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Dispersion Characteristics of Nearshore Coastal Waters

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SUMMARY A brief introduction to mixing processes in the sea is presented, leading to the formulation of a predictive model for continuous discharge. An experimental technique developed for the design of a sewage effluent outfall system is discussed and the results compared with available models. Data from the results of 22 single dye release experiments at one coastal site over a 15 month period is shown to represent a significant contribution to world data, and is presented in a form suitable for design. Comparison is also made between a single point release and a continuous dye release experiment conducted on the same day, and conclusions drawn regarding the accuracy of model predictions.

1 INTRODUCTION

The Hydraulics Laboratory of the Department of Public Works N.S.W. has been commissioned to undertake several studies of proposed effluent outfalls for rapidly growing coastal communities. In general these consist of relatively low flows of secondary treated effluent and for this reason it is not economically feasible to consider extensive submarine disposal systems. In most cases the outfalls are located on a suitably prominent headland with jet discharges issuing from the edge of a rock platform. High initial dilutions are then not attainable and the problem reduces to one of subsequent dispersion of the effluent field within the nearshore region.

The data to be discussed in this paper was collected between January 1979 and March 1980 at Norah Head on the N.S.W. Central Coast midway between Sydney and Newcastle. This study (ref.1) was commissioned by the Department of Public Works Gosford/Wyong Regional Sewerage Project and is part of a large regional sewerage system planned for this area.

Laboratory measurements included ocean currents, winds, sea state, water clarity and temperature-salinity profiles to define the pre-discharge environment. Monitoring of the dispersion characteristics of the region was accomplished through regular dye release experiments. Numerical modelling and prediction techniques were then used for determining design parameters for the outfall based on the data collected.

Field monitoring exercises were undertaken at intervals of four to five weeks and normally consisted of three consecutive days monitoring. A total of 26 days were monitored. The investigation team normally comprised three two-man sections - shore party, survey boat party and light aircraft party.

2 MIXING PROCESSES - BACKGROUND

Oceanic mixing processes occur over a broad range of time and space scales from molecular diffusion through to oceanic circulations (ref.2). In the case of nearshore effluent discharge, we are interested in space scales of the order a few kilometres and time scales of a few hours. Within this context the mixing processes are generally classified into near field processes and far field processes.

The near field problem deals with the immediate mixing induced by the discharge of the buoyant effluent through a nozzle or diffuser system into the ambient ocean waters and will not be discussed here. The far field problem begins as the effluent loses momentum and merges with the receiving waters. Mixing then results from what appear to be random water movements (turbulent diffusion) superimposed on velocity shears (dispersion). The division between what can be termed diffusion or dispersion is again dependent on the scale of observation. Typically, large scale circulations (or eddies) forced by the frictional influence of the wind, break up into successively smaller and smaller eddies as energy is transferred to smaller scales, and is finally dissipated at the molecular level.

The rate of mixing in a particular area of the sea therefore depends on the distribution of eddy sizes which are predominant there. Eddies which are approximately of the same scale as the effluent field will continually break it up and bring in cleaner water and, as the field grows in size, progressively larger and larger eddies become important.

3 PREDICTING FAR FIELD PROCESSES

The rate of oceanic mixing on a given occasion can be assessed by actually measuring the decay in peak concentration and the spatial spread of a mass M of traceable substance (generally a dye) introduced into the sea as an 'instantaneous point source'. A convenient measure of the extent of such a dye patch in a particular direction is the patch variance. Consider a Lagrangian coordinate system moving with the centre of mass of the patch such that the x-y plane is horizontal, the x axis aligned to the current direction and the z axis directed vertically upwards. Denoting the mean dye concentration as $S(x,y,z,t)$, the patch variance at time t is then defined as, for example

$$\sigma_x^2 = \int_{-\infty}^{\infty} x^2 S(x,o,o,t)\,dx \Big/ \int_{-\infty}^{\infty} S(x,o,o,t)\,dx \qquad (1)$$

with σ_y^2 and σ_z^2 being similarly defined. Apart from the variance in the mutually perpendicular directions, a further measure of the horizontal

spread is useful where the shape of diffusing patches is very complex. This is the mean horizontal variance σ_r^2 where the areas A(S) enclosed by particular isolines on the x-y plane are calculated and equivalent radii established as $r(S) = \sqrt{A(S)/\pi}$. The variance σ_r^2 is then defined in a likewise manner to Equation (1). If we make the apriori assumption that the surfaces of equal concentration can be well approximated by ellipsoids centred at (0,0,0) and that the distribution S(x,y,z,t) is nearly Gaussian along the major and minor axes of the ellipsoids, then $\sigma_r^2 = \sigma_x \sigma_y$ and the peak concentration is given by

$$\frac{C_p}{M} = S_i(o,o,o,t) = \frac{1}{(\sqrt{2\pi}\sigma_x)(\sqrt{2\pi}\sigma_y)(\sqrt{2\pi}\sigma_z)} \qquad (2)$$

where by definition $S_i = S/M$.

If the dye is released at the surface then $\sqrt{2\pi}\sigma_z$ is generally replaced by $0.5\sqrt{2\pi}\sigma_z$. If a 2-dimensional process is applicable the term can be replaced by a mixing depth D.

The results from instantaneous release experiments can then be used to solve the more practical problem of the concentration distribution from a continuous source of intensity q operating over a time T. This is generally considered as a superposition of a large number of instantaneous releases at Δt intervals and each of magnitude $M = q\,\Delta t$, i.e.

$$S_c(X,y,z) = q \int_0^T S_i(X - U_o t, y, z, t)\,dt \qquad (3)$$

where X is the distance from the source and Uo is the advective velocity. Under steady state conditions the contribution of diffusion in the x direction can generally be ignored (ref.2) and the centreline concentration approximated by

$$S_c(X) = \frac{q\,\Delta t}{(U_o \Delta t)(\sqrt{2\pi}\sigma_y)(\sqrt{2\pi}\sigma_z)} \qquad (4)$$

where σ_y, σ_z are as for the instantaneous release at time $t = X/U_o$.

A more scientific approach to the above is to attempt to relate the observations to definable physical mechanisms. The starting point for many predictive models is the (semi-empirical) mass transport equation:

$$\frac{\partial S}{\partial t} + u\frac{\partial S}{\partial x} + v\frac{\partial S}{\partial y} + w\frac{\partial S}{\partial z} = \frac{\partial}{\partial x}\left(E_x \frac{\partial S}{\partial x}\right) + \frac{\partial}{\partial y}\left(E_y \frac{\partial S}{\partial y}\right) + \frac{\partial}{\partial z}\left(E_z \frac{\partial S}{\partial z}\right) \qquad (5)$$

where u,v,w are velocity components in the x,y,z directions with respect to the Langrangian reference frame, and the coefficients E_x, E_y, E_z are termed the eddy diffusivities in the respective directions and have units L^2T^{-1} (being analogous to molecular diffusion coefficients). However, because of the range of eddy sizes in the ocean turbulence spectrum, it is generally accepted that these coefficients are functions of patch scale (≡time after release) and the various models available differ in the types of assumptions and simplifications used to obtain workable solutions to this equation. The choice of a particular model is dependent on the type of problem to be solved. For the open coast situation the application of quasi-analytical models (refs.2,3,4) have proved very successful and two of these are discussed below.

The Okubo-Carter shear diffusion model (ref.2) is one of the more complex models which provides a full 3-dimensional solution and includes the role of current shear in the mixing process by allowing constant velocity gradients Ω_y and Ω_z in the x direction velocity. However it assumes the eddy diffusivities are constant. The Okubo-Pritchard 2-D diffusion velocity model (ref.2) is typical of the simpler type of model which neglects shears but allows for the diffusivity to increase proportionally with time after release.

The authors have generalised these two models in an attempt to better describe the observations of dye releases during this study. This generalised model is based on the following assumptions:

$$u = \Omega_y y + \Omega_z z \qquad (6)$$

$$E_x = e_x t^{2m-1} \quad E_y = e_y t^{2n-1} \quad E_z = e_z t^{2p-1} \qquad (7)$$

The solution of Equation (5) for an instantaneous release of mass M can then be shown to be:

$$S = \frac{M}{(\sqrt{2\pi})^3 \sigma_x \sigma_y \sigma_z} \exp - \left\{ \frac{[x - .5(\Omega_y y + \Omega_z z)t]^2}{2\sigma_x^2} + \frac{y^2}{2\sigma_y^2} + \frac{z^2}{2\sigma_z^2} \right\}$$

$$\sigma_x^2 = \frac{1}{m} E_x t \left\{ 1 + \bar{\Phi}^2 t^2 \right\} \text{ where } \bar{\Phi}^2 = \frac{m}{4n+4} \Omega_y^2 \frac{E_y}{E_x} + \frac{m}{4p+4} \Omega_z^2 \frac{E_z}{E_x} \qquad (8)$$

$$\sigma_y^2 = \frac{1}{n} E_y t \qquad \sigma_z^2 = \frac{1}{p} E_z t \qquad \sigma_r^2 = \sigma_x \sigma_y$$

The Okubo-Carter shear diffusion model corresponds with m=n=p=0.5, whilst the diffusion velocity model corresponds with m=n=1, $e_x = e_y = 0.5\omega^2$ where ω is termed the diffusion velocity, $\Omega_y = \Omega_z = 0$ and $\sqrt{2\pi}\sigma_z$ replaced by a mixing depth D. Considering the expression for σ_x^2 it is seen that at large time when $\bar{\Phi}^2 t^2 \gg 1$ mixing due to shear will dominate over longitudinal diffusion and the expression for the longitudinal variance will simplify to

$$\sigma_x^2 = \left(\frac{1}{4n+4} \Omega_y^2 E_y + \frac{1}{4p+4} \Omega_z^2 E_z \right) t^3 \qquad (9)$$

4 DYE RELEASE EXPERIMENTS

4.1 General

The organic fluorescent dye Rhodamine WT (liquid form) has been found to be the most convenient tracer for dispersion experiments conducted by the Laboratory. This bright red dye is particularly stable in the marine environment, is easily defined in aerial photographs and is detectable in concentrations of the order 1 part in 10^{12}.

Specially prepared 6 m twin hull power boats were used in the dye release experiments, designed for inshore work where manouvrability can be important. Boat equipment includes accurate radar position fixing relative to fixed shore stations, a Turner Designs flow-through field fluorometer, a computer-based data recording system and ancilliary pumping gear. The real-time data recording system became available in July 1979 and was developed by the Laboratory to enable continuous recording of elapsed time, boat position and fluorometer output onto cassette tape in digital format, as well as providing operator hard copy in the form of printed output and chart records.

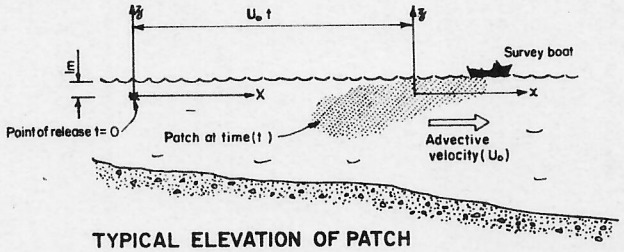
Colour aerial photography and aerial guidance was used extensively throughout the dye release experiments.

4.2 Single Release Experiments

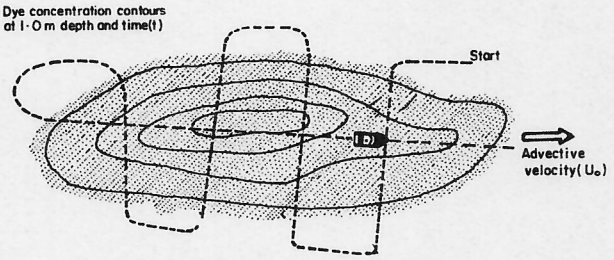
A total of 35 single release experiments were performed during the investigation but only 22 of

these were amenable to a thorough parameter analysis. The release position was generally 150m to 200m offshore.

The amount released varied between 4 to 8L of the raw liquid dye. Observation times varied from three to six hours depending on conditions. Normally, horizontal traverses of the spreading patch were made at half to one hour intervals and at a sampling depth of 1m. Vertical profiles of dye concentration were measured at the same intervals as the horizontal traverses and extended to 5m below the surface. Figure 1 illustrates the procedure used in monitoring a single dye release.



TYPICAL ELEVATION OF PATCH



TYPICAL PLAN VIEW OF PATCH

Figure 1 Monitoring a point release

4.3 Continuous Release Experiments

Three continuous releases were made using a peristaltic pump with release rates up to 200mL min of raw dye and pump times up to four hours. Releases were made from a moored boat at the usual release point.

5 DATA ANALYSIS PROCEDURE

A complete software system was developed to decode the recorded data, perform detailed error checking and finally produce computer generated plan plots of the survey boat path and dye patch concentration profiles in both the horizontal and vertical. Figure 2a and b show a typical transverse and longitudinal dye concentration profile. The highest concentration from each horizontal traverse is automatically extracted and Figure 2d shows the results for one particular release (normalised by mass released).

With the aid of aerial photography, the survey boat path/concentration data was used to construct complete contours of concentration at various times. Further processing included the digitising of these hand drawn contours and then computer analysis to determine the growth of patch variance with time. Suitable local x and y axes were chosen with the origin close to the centre of mass of the patch. Figure 2c shows a typical set of variance values obtained, while Figure 3 details the contour plan for traverse 4 of the same release. Data was time adjusted to allow for the effects of the advective velocity transporting the patch during the time of measurement.

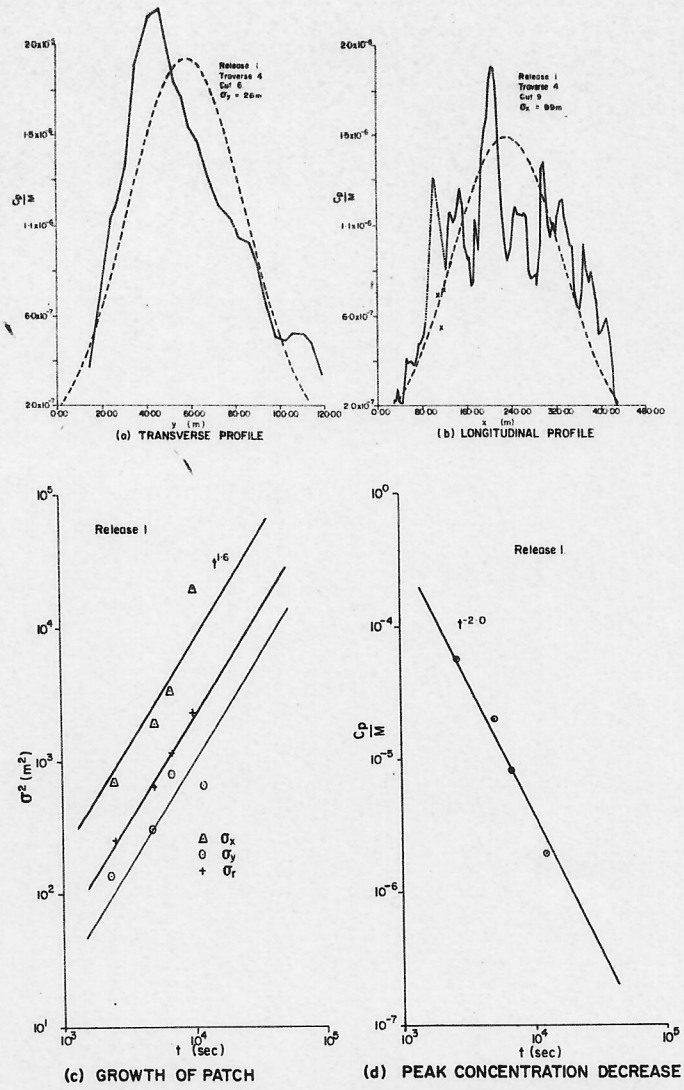


Figure 2 Instantaneous point release 10/7/79

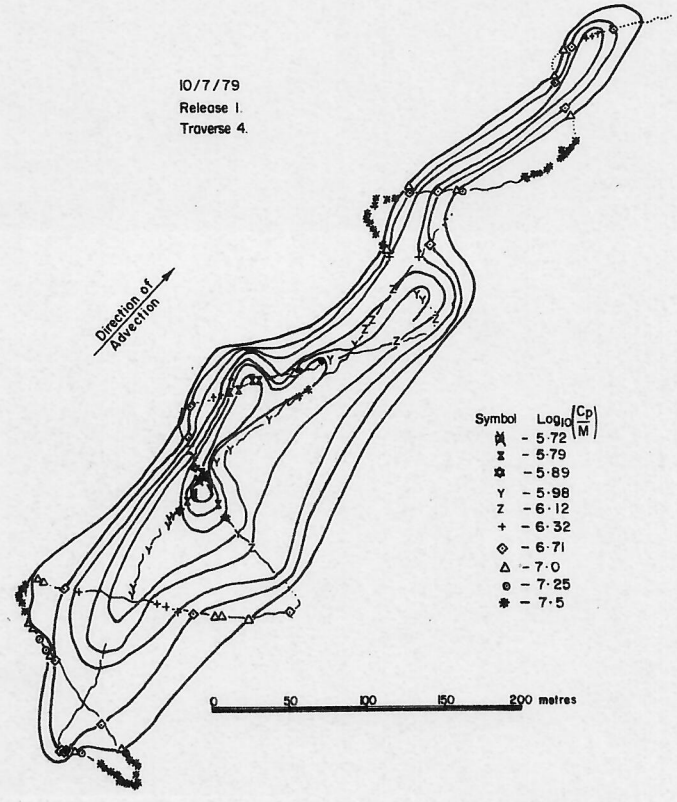


Figure 3 Concentration contours 10/7/79

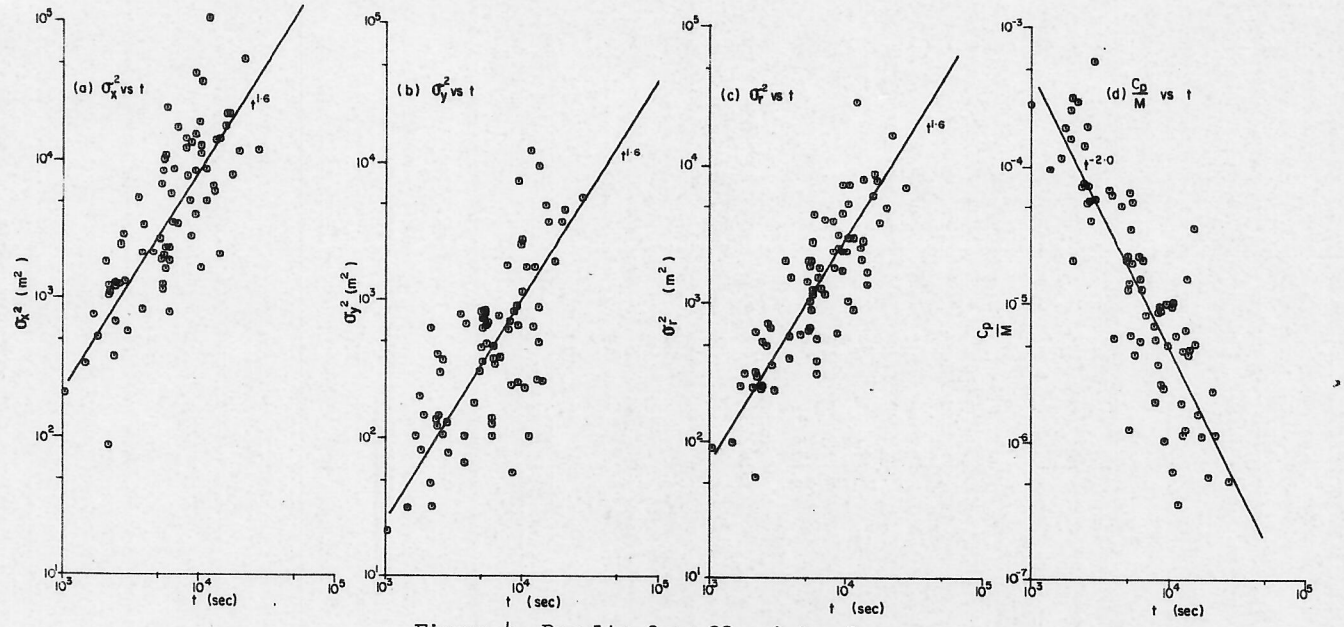


Figure 4 Results from 22 point releases

6 DISCUSSION OF RESULTS

6.1 Single Release Experiments

The grouped data is shown in Figure 4 where the regression slopes were chosen to minimise the total unexplained variance about regression lines fitted individually to the data from each release. The generalised shear diffusion model is fitted to the data by setting m=n=0.8, p=0.4, $\Omega_y = \Omega_z = 0$, viz.

$$\sigma_x = \sigma_r^2/\sigma_y = 1{\cdot}25\, e_x t^{1\cdot6} \qquad \sigma_y^2 = 1{\cdot}25\, e_y t^{1\cdot6}$$

$$\sigma_z^2 = 2{\cdot}5\, e_z t^{0\cdot8} \qquad \sigma_r^2 = 1{\cdot}25\, e_r t^{1\cdot6} \quad (10)$$

$$C_p/M = \left\{0{\cdot}5\,(\sqrt{2\pi})^3 \sigma_r^2 \sigma_z\right\}^{-1}$$

Although shear is an obvious mechanism in the mixing process, it does not dominate over turbulent diffusion for the small time and space scales of these experiments. This was borne out by the difficulty in measuring current shears in the field.

Figure 5 shows the observed frequency of occurrence of the diffusion parameters e_y, e_r, e_x and a composite parameter $e_r\sqrt{e_z}$. Table 1 presents these parameter calculations for the instantaneous release of 18/3/80 together with the diffusion velocity model fit.

6.2 Continuous Release Experiments

The release of 18/3/80 has been selected for discussion because of near ideal monitoring conditions on that day. Seas were smooth - slight on a low swell with a light NE wind and a steady southward current of 0.15ms^{-1} persisted throughout the day. The continuous release commenced only 1hr after the finish of the point release monitoring and raw dye was released at the rate of 100mL min^{-1} (≡ 0.4gs^{-1} traceable Rhodamine). The observed plume centreline concentrations after 1hr and 2.5hr are graphed in Figure 6. Also shown are the Cp(X) curves predicted by the generalised shear diffusion ('best fit') model and the diffusion velocity model using the results of the instantaneous release. The model equations are also shown on Figure 6.

It is seen that the best fit model predicts concentrations 3 times higher than observed and that this is accounted for by the continuous plume being 3 times (=0.08/0.026) wider than the corresponding instantaneous release width. This

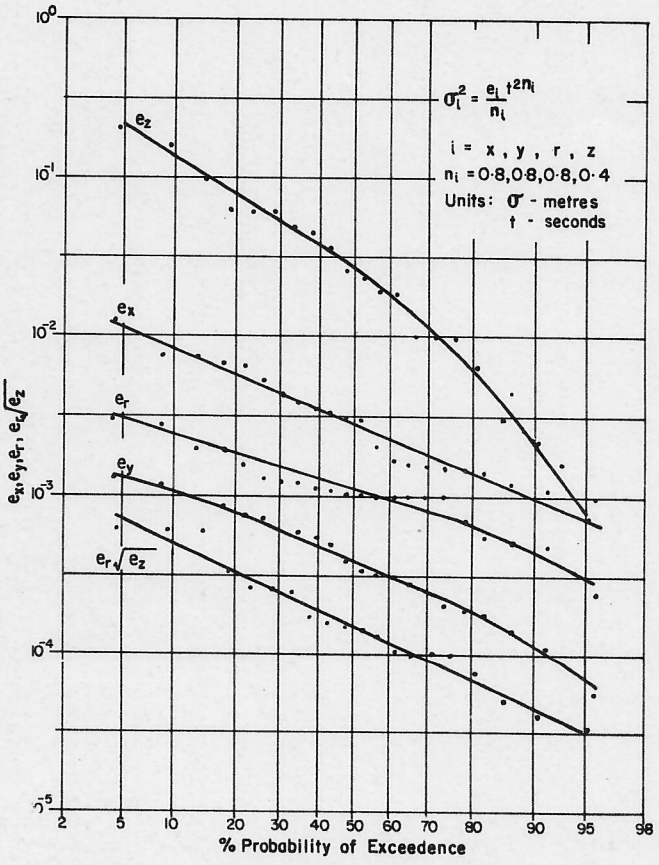


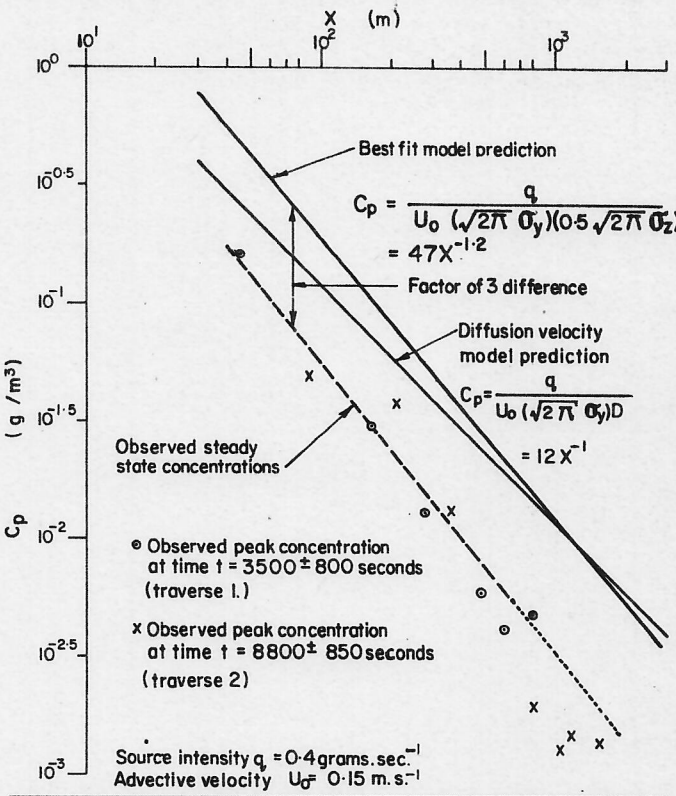
Figure 5 Diffusion parameter frequencies

TABLE I

INSTANTANEOUS RELEASE 18/3/80

Observed Data				Best Fit Model	Diffusion Velocity Model
t	2015	5360	12530	$\sigma_y = 0{\cdot}025t^{0\cdot8}$	$\sigma_y = 0{\cdot}004t$
σ_y	12	29	42	$\sigma_r = 0{\cdot}033t^{0\cdot8}$	$\sigma_r = 0{\cdot}006t$
σ_r	18	32	50	$\sigma_x = \sigma_r^2/\sigma_y$	
σ_x	26	35	81	$\frac{C_p}{M} = 1620t^{-2}$	
t	1900	5115	13415	$\sigma_z = \left\{0{\cdot}5(\sqrt{2\pi})^3 \frac{C_p}{M}\sigma_r^2\right\}^{-1}$	$D = \left\{2\pi \frac{C_p}{M}\sigma_r^2\right\}^{-1}$
log C_p/M	-3·59	-4·19	-4·82	$= 0{\cdot}072t^{0\cdot4}$	$= 2{\cdot}75$
Units: metres, seconds					

situation cannot be explained by an increase in the diffusion parameter σ_y between the times of the instantaneous and continuous releases; even if σ_y increased to the highest value observed during the entire study (and this seems unlikely) this would imply a factor of only 1.5. This discrepancy must be due to the assumption of superposition wherein it is implicit that all individual pulses making up the continuous release follow the same path and are not subject to random deviations caused by midrange eddies. Superposition is therefore conservative (on this occasion) by a factor of between 2 and 3.



Observed plume width (traverse 1.)

X	σ_y
45 m	7 m
160	20
275	33
485	54
605	86

$\sigma_y = 0.36X^{0.8}$
$= 0.36(U_0 t)^{0.8}$
$= 0.08t^{0.8}$

Figure 6 Continuous release 18/3/80

7 COMPARISON WITH WORLD DATA

Figure 7a shows σ_y^2 data for a range of estuarine, coastal and open sea areas presented by Talbot (Figure 4b, Ref.4). Norah Head data is shown superimposed on this figure, largely filling a gap at the lower end of the time scale. World σ_r^2 data is shown in Figure 7b (Figure 1, ref.4). The best fit lines shown do not include Norah Head data.

8 CONCLUSIONS

A well proven experimental technique based on fluorometric tracing has been developed for the measurement of dispersion characteristics of coastal waters. The results from an intensive monitoring programme at a single coastal site have

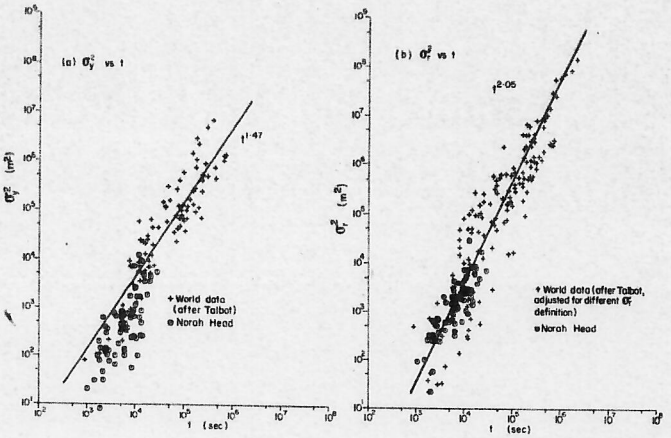


Figure 7 Comparison with world data

contributed significantly to world and, in particular, Australian data for the smaller time and space scales typical of nearshore effluent discharge. This data has been presented in a form suitable for design and shows that relatively simple predictive models can be adequate. The predictive advantages of more complex models are offset by the difficulties in differentiating and measuring the necessary physical parameters, such as current shears in the horizontal and vertical.

Because adequate experimental data is critical to the success of any model it is important that economies be made in experimental procedures, data reduction and analysis. The importance of modern computerised data logging equipment and software analysis systems cannot be understated and now makes increased experimentation possible.

A comparison of a single point release experiment and a continuous release experiment indicates that model predictions based on superposition techniques may be conservative by a factor of 2 to 3.

9 ACKNOWLEDGMENTS

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