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OCEANIC WASTEWATER OUTFALL PLUME CHARACTERISTICS MEASURED ACOUSTICALLY

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A study, called SEFLOE, of the dispersion characteristics of several wastewater outfalls was conducted off of the coast of Southeast Florida (USA). In this study, the feasibility of utilizing high frequency (20 kHz and 200 kHz) acoustic echoes to characterize the dilution characteristics of the effluent wastewater was examined. It is hypothesized that the background corrected acoustic backscattered intensity may be used to guide chemical/biological sampling, and that one or more plume subfields may be revealed by the scattering strength field. Data from SEAFLOE have indicated that the wastewater plume field is divided into regions of higher concentration spatially separated by regions of lower concentration; we call these regions of higher concentration "boluses". When the water column is density stratified, subsurface plumes may peel off of the main rising plume and remain at equilibrium on a density gradient.

KEY WORDS Acoustics, Wastewater, Outfall

INTRODUCTION

A substantial amount of human wastes is discharged, after various degrees of treatment, into the coastal ocean via ocean wastewater outfalls. In order to mitigate potential negative environmental effects, governments attempt to regulate those activities which are identified as being potentially harmful to the environment. If the purpose of these regulations is to protect the environment and to provide a framework upon which to build a healthy, environmentally and economically balanced society, the rationale behind the regulations must be based on an accurate and objective assessment of the effects of the activities in question (Duedall *et al.*, 1983).

One area of increasing concern to environmental agencies is the regulation of waste disposal in the coastal and offshore environment. The most common method of liquid waste disposal in this environment is through the use of outfalls, the designs of which may vary from a pipe discharging raw wastes into an open ditch to sophisticated systems of multi-port diffusers discharging highly treated wastes into the ocean miles offshore.

In attempting to assess the effect of an outfall on the environment, two important questions that come to mind are: where does the effluent go, and what happens to it? One might think the answer to these questions would be rather simple to establish. In the case of a large output into a small enclosed or semi-enclosed body of water, these answers are fairly straightforward to establish through relatively simple hydraulic models and environmental sampling. However, when dealing with a large open body of water, the fate of an effluent discharged into that body becomes much more dependent upon the dynamics and structure present in the receiving water mass, and the problem of predicting effluent dispersion by fluid dynamical models becomes much more difficult (Fischer *et al.*, 1979; Roberts *et al.*, 1990). The problem of environmental sampling is complicated by the great number of samples one would need to take in a highly structured environment in order to obtain statistically meaningful data.

This paper discusses the use of acoustic backscatter measurement as a tool to obtain a statistically valid data set which describes the fate of buoyant wastewater plumes in the offshore environment, and presents data from several experiments conducted in the vicinity of several wastewater outfalls in south Florida waters.

THEORETICAL BACKGROUND

Sound waves propagating through sea water are refracted, reflected and/or scattered by discontinuities in the density and compressibility of the medium. These discontinuities can be in the form of gradients in the acoustic properties of the fluid medium, or as suspended solid particulates or gas bubbles. Regardless of the nature of the discontinuity, if the net effect of it's presence is to cause a gradient in the acoustic impedance, defined as the product of density and speed of sound, then there will be refraction, reflection, and/or scattering (Clay and Medwin, 1977; Urick, 1967).

The use of high frequency acoustics in studying dispersion of wastes in the ocean has been practiced for over a decade (Proni *et al.*, 1976). Tsai (1984) documented work done over a period of about five years utilizing acoustics in the study of pharmaceutical wastes, sewage sludge, and drilling fluid discharges. In these studies, plumes of various materials were detected over a wide range of concentrations and sediment loads. Measurable echoes have been detected from waters containing less than 0.2 mg/l of suspended sediment at distances on the order of 100 m from the sound transducer. The limiting factor on the ability of the acoustical methodology to detect wastewater outfall particulate material is the level of background material existing in the receiving coastal ocean waters. An initial total suspended load on the order of 30 mg/l was anticipated for the wastewater effluent. Detection of material after a thousand to one dilution, i.e. 0.03 mg/l, was expected to pose no difficulty at the source to scatterer ranges expected for the frequencies of the acoustical systems utilized.

The principal quantity measured by the acoustic system is the intensity of sound scattered as a function of time, $I(t)$. Given a fixed source level, and absorption coefficient, the variation in received intensity from a given range cell is a function primarily of the scattering coefficient (R) at that range where;

$$R = I_s/I_i$$

where I_s and I_i are the scattered intensity and the incident intensity respectively both referenced to a distance of 1 metre from the center of the scattering volume.

The scattering strength is defined by the expression;

$$S = 10\log_{10}(R)$$

For a scattering volume with a distribution N_i of scatterers, the volume backscattering strength (S_v) can be expressed by the equation;

$$S_v = 10 \log_{10}\left(\sum_i N_i \sigma_i\right)$$

where σ_i is the backscattering cross section of a single particle of size class i.

If we define a concentration ratio δ such that;

$$\delta(r, \theta, \phi) = C(r, \theta, \phi)/C_0$$

where $C(r, \theta, \phi)$ is the particulate concentration in an elemental volume centred at location (r, θ, ϕ), and C_0 is the particulate concentration of whole effluent, then for the insonified volume V, the mean concentration ratio is given by;

$$\bar{\delta} = 1/V \iiint_v \delta \, dv$$

Since secondary treated wastewater undergoes a process of settling before discharge into the ocean, those remaining particles present in the effluent will have long settling times. An issue of importance not only for interpretation of acoustical data, but also for plume dynamics, chemical data analysis and biological data analysis, is floc formation. It has been suggested that particles in the effluent flocculate and form particles whose size distribution shifts to a much larger size range than that of the particles initially issuing with the effluent. These flocs would have a different density, compressibility and settling velocity from those particles initially issuing with the effluent. The issues of floc formation, rates of floc formation and the relationship of turbulent mixing (e.g. entrainment) processes to floc formation are complex. The rate of change in space and time of the particle distribution is of importance in interpreting acoustical data. For example, is the principal change which occurs a shift from a relatively narrow unimodal initial particle size distribution to a broad quasi-bimodal distribution and is there a preferred spatial location for this change to occur? In particular, is the change which occurs likely to coincide with spatial regions in the plume where incursions into the plume structure, due to turbulent entrainment by ambient water, are occurring? Clearly, further research into particle size distribution changes is required. One potential implication for acoustical systems is that multiple-frequency systems may be required for particle size distribution information in addition to amplitude information at one frequency only. For the purposes of this paper in which the emphasis is on the introduction of acoustical methodology to wastewater outfall studies, the complex and important issue of floc formation will not be addressed. It is, therefore, assumed in the equations to follow that the normalized distribution function does not vary greatly during the dilution process. This allows us (i.e. by neglecting flocculation) to define the particulate distribution in the scattering volume by:

$$N_i = \bar{\delta} n_i$$

where n_i is the number of particles of class i which would be present in the scattering volume if it were occupied exclusively by whole effluent.

The backscattering strength can then be expressed in the following manner:

$$S_v = 10 \log_{10} \left(\bar{\delta} \sum_i n_i \sigma_i \right)$$

or

$$S_v = 10 \log_{10} \left(\sum_i n_i \sigma_i \right) + 10 \log_{10} (\bar{\delta}).$$

Since the mean concentration in the scattering volume is given by

$$\bar{C} = \bar{\delta} C_0,$$

the equation for volume backscattering strength can be written as;

$$S_v = 10 \log_{10} \left(\sum_i n_i \sigma_i \right) + 10 \log_{10} (C) - 10 \log_{10} (C_0),$$

thus, for a given type of particulate cloud, scattering strength is a function of the mean concentration within the scattering volume.

It can easily be shown then that the concentration ratio between two scattering volumes (δ_{12}) is given by:

$$\delta_{12} = C_1/C_2 = \log_{10}^{-1} [(S_1 - S_2)/10].$$

The wastewater plume and the receiving water mass can both be described as fields consisting of a series of subfields in space and time such that;

$$F(r, \theta, z, t) = F(f_1, f_2, \ldots, f_n)$$

and

$$W(r, \theta, z, t) = W(w_1, w_2, \ldots, w_n)$$

where W represents the receiving water mass field, and F represents the waste-water plume field. The subfields f_i, and w_i are parameters such as salinity, density, temperature, suspended particulate load, etc.

When measurements are taken of these fields, a new field is introduced which we will call an estimator field E such that;

$$E(r, \theta, z, t) = E(e_1, e_2, \ldots, e_n).$$

This field consists of those parameters which are measured and used to describe the character of the total field T where;

$$T(r, \theta, z, t) = F(r, \theta, z, t) + W(r, \theta, z, t).$$

These estimator parameters are not necessarily the parameters describing the total field itself, but can also consist of measured parameters whose relationship to field parameters is known. Some examples of estimator parameters are dye concentration, conductivity, temperature, pH, and acoustic volume backscattering strength.

The estimator field of primary interest here is the volume backscattered intensity I_v. For the purposes of analysis in this paper, it is assumed that the total volume backscattered intensity I_t is the superposition of the intensities of sound backscattered from the receiving watermass I_b and the injected wastewater I_p such that;

$$I_t = I_b + I_p$$

A more complex relationship which takes into account interactions between the injected wastewater and the receiving water mass will be left for future analysis. The total volume backscatter coefficient is given by;

$$R_t = I_t/I_i = (I_b + I_p)/I_i.$$

The backscattering coefficient of the injected wastewater is thus given by;

$$R_p = (I_t - I_b)/I_i,$$

which gives scattering strength as;

$$S_p = 10 \log (R_p).$$

EXPERIMENTAL RESULTS

Beginning in October of 1987, a series of experiments were conducted at several south Florida wastewater (see Figure 1) outfalls to study the dispersion, mixing, and diluting characteristics of the wastewater plumes. Data from two of these

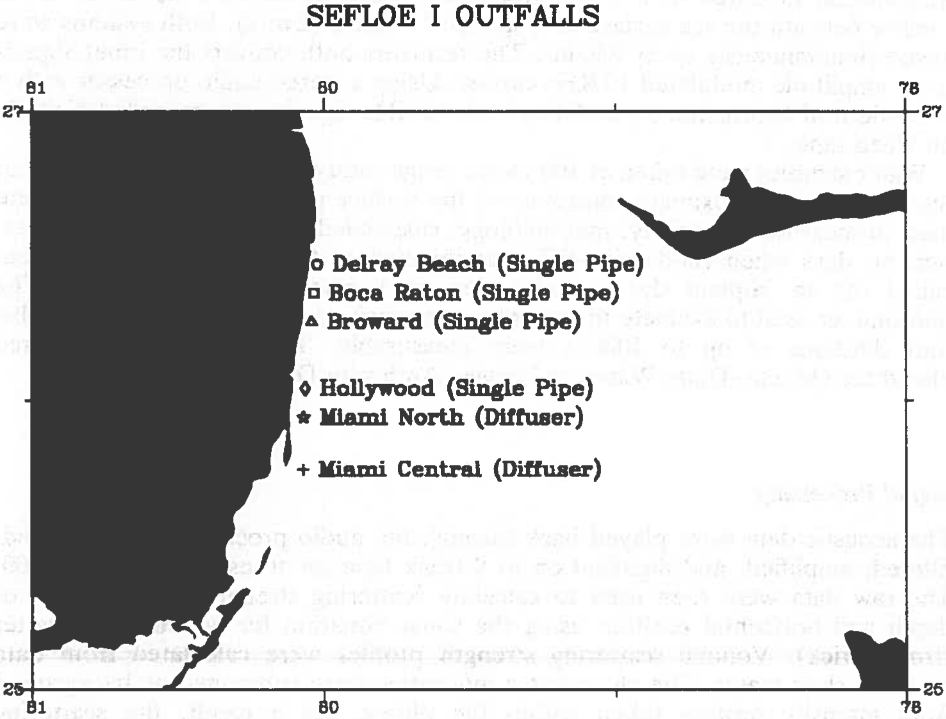

Figure 1 Locations of outfalls studied in SEFLOE.

outfalls, the Miami-Dade North District outfall, and the Miami-Dade Central District outfall, are presented in this paper. These two outfalls are both multi-port outfalls located in approximately 100 feet of water and discharging at rates of between 60 and 110 million gallons per day (mgd) with average daily flow rates of about 75 mgd. The North District outfall discharges through 10 diffuser stacks located 40 feet apart each with two horizontally-oriented, 24-inch diameter opposing circular ports. The Central district outfall has five vertically-oriented, 48-inch diameter circular ports spaced 32 feet apart. Acoustic backscatter measurements were used to define the spatial characteristics of the wastewater concentration field. To our knowledge, this is the first time that acoustic backscatter has been used to measure dilution of a wastewater plume. The project was designated by the name South East Florida Outfall Experiment (SEFLOE).

EXPERIMENTAL DESIGN

Plume dispersion was measured in the SEFLOE project by measuring acoustic scattering strength as a function of depth and horizontal range over various cross sections of the water column around and over the outfall. Two monostatic echo sounding systems which typically operate at 200 KHz and 20 KHz were used. The transducers, mounted in a single tow body, were towed at a depth of about 1 metre beneath the sea surface at a speed of 4 knots (2 m/s). Both systems were keyed simultaneously every 240 ms. The receivers both convert the input signals to an amplitude modulated 10 KHz carrier. Using a stereo audio processor with a bandwidth of approximately 20 KHz, both 10 KHz signals were recorded digitally on video tape.

Water samples were taken at 100 metre range intervals from the surface boil at the edges and approximate centreline of the surface plume. These samples were used to measure biotoxicity, microbiology, suspended solids, and dye concentration on days when rhodamine-WT was injected at the plant. The experiment called for an in-plant dye concentration of 1 part per million (ppm). The fluorometer used to evaluate the samples was sensitive to 1 part per billion (ppb), thus dilutions of up to 1000:1 were measurable. These data are discussed elsewhere (Miami–Dade Water and Sewer Authority Department, 1989).

Signal Processing

The acoustic data were played back through the audio processor, demodulated, filtered, amplified, and digitized on to 9 track tape for transfer to a VAX 8700. The raw data were then used to calculate scattering strength as a function of depth and horizontal position using the sonar equation for volume backscatter (from Urick). Volume scattering strength profiles were calculated from data taken in clear water. The clear water intensities were subtracted as background from intensity profiles taken within the plume. As a result, the scattering strengths used for analysis represent only scattering above background levels.

Data Analysis

Contour plots of S_v show the spatial distribution of the wastewater field along the ship's track (Figures 2 and 3). The apparent rapidity with which the plume rises to the surface is clearly evident. The effluent wastewater exits the pipe horizontally in the case shown in Figure 2, thus this rapid rise can be attributed to buoyant effects and not to residual momentum of the wastewater. Since the vertical transport of plume material is driven by density, effluent which reaches an equilibrium density before surfacing may be trapped beneath the surface and will disperse through passive diffusion. Evidence of this trapping is seen in Figure 3 at a depth of about 12 meters, this depth coinciding with the bottom of the mixed layer as shown by the density profile in Figure 4.

The contour plots show that the plume appears to be made up of localized patches of scattering, these patches or "boluses" were observed at every outfall. The patchiness is accompanied by a general reduction of the peak scattering strength within the boluses as range increases; this is seen more clearly in Figure 5 where the peak value of each vertical scattering strength profile (for the data shown in Figure 3) has been plotted as a function of range. The centres of maximum concentration within the boluses decay as the effluent moves away from the outfall.

The spatial inhomogeneity of the plume introduces serious problems when trying to assess dilution rates from even the most carefully selected point samples taken within the boundaries of the plume. Since the peak concentrations are spatially dispersed, the probability of sampling a peak becomes quite small using point sampling techniques, as a result, peak concentrations may be underestimated. An added consideration is the spatial intermittency of the concentration field. The spatial intermittency can be defined as the ratio obtained by dividing the volume of water in the plume at or below background concentration by the total volume of the plume. If intermittency is not taken into account, the mean concentration at a given range can be underestimated as well by conventional methods.

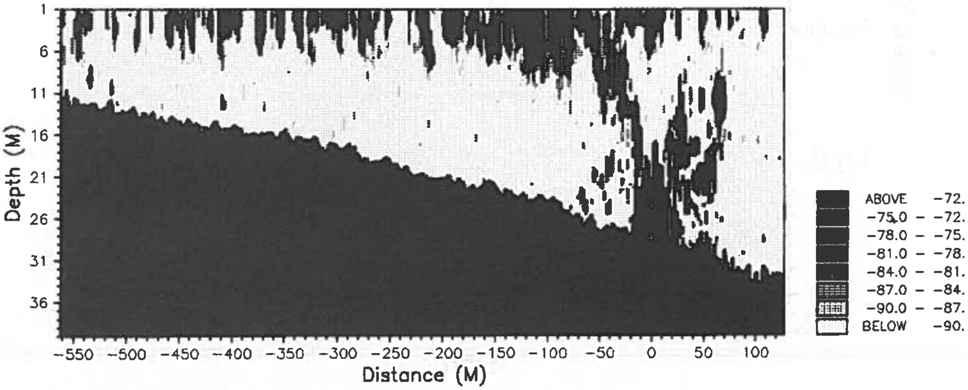

Figure 2 Contour plot of acoustic scattering strength as a function of depth and distance from outfall for Miami–Dade North District outfall (units are in decibels).

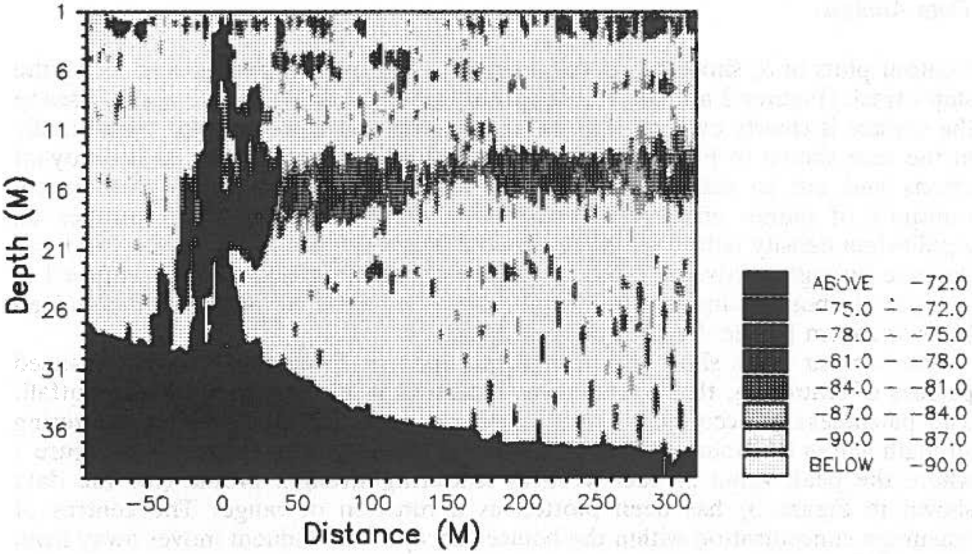

Figure 3 Contour plot of acoustic scattering strength as a function of depth and distance from outfall for Miami-Dade Central District outfall. Negative distance indicates ship movement was in the direction of the outfall (units are in decibels).

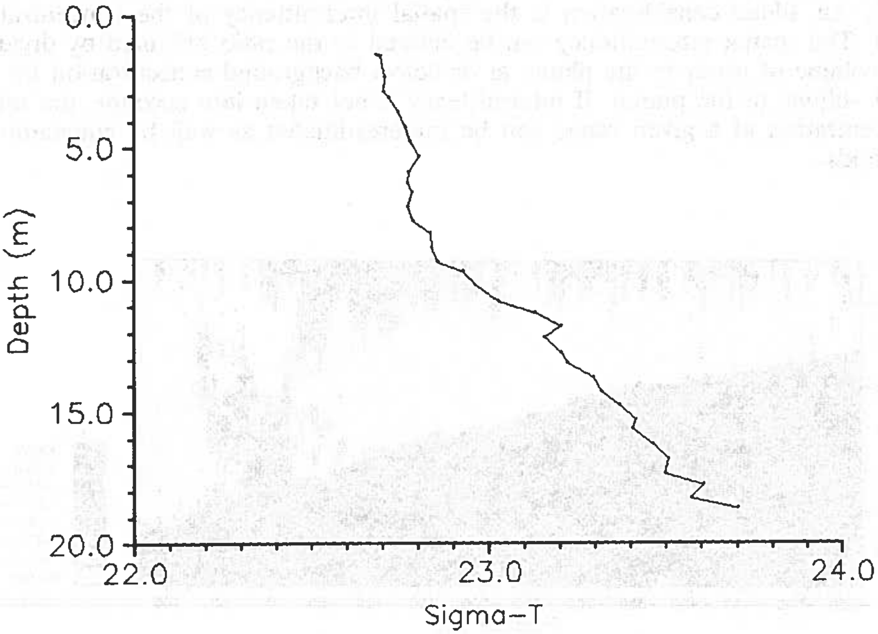

Figure 4 Sigma-t plotted as a function of depth for the receiving watermass of Figure 3 (sigma-$t = (\rho - 1) \times 1000$ where ρ is in gm/cc).

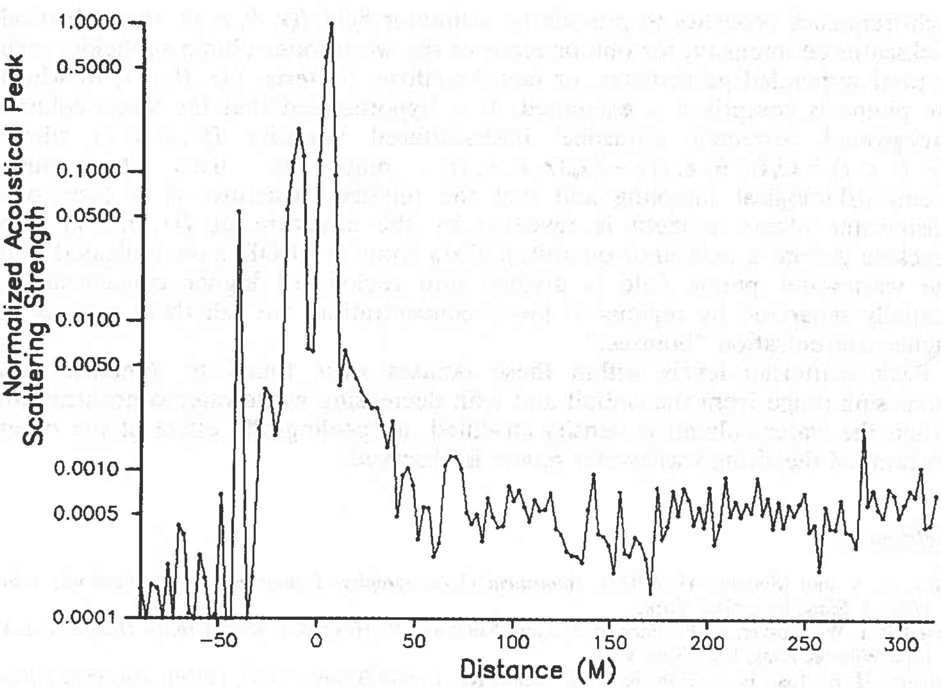

Figure 5 Normalized peak scattering strength as a function of range for the acoustic data presented in Figure 3. The data is normalized to the scattering strength of the effluent plume over the outfall.

CONCLUSIONS

(1) It has been shown that high frequency acoustic echo ranging is a useful tool for measuring spatial characteristics of secondary treated waste-water effluent discharged from two ocean outfalls.
(2) For the total suspended material concentrations typical of Southeast Florida Outfalls, i.e. 30 mg/1, approximately four orders of magnitude of dilution are measurable before the acoustical backscatter signal reaches background levels.
(3) A complex plume structure has been revealed with significant spatial variability in the plume concentration field.
(4) Visualization of effluent trapped in midwater by density gradients is possible. Initial efforts directed at comparing acoustic scattering strength to effluent concentration have yielded encouraging results.

SUMMARY

The measurement of wastewater plume features is complex and plume sampling is difficult in the ocean. A coastal marine study directed toward the measurement of municipal wastewater outfall plume fields, SEFLOE, has been conducted off the coast of southeast Florida (USA). In this study, the feasibility of utilizing high-frequency acoustics to provide an estimator field $I(r, \theta, z, t)$, the acoustical backscattered intensity, for one or more of the wastewater plume subfields, such as total suspended particulates, or faecal coliform bacteria, $f_i(r, \theta, z, t)$ of which the plume is comprised is examined. It is hypothesized that the water-column background corrected acoustical backscattered intensity $I(r, \theta, z, t)$ where $I(r, \theta, z, t) = \langle I_f(r, \theta, z, t)\rangle - \langle I_w(r, \theta, z, t)\rangle$ may be used to guide chemical/biological sampling and that the physical structure of at least one wastewater plume subfield is revealed by the structure of $I(r, \theta, z, t)$ (the brackets denote a measured quantity). Data from SEFLOE have indicated that the wastewater plume field is divided into regions of higher concentration, spatially separated by regions of lower concentration; we call these regions of higher concentration "boluses."

Peak scattering levels within these boluses were found to diminish with increasing range from the outfall and with decreasing wastewater concentration. When the water column is density stratified, a "peeling-off" effect of the outer portions of the rising wastewater plume is observed.

References

Clay, C. S. and Medwin, H. (1977). *Acoustical Oceanography: Principles and Applications*, John Wiley & Sons, Inc., New York.

Duedall, I. W., Kester, D. P., Park, P. K., and Ketchum, B. H. (1983). *Wastes In the Ocean*, Vol. 4, John Wiley & Sons, Inc., New York.

Fischer, H. B., List, E. J., Koh, R. C. Y., Imberger, J., and Brooks, N. H. (1979). *Mixing in Inland and Coastal Waters*, Academic Press, Inc., San Diego, California.

Miami–Dade Water and Sewer Authority Department (1989). Southeast Florida Outfalls Experiment (SEFLOE) for North and Central Wastewater Treatment Plants, MDWSAD, Miami, Florida.

Proni, J. R., Newman, F. C., Sellers, R. L., and Parker, C. (1976). Acoustic Tracking of Ocean-Dumped Sewage Sludge, *Science*, **193**.

Roberts, P. J. W. (1990). Outfall Design Considerations. In: *The Sea, Ocean Eng. Science*, Vol. 9, John Wiley & Sons, Inc., New York.

Tennekes, H. and Lumley, J. L. (1972). *A First Course in Turbulence*, MIT Press, Cambridge, Massachusetts.

Tsai, J. (1984). Acoustic Remote Sensing of Waste Disposal in the Ocean, NOAA Technical Memorandum ERL AOML-59, U.S. Department of Commerce, NOAA.

Urick, R. (1967). *Principles of Underwater Sound for Engineers*, McGraw-Hill Book Company, New York.