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# Comparison of near-field dilutions derived from in situ measurements and simulated dilutions at the Sand Island sewage outfall plume, HI.

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## Abstract

Near-field dilutions of the Sand Island Treatment Plant (SITP) wastewater plume were derived from salinity measurements made at the sewage outfall between Sept. 25 - Oct. 1, 1994, a period of unusual stratification of the water column. Temperature stratification and weak currents kept the plume deeply submerged. Of several methods considered for calculating dilution from in situ measurements, dilution calculated from salinity using linear interpolation of the background salinity depth profile through the plume depths was preferred. The results derived from in situ measurements were compared with dilutions simulated using the Roberts, Snyder, and Baumgartner (RSB) model. Despite the complexity of the environment, including high temporal and spatial variability of currents and temperature, the results of the model are of the same order as the values derived from in situ data.

## Introduction

The Sand Island, Honolulu, HI, outfall was designed to maintain submergence of the effluent plume most of the time. At the outfall site, it has been reported that typically the winter stratification is weak and the surface mixed layer deep. Therefore, to meet the submergence goal, the sewage diffuser was located at a depth of 69-71m, about 4km offshore. With this design, dilutions of approximately 1:100 were expected during summer periods with strong stratification, and 1:300 - 1:1000 during winter periods with weak stratification (Fischer et al, 1979).

## Materials and methods

The Sand Island Wastewater Treatment Plant is a primary treatment plant processing an average of $284 * 10^6$ liters per day. In situ measurements were obtained between Sept. 25 and Oct. 1, 1994 from an instrumented platform including conductivity, temperature and depth sensors (CTD, Sea-Bird Electronics model SBE 9/11+), and a beam transmissometer (660 nm wavelength, 0.25 m pathlength, Sea Tech, Inc.).

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Sampling was performed using towyos and vertical profiles. Towyo casts and vertical profiles collected at the center (Cast 1) or over the western end of the outfall (Casts 2-11), where the highest effluent concentrations were found, were selected for the present study. Detailed information on the towyos and stations can be found elsewhere (Jones et al., 1995).

## Dilution calculation methods

Dilution is calculated using effluent discharge volume, Ve, salinity, Se, ambient water volume, Va, and salinity, Sa. Dilution, D, is defined as:

$$D = (Ve + Va)/ Ve^{*} \qquad (1)$$

Dilution is often symbolized by S rather than D; but for clarity, in the following equations D is used for dilution and S for salinity. The conservative tracer, salinity, follows the equation of conservation of flux:

$$Ve * Se + Va * Sa = (Ve + Va) * Sm \qquad (2)$$

where Sm is the measured salinity of the mixed (effluent and ambient) waters of volume (Ve + Va). In principle, $Se < Sm < Sa$. The dilution can then be written as:

$$D = (Sa - Se) / (Sa - Sm) \qquad (3)$$

In the present analysis, the salinity of the effluent, Se, is assumed to be zero. To provide an estimate of the possible magnitude of error associated with this assumption, it can be noted that setting Se=2 practical salinity units (psu) leads to a 6.2 % decrease in the values obtained for the near-field dilution calculations. This potential source of error is negligible compared to the errors associated with the calculation of Sa, as detailed below.

Three approaches for estimating dilution (Dme, for measured dilution) from salinity and temperature are described below and the results of each method are compared in Fig. 1b. In the first method (method 1), Sa is treated as a constant, with the particular value of Sa chosen as the salinity at the diffuser depth (69.8 m) at a site not affected by (i.e. distant from) the diffuser (Fig. 1a). Dme calculated in this manner can be interpreted as the initial dilution, assuming that effluent wastewater mixed with entrained water at 69.8 m and rose without additional mixing to the equilibrium depth where dilution is calculated. Alternative methods utilize depth-varying values of Sa, Sa(z). In method 2, Sa(z) is calculated by choosing two depths, one above and one below the plume, and linearly interpolating the salinity between these two depths across the vertical region affected by the effluent plume. In method 3, Sa(z) is calculated as a function of the measured temperature (Washburn et al., 1992) via linear interpolation of the temperature-salinity (T-S) plot through the plume depths (Fig. 1c). This method assumes that the effect of the effluent on T is minimal and does not significantly affect Sa.

Within the plume core, the dilutions calculated with methods 1 and 3 are similar (Fig. 1b). Method 1 is bound to underestimate Dme since it assumes zero mixing between the diffuser depth and the equilibrium depth of the plume, a clearly unrealistic assumption. It leads to results 20% lower than those found using method 2. Dme

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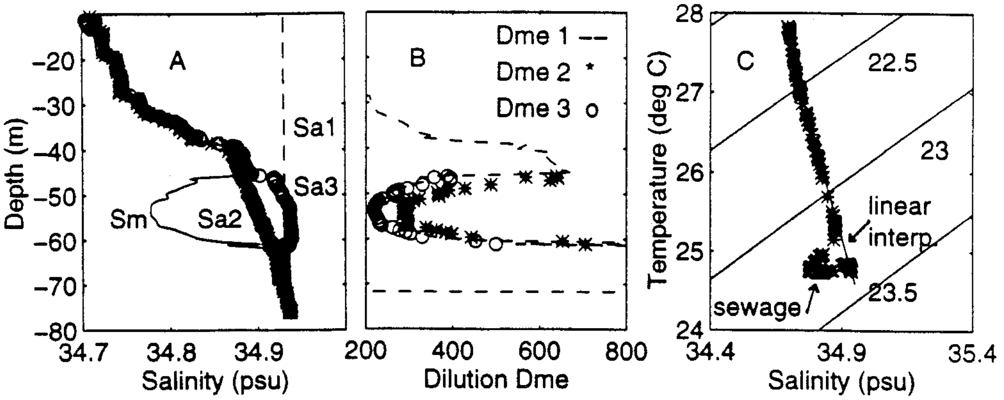
[*] Depth-dependence has been omitted from the notation but is inherent in all terms of equations (1)-(3).



Figures 1 - Cast 6 a) Measured salinity, Sm, salinities Sa used in method i, Sai, b) Dme from method i, Dme i c) T-S diagram with lines of constant density indicated by the solid diagonal lines.

calculated with method 3 are ~28 % lower than those obtained with method 2 because the temperature decrease associated with the plume is ignored. Neglecting this temperature decrease leads to an overestimation of the derived salinity Sa(z), since the T-S curve decreases monotonically (Fig. 1c). Method 2 assumes linearity of the salinity curve between two depths. Other salinity profiles collected during the cruise (Jones et al., 1995) indicated that method 2 did not lead to a systematic bias, so this method was chosen for the field validation of the RSB model dilutions (Dmo). Although method 2 is free of an inherent negative bias, results obtained using this method depend on the subjective choice of the two end points, below and above the plume. The choice of endpoints was guided by comparisons with ambient salinity profiles at sites distant from the plume.

The Mamala Bay study included a near-field plume modeling component based on the RSB model (Roberts, 1994b). The RSB model uses time series of velocity direction and amplitude (10m above the sewage diffuser depth), temperature stratification, and discharge flow rates to predict the initial mixing length (IML). IML is the distance from the diffuser at which the wastewater plume is said to be established and at which mixing starts to be dominated by the ambient turbulence; IML corresponds to the downstream end of the "near-field" or "initial mixing region". The model also calculates height of rise and minimum dilution, Dmo, of the plume at the IML (Baumgartner et al, 1994).

## Results

The plume was detected by decreased salinity and increased beam attenuation at 660 nm. The cruise period coincided with the longest period of stratification found between June and October 1994 (Jones et al., 1995). The water column usually destratifies at a particular phase of each tidal cycle (Hamilton et al., 1995). With the unusually persistent stratification present during the study period, the effluent plume from the SITP remained deep (below 40 m) and initial dilutions were generally low at the measurement casts (Fig. 2).

The rapid variations in the RSB model inputs (velocity and temperature above the sewage diffusers) at the Sand Island site were reflected in similar variability of the RSB outputs (simulated height of rise and dilution) on small temporal scales (Fig. 2 and Roberts, 1994b). Table 1 presents the data corresponding to the cast dilutions and simultaneous model results. On average, Dmo exceeded Dme by 85% (1st quartile: +0.8%; 3rd quartile +120%).

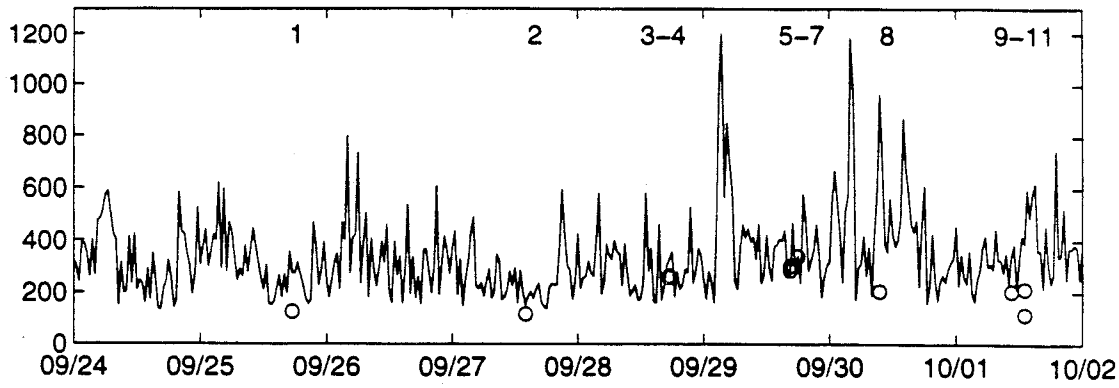


Figure 2. Near-field Dmo (solid line), and Dme (open circles - cast number indicated along the upper axis).

The low Froude numbers ($Fr=u^3/b$, with velocity amplitude, u, and source flux of buoyancy per unit diffuser length, b) obtained during most of the casts also contributed to the low dilutions (Table 1). The biggest difference between Dme and Dmo is found for cast 8, the only cast with high Fr. Here the high Dmo is not mirrored by a similarly large Dme. If the values for cast 8 are excluded, the mean difference between Dmo and Dme drops to 58%.

| Cast | Zme | Zmo | Fr | Dme | Dmo |
|---|---|---|---|---|---|
| 1 | -60.0 | -53.1 | 0.94 | 125 | 275 |
| 2 | -65.5 | -56.7 | 0.00 | 116 | 150 |
| 3 | -44.5 | -56.5 | 1.89 | 264 | 332 |
| 4 | -55.0 | -56.5 | 1.89 | 259 | 332 |
| 5 | -56.0 | -50.0 | 0.11 | 303 | 269 |
| 6 | -53.0 | -50.0 | 0.11 | 286 | 269 |
| 7 | -59.0 | -50.8 | 1.01 | 339 | 342 |
| 8 | -68.0 | -41.7 | 6.01 | 205 | 964 |
| 9 | -54.0 | -55.3 | 2.66 | 205 | 342 |
| 10 | -60.0 | -49.8 | 3.52 | 115 | 392 |
| 11 | -57.5 | -49.8 | 3.52 | 214 | 392 |
| All | -57.5 | -51.8 | 1.97 | 221 | 369 |

Table 1 - Measured (Zme) and modeled (Zmo) depths (in meters) of the minimum dilution, Froude number, Dme and Dmo.

## Conclusions and Recommendations

Calculation of Dme from measured salinity using linear interpolation of the background salinity depth profile (method 2) is recommended since it does not have obvious inherent bias. An appropriate choice of endpoints for the interpolation can be guided by examination of ambient salinity profiles not affected by (i.e. distant from) the plume. Dme derived from method 2 are in the range of 1:115-1:339, higher (lower) than the dilutions estimated at the design stage of the diffuser for summer (winter) conditions (Fisher, 1979). These Dme reflect stronger currents and weaker stratification than those associated with a dilution of 1:100. Indeed strong stratification never occured for longer than a portion of the tidal cycle and, during the cruise, these short events did not coincide with weak currents nor with the measurement casts (Jones et al., 1995).

Observations and near-field model dilutions are in best agreement for periods with a stratified water column and weak currents (low Froude number). For stronger currents (e.g., cast 8) the RSB model predicts greater dilution than that calculated from salinity. Since the IML output by the model increases with stronger currents, it is possible that under strong current conditions the in situ measurements were taken closer to the diffuser than the IML distance. Under strong current conditions, in situ measurements taken at the IML might yield better correspondence between Dme and Dmo. Unfortunately, assessment of the relationship between the position of the measurement casts and the model output IML for all current conditions is not possible, due to uncertainties in the cast-diffuser distance, and the variability of the IML. On average, the RSB model Dmo exceeded Dme by 85%. Closer correspondences have been obtained for added tracer studies, which allow a more direct calculation of dilution than can be achieved using conservative ambient tracers such as salinity, at the Malabar outfall, New South Wales, Australia and at the San Francisco outfall, CA (Roberts, 1994a). In the latter case, RSB Dmo were 12-20% greater than Dme.

Plume behaviors are extremely complex in environments in which stratification is variable and current amplitudes and directions change arbitrarily both with depth (shear) and time. Representation of the complexity of these environments is beyond the capacity of available models. In the present study, the RSB results capture the gross characteristics of the observed wastefield. Whether the discrepancies found between Dme and Dmo in this study resulted from limitations in the model, inaccuracies in the model inputs, or uncertainties in Dme cannot be concluded, although studies to investigate model sensitivity to particular inputs may yield additional insights.

Further field validation of the plume model should be undertaken during periods with no temperature stratification in order to test, first, if the plume is detectable under well-mixed conditions (use of added tracer would probably be necessary), and second, whether agreement between dilutions derived from in situ data and RSB model outputs is maintained. Validation of the RSB model or its potential modification will allow more effective diffuser design in the future, as well as the extension of predictibility of plume behavior to a variety of conditions for which in situ data are not available.

## Acknowledgments

This study was funded by the Mamala Bay Commission of the Hawaii Community Foundation. We are grateful for their support and permission to publish this paper. We thank D.W. Adelson for helpful suggestions regarding the manuscript.

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