrium at some intermediate depth and levels out parallel to the surface.

Once the mixed effluent reaches the sea surface or an intermediate equilibrium depth, it tends to move with the prevailing currents. Further mixing and dilution from eddy diffusion continue at this stage while the plume moves with the ambient current field. The spread of effluent after initial dilution is known as secondary dispersion. The general path of an effluent plume emerging from a diffuser into stratified water is shown in Figure 1.

The Sand Island wastewater outfall discharges an average of 75 million gallons per day (4.47 m³/s) of primary
treated wastewater into Mamala Bay. Wastewater treatment at the Sand Island plant consists of aeration, flotation and primary sedimentation. At present, no disinfection of wastewater occurs at the treatment plant. The effluent from primary sedimentation tanks is discharged into the ocean through an outfall diffuser located about 2 miles offshore in 230 feet of water. The location of the plant and outfall are shown in Figure 2.

![Figure 1](image1.png)

**Figure 1.** Schematic depiction of wastewater behavior in coastal waters.

**Figure 2.** Location of plant and outfall.

The diffuser is 3,400 feet in length and has 282 pairs of discharge ports 3.54 inches in diameter and oriented in a horizontal direction. The average specific gravity of effluent is 0.99 and that of receiving water is 1.0235.

**Governing Equations**

In calculating the path and dilution of the wastewater plume during initial dilution, a three-dimensional model that can handle multiple port diffusers was developed by the Environmental Protection Agency based on Hirst (1971a,b), Davis (1975) and Kannberg and Davis (1976). It considers variable profiles through the zone of flow establishment (immediately after jet phase) and through the merging zone of multiple plumes. The changing geometric form of merging multiple plumes is achieved by using an equivalent two-dimensional slot plume geometry rather than a series of individual round plumes.

All quantities are assumed uniformly distributed in the plume at the point of discharge. In the zone of flow establishment, these uniform profiles change to similar profiles as the boundary layer diffuses inward to the centerline of the jet. The rate at which the profiles of velocity, concentration, and temperature develop may vary.

The model is based on the following definitions:

Conservation of mass:

\[
\frac{d}{ds} \int V r \, dr = E
\]

Conservation of energy:

\[
\frac{d}{ds} \int V (T - T_\infty) r \, dr = \frac{dT_\infty - T}{ds} \int V r \, dr
\]

Conservation of pollutant:

\[
\frac{d}{ds} \int V (C - C_\infty) r \, dr = \frac{dC_\infty - C}{ds} \int V r \, dr
\]

Conservation of momentum:

\[
\frac{d}{ds} \int V^2 r \, dr = UE \sin \theta_1 \cos \theta_2 + \frac{g}{\rho_d} (\rho_\infty - \rho) \sin \theta_1 \cos \theta_2 \sin r \, dr\theta_2
\]

where

- \(g\) is the acceleration due to gravity
- \(V\) is the velocity of the jet
- \(r\) is the distance from center
- \(E\) is the entrainment
- \(T\) is the temperature
- \(C\) is the concentration
- \(S\) is the displacement
- \(\rho\) is the density
- \(U\) is the ambient velocity
- \(\theta_1\) is the horizontal angle between the plume centerline and the x axis and
- \(\theta_2\) is the vertical angle between the plume centerline and the horizontal.

The natural coordinates of the plume are converted to Cartesian coordinates by assuming...
1. Mean flow is steady.
2. The fluid is incompressible and density is included only in the buoyant terms.
3. All other fluid properties are constant.
4. There is no frictional heating.
5. Pressure variations are purely hydrostatic.
6. Ambient turbulence effects are included in the entrainment function only.
7. Flow within the jets before merging is axisymmetric and is a free boundary layer flow type.

**Figure 3.** Location of instrument moorings relative to outfall.

The model used in this study was developed by the Environmental Protection Agency to calculate dilution and plume trapping depth for different environmental conditions. Results indicated that the probability of any event occurring depended on the sampling interval used for stratification measurements. In the past, only seasonal stratification measurements were taken. However, preliminary field data showed that density stratification occurs at a much higher frequency than earlier assumed. These high-frequency variations are induced by tides and are more energetic close to the bottom in Mamala Bay, indicating some relationship of internal waves with topography.

An experiment was designed to measure the current and temperature profiles close to the outfall diffuser to study the effect of sampling interval on calculated plume surfacing probability. An acoustic Doppler current profiler and a thermistor string were deployed at 200 feet depth to measure current and temperature profiles at one-minute intervals. Subsurface buoys moored at a 50-foot depth supported the instrument strings. The velocity and temperature profiles extended from a 50-foot depth to the bottom.

High-frequency data acquisition created large amounts of data that easily exceeded memory and battery capacity, thereby requiring frequent in-field servicing. A cable was attached to the data loggers to enable monthly data downloading. Divers dove to the data logger and retrieved the free end of the data cable for downloading to a portable computer aboard a small boat. Batteries were replaced at three-month intervals by removing the ADCP profiler from the mooring. The thermistor string provided limited data because of flooding. ADCP current profile data were collected for 18 months.

The location of the instrument moorings relative to the outfall is shown in Figure 3. The configurations of the two instrument strings are shown in Figures 4 and 5. Samples of temperature and velocity data are shown in Figure 6.

**Data Analysis**

Data collected during this effort were used as input into the initial dilution model described earlier. Results of modeling were used to investigate the dependence of the plume surfacing probability on the frequency of data sampling. The model was run at one-minute intervals;
results on dilution, plume dimensions, and plume trapping depth were stored for later analysis.

Each parameter (dilution and plume trapping depth) was sampled from the result file at different frequencies to simulate different data sampling frequencies. Results were evaluated to determine the optimum data sampling frequency for an outfall design. An economic analysis was also made to evaluate cost benefit relations for each combination.

The optimum frequency for measuring receiving water data was found by weighting the cost of data collection with the accuracy of the predictions. Initially, seasonal or monthly stratification was used to determine design parameters for outfalls. In the present analysis, the optimum frequency for environmental data collection was found to be between 15 and 20 minutes.

In order to investigate underlying variations in receiving water parameters that contribute to relatively rapid changes in plume behavior, the data collected were further analyzed using conventional methods. The data set was divided into one-hour sub-samples and the variance of each segment was calculated. Results were plotted as an hourly variance time series as shown in Figure 7 for the month of September 1997.

Figure 6. Samples of temperature and velocity data.
Data were high-passed with a Fourier filter with a cutoff at 60 minutes to filter out low frequency variations that dominated the raw data. A cosine taper was used at the cutoff to reduce data contamination. High-passed temperature data showed a weak periodicity at about 40 minutes. The signal was enhanced by demodulating data at this period. The original high-passed and demodulated, high passed data are shown in Figure 8.

Spectral density of high-passed data at different depths was calculated using a data segment length of 256 minutes. The spectral density distribution of high frequency temperature and velocity data for September 1997 are shown in Figure 9.

**Figure 7.** Depth averaged hourly temperature variance for September 1997.

**Figure 8.** Typical temperature series of raw data, high-passed data, and demodulated high-pass data for temperature at 110 ft depth.

**Figure 9.** Spectral density of high-frequency temperature and velocity data.

**References**


