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Some Aspects of Coastal Transport Modelling Related to Marine Pollution

By:
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SOME ASPECTS OF COASTAL TRANSPORT MODELLING RELATED TO MARINE POLLUTION

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1. INTRODUCTION

Most direct human impact occurs close to the shore and therefore the nearshore zones are the areas of most immediate interest to the public. The nearshore zone is unique in its hydrodynamics, and the related physical transport and dispersion properties of the nearshore flow for waste disposal, nearshore erosion, recreation, navigation and many other uses of the nearshore waters.

The physical factors that govern the nearshore flow structure are the wind stress, tides, bathymetry, stratification of the water column, coriolis force and effects of lateral and bottom friction. All these physical factors contribute to generate a complex nearshore flow field as compared to the offshore flow field. There are several conceptual models and theoretical ideas concerning the dynamics of the coastal waters. However, it is difficult to identify the relative effects of different physical processes in any specific situation to arrive at an adequate predictive deterministic model.

To obtain details of contaminant dispersal through the marine ecosystem, a complex circulation model coupled to water quality model is required. All the processes that govern contaminant transport on short or long time and length scales are to be identified. Dispersion processes are important on short length and time scales, whereas detached eddies or river plumes are the dominant transport processes on long scale. For coastal environments, the important physical processes are site-specific. After determining the processes, we have to parameterize them. The parameter values included in a particular model are basically selected according to site-specific judgements based on data or a knowledge of the coastal environment. The final step is verification of the model, sensitivity analysis (including calibration) and validation. The calibration procedure requires field and laboratory data sufficient to parameterize model processes. All the processes on many different time and length scales occur in the sea can not be included in the model. In this report some aspects of coastal transport model related to marine pollution is discussed.

2. COASTAL CIRCULATION

The mean coastal flow is subject to several effects: wind stress, friction, earth's rotation, fresh water inflow, and coastally trapped waves. The development of a large scale coastal hydrodynamical model to get the mean flow is difficult and complex. Many model studies have been carried out on the wind-driven circulations in natural basins, like bays, shallow seas, lakes etc. However, in this chapter tide-induced residual flow, useful for coastal areas of the seas which are effected by tidal forcings, is illustrated.

2.1 Coastal Hydrodynamical Model

The evolution of pollutants mainly depends on the residual circulation which renews the water in front of the outfall structure and will carry pollutants away from it. Residual circulation is highly complex, both spatially and through its time evolution. The origin of such circulation is mainly two-fold, the tide and weather systems like cyclones, storms etc. Residual current (Tee, 1977) is a part of the current that is left after removal of the diurnal, semi-diurnal, and high frequency signals. The average residual current is a mean of this low frequency current. These currents are generated by tides through (i) non linear bottom friction, (ii) the non linear terms in the continuity equation, and (iii) the non linear advective terms in the momentum equation. Earlier, in many studies (Ramming, 1972; Leendertse, 1967; Flather and Heaps, 1975; Hunter, 1972, Nihoul and Ronday, 1975 etc.), the advective terms in the momentum equations are neglected. We discuss here a model (Tee, 1976) in which all the non-linear terms in the hydrodynamic equations are considered and can be applied with some modifications for coastal areas of the sea.

Generally, two dimensional tidal equations are used except in an area where there is a predominant directional flow and in which case one dimensional model may be applied. In the coastal areas, especially shallow seas, a two dimensional model is used because of the complexity of the region. In this model, a simple numerical technique is used so that a neutral stability analysis can be applied to the linearized equations and the non-slip boundary condtions can be applied.

The model is based on the following equations:

$$\frac{\partial u}{\partial t}+\underline{u}.\nabla u=fv-g\frac{\partial^2\zeta}{\partial x}+Ah\nabla^2 u-\frac{\gamma|\underline{u}|u}{H}$$

$$\frac{\partial v}{\partial t}+\underline{u}.\nabla v=-fu-g\frac{\partial^2\zeta}{\partial x}+Ah\nabla^2 v-\frac{\gamma|\underline{u}|v}{H}$$

$$\frac{\partial\zeta}{\partial t}+\frac{\partial(Hu)}{\partial x}+\frac{\partial(Hv)}{\partial y}=0$$

where

$$\nabla^2=\frac{\partial^2}{\partial x^2}+\frac{\partial^2}{\partial y^2}$$

is the horizontal Laplacian operator, zeta - the height of water surface above mean sea level, u - depth averaged horizontal velocity vector with components u and v along x and y axes, H = Zeta + D, the total depth of the water column, D is the depth of the bottom below mean sea level, g - gravity, f - coriolis parameter, r - bottom friction coefficient, A_h - eddy viscosity coefficient.

These are the equation of motion for long waves in a shallow sea which become the basis for the studies of tides in shallow water (Dronker, 1964).

The depth averaged currents

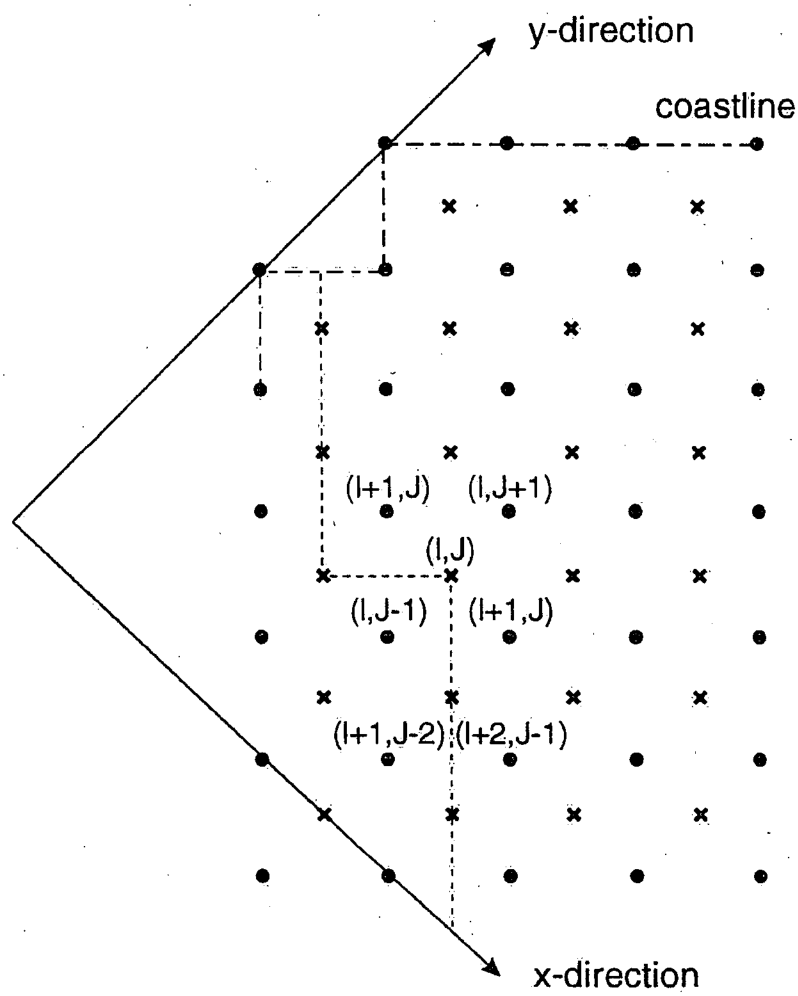
$$\underline{u}=\frac{1}{H}\int_{-D}^{\zeta} u'' dz$$

u'' - horizontal current velocity at depth Z below the sea surface.

In order to obtain the depth mean form of the advective terms in the first equation, it is assumed that the current and its gradient do not vary significantly in the vertical. Here the tide-generating force is neglected.

The above equations can now be rewritten in finite difference form using the central difference approximation and particular type of grid for calculating the numerical computation. The general computational scheme is shown in Fig. 2.1. We get u, v and the sea surface elevation after solving those equations.

The initial and boundary conditions applied in this model are (1) at closed boundaries the normal velocity is zero and (2) at open boundaries the water levels are prescribed. If the study area is along one latitude, the coriolis parameter can be taken as constant. The values of bottom friction coefficient and eddy viscosity coefficient in shallow water are not known. Dronker (1964) has given some values for bottom friction. The value of eddy viscosity depends on the space resolution in the calculation. It varies from 0, 1, 10 and 100 m^2/sec. Tee (1976) showed that the general circulation pattern of the residual current did not vary significantly with various values of r and A_h.



2.1 General numerical computational scheme. (Tee, 1977)

The (Eulerian) residual current U_R is calculated by integrating the current u over M_2 period T,

$$u_R = \frac{1}{T}\int_0^T u\,dt$$

The above equation is represented in finite difference form as

$$u_R = \frac{1}{N}\sum_{i=1}^{N} u$$

where

$$N = \frac{T}{\Delta T}$$

After getting the general circulation pattern from the model, it has to be verified with the observed time series current meter data has to be verified.

2.2 Objective Analysis

In the absence of a reliable hydrodynamical model, observed data can be used to obtain the mean flow. However, it is difficult to obtain an accurate interpolation of the data on a numerical grid from the measured mean velocities. The interpolated currents used in the mass balance equation will not conserve mass. To produce a smoothed interpolation of the generated currents, Sasaki (1970) and Sherman (1976) followed an optimization procedure with a continuity constraint. Such procedure is known as an objective analysis method.

The currents cause mass imbalances and are minimized by expressing them as the following function:

$$F(u,v,\lambda)=\iint_A [w_1^2(u-u_o)^2+w_2^2(v-v_o)^2+\lambda(\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y})]\,\partial x \partial y$$

where u and v are the final adjusted velocities.

u_o and v_o are the interpolated or observed velocities.

λ (x,y) - the Lagrange multiplier.

and w_1 and w_2 - weights assigned according to the observational errors or statistical variances of the observed field.

According to the variational principle, the extreme solution of the function F minimizes the variance of the difference between the interpolated or observed variables and the adjusted variables subject to the constraint that satisfies the continuity equation. This solution is obtained by solving the Euler-Lagrange equations (Sherman, 1976).

$$u=u_o+\frac{1}{2w_1^2}\frac{\partial \lambda}{\partial x},\ v=v_o+\frac{1}{2w_2^2}\frac{\partial \lambda}{\partial y}$$

$$\frac{\partial u}{\partial x}+\frac{\partial u}{\partial y}=0$$

The boundary conditions are either a flow through type or an impenetrable wall. By differentiating and substituting u and v in the continuity equation:

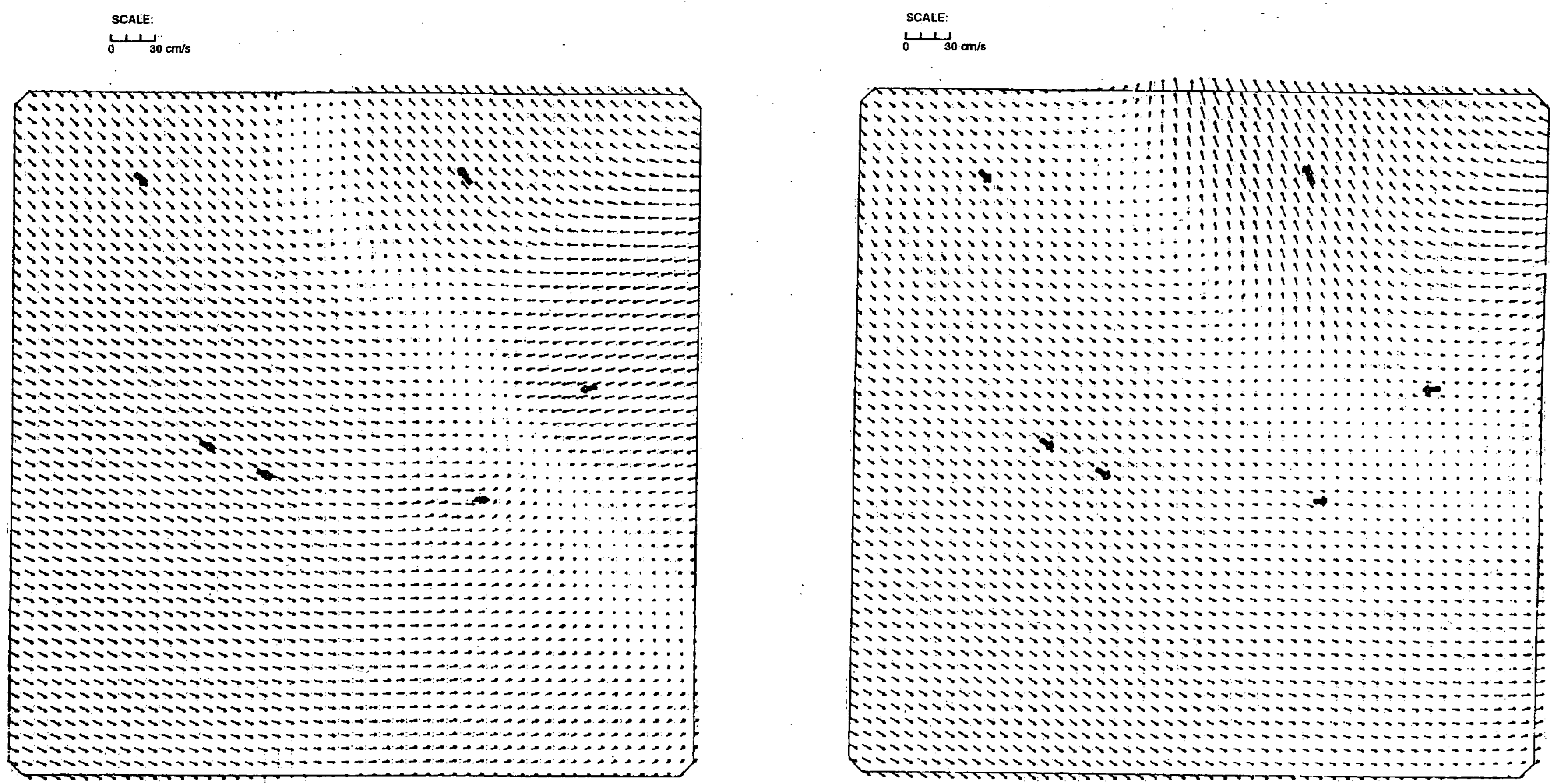
$$\frac{1}{2w_1^2}\frac{\partial^2\lambda}{\partial x^2}+\frac{1}{2w_2^2}\frac{\partial^2\lambda}{\partial y^2}=\frac{\partial u_o}{\partial x}+\frac{\partial v_o}{\partial y}$$

which is solved for lambda using the successive over-relaxations finite difference method, the fast Poisson Solvers or the finite element method. The values of u and v are obtained from the above two equations after substituting the value of lambda. Figure 2.2 shows an example of interpolated currents before and after applying the objective analysis method.

2.3 Coastal Flow Climatology

Several models and theories (Ramming, 1972; Csanady, 1982; Simons, 1980) exist on the dynamics of the coastal waters. However, there is no adequate predictive deterministic model to identify the relative effects of different physical processes at a particular site. In this situation, experiments which can provide statistical and climatological summaries of coastal currents, water temperature, dispersal characteristics and meteorological data for any specific site have to be conducted. This data is generally long-term time series data base to describe coastal circulation and from it one can develop and validate coastal hydrodynamical and transport models for effluent discharges. These experiments should cover the nearshore area, where plumes are generated as well as offshore to resolve large scale nearshore/offshore mass exchange processes in the coastal boundary layer.

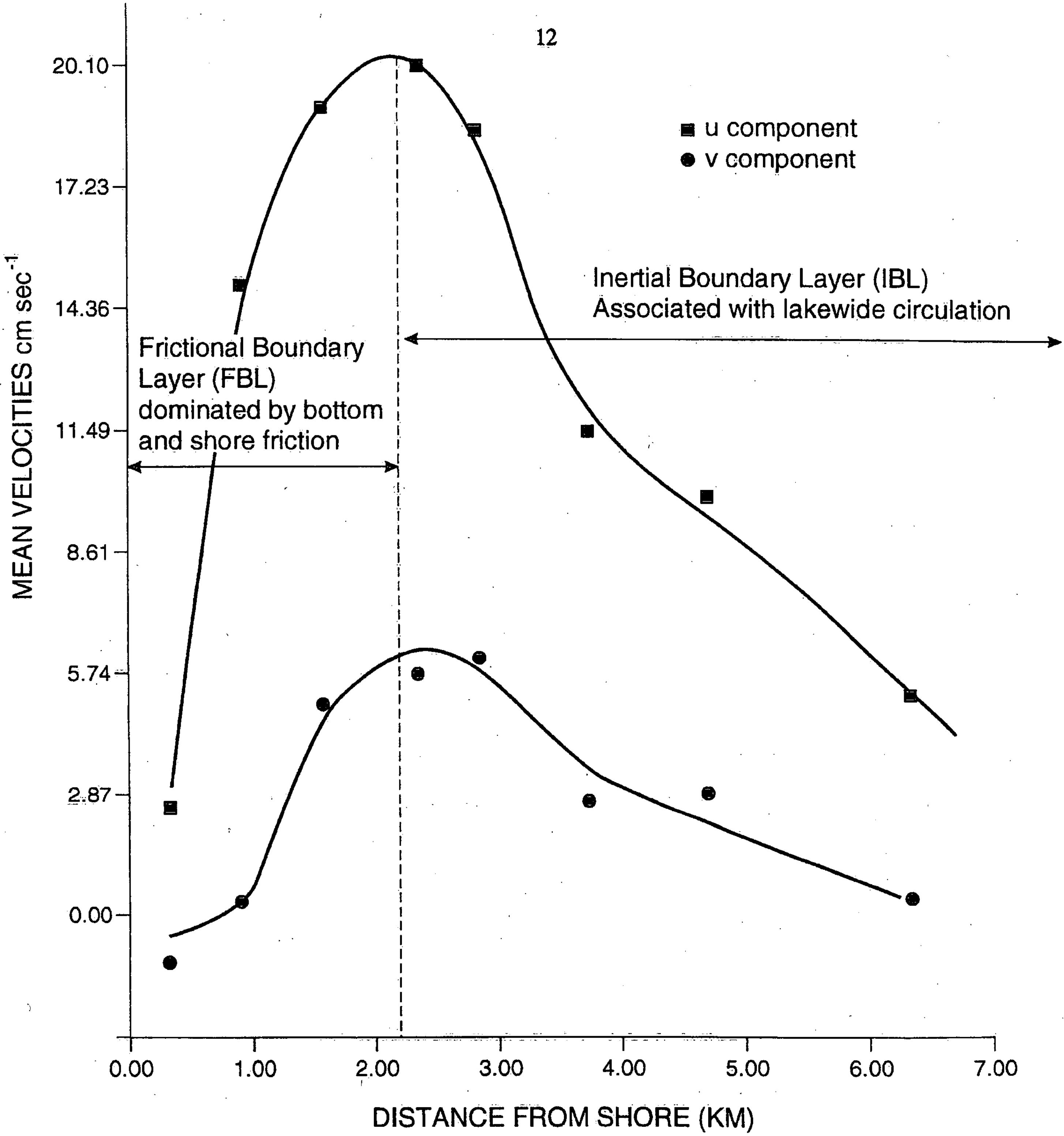
Current meter data collected for many years in the coastal zones give different types of flow regimes. These flows vary from place to place and also seasonally, thus



Before

After

2.2 An example of interpolated currents before and after applying objective analysis. (Lam, et al., 1986) it is sometimes difficult to analyse. The nearshore models developed so far are not able to predict this type of complex flow. Therefore, it is better to depend on statistical estimates of the measured flows. It should be noted that some of the flow regimes identified are not easily analysed with existing nearshore models. It may be either because of the inherent complexity of the flow regime or the lack of sufficient information on boundary conditions and forcing functions. The data collected on coastal currents for the last two decades has to be verified and the current climatology must be classified with respect to the direction and speed of the current. If the coastal area is effected by the tides, the flow is mainly tidal flow. This means the flow will be in two directions, flood and ebb. The range of the speed is also to be divided accordingly. To obtain the coastal current climatology, the frequency distribution of current speed and direction has to be calculated. Several years of observed data are necessary to get a realistic picture of coastal current climatology for a certain coastal region. Elements of coastal current climatology include mean flow properties, coastal boundary layer characteristics, kinetic energy spectra, and turbulence structure. Coastal current climatology may indicate predominant shore-parallel currents. For example, lasting for few days which transport contaminants for several kilometers without major mixing across the shore. Such current regimes exhibit typical boundary layer characteristics. The mean currents of time scales of a few days or longer where wind generated currents are dominated have to be calculated to know the boundary layer characteristics in the coastal zone. A typical picture of the variability of the mean currents with distance from the shoreline of Lake Huron is shown in Fig. 2.3. In the case of the tidal current regime, time scales of 13 hours or less can be chosen to eliminate the tidal frequency. One can also include stratification parameters, fresh water inflow and relevant meteorological parameters in the coastal current climatological data base.



2.3 A typical picture of the variability of the mean currents with distance from the shoreline of Lake Huron. (Murthy & Dunbar, 1981)

3. COASTAL DIFFUSION PROCESSES

The circulation in the world oceans are generally very complex turbulent motions. There are eddy-like motions of varying intensity and scales in the circulation. These eddy-like motions occur in both horizontal and vertical directions. The scale of horizontal eddies are much larger than the vertical eddies because the oceans are many times wider than they are deep. As a result of this, the large-scale water movements and the associated transport and dispersion of chemical and biological species exist from one area to another. The activities of discharging municipal and industrial wastes including waste heat from thermonuclear power plants near the coastal areas of the oceans paved the way for conducting extensive theoretical and experimental studies of turbulent diffusion processes in the near shore regions. However, turbulent diffusion processes are complex and theoretical predictions of transport and dispersion of these wastes are far from satisfactory. Thus, an understanding of the various manifestations of turbulent diffusion processes is largely dependent on the empirical approach of conducting field diffusion experiments.

When some quantity of pollutant is released into coastal waters, it is subject to two important physical processes; advection and diffusion. The former is the bulk transport of a parcel of pollutant by the mean component of the current, whereas the latter is the spreading of the pollutant parcel as a consequence of the turbulence associated with the currents. In this chapter the description of diffusion processes and parameterization of these processes in order to develop coastal pollutant transport models is discussed. First the Lagrangian techniques for measuring the diffusive processes are described.

3.1 Lagrangian Techniques to Measure Diffusion Processes

It is convenient to use fluorescent dye plumes generated by a continuous release source to study turbulent diffusion processes in the coastal zones. The plume is generally generated by releasing rhodamine B dye solution at a specified depth and at a constant rate. The continuous plume experiments are conducted in coastal waters appropriate for pollutant outfall location. The dye is released continuously from a point source and the plume thus generated due to currents is allowed to develop for 2 - 3 hours. The early stages of diffusion are difficult to sample because the dye plume has high concentrations which are beyond the measuring range of the fluorometer. After the plume is fully developed, concentration distributions c(x,y) are obtained at a fixed distance and at a fixed depth in cross-sections established perpendicular to the mean plume direction. While conducting the experiment, the current velocity and temperature profiles are also measured at the location of the dye source. In order to obtain adequate data, it is necessary to do each experiment for at least one tidal cycle.

The instantaneous fluorescent dye patch is used for studying large-scale diffusion processes. In this experiment the dye patch is generated at selected depths by instantaneous release of fluorescent dye solution and follow the patch which is diluted by the currents and their eddies. The density of dye solution is adjusted to the *in situ* density by adding methanol and water. The sampling is undertaken using shipborne fluorometers across the patch. These experiments are generally conducted in the vicinity of a current meter mooring and meteorological observatory to get the environmental data to interpret diffusion data and results.

Drifters are also used for studying dispersion by oceanic turbulence. Lagrangian drifters are useful in studying eddy diffusion in the upper layers of the ocean at large horizontal scales. Fahrbach *et al.* (1986) used radar-tracked, near-surface drifters in their studies of the eddy diffusion of patches at scales 100 - 10000 m. The motion of clusters of drifters in stratified coastal waters was studied by Pal and Sanderson (1992). The drifters each consisted of a crossed-vane drogue tethered to a surface float. However, these drifters are widely used to study large-scale circulation in the open sea areas. Discussion of those experiments is beyond the scope of this report.

A computation of diffusion characteristics are discussed here. The diffusion characteristics are computed using the concentration distributions from tracer experiments.

Based on the data from dye release experiments we can produce the diffusion diagrams. A diffusion diagram is the variance of the horizontal distribution of material versus the diffusion time. The horizontal distribution of substance is usually asymmetric so two variances, along the major and minor axes, are necessary to describe the rate of dispersion. However, a radially symmetric equivalent distribution has been used in this type of experiment. At a diffusion time t (i.e., time elapsed since dye release), the shape of the isolines of any concentration is irregular; the patch is often elongated. However, the variance associated with a radially symmetric distribution can be related through a measure of the eccentricity to the variance for a two-dimensional elliptical distribution which itself is a proper mathematical model for an elongated patch of dye (Okubo, 1965). After obtaining the data on r_e, the radium of a circular area versus S(t, r_e), the radially symmetrical concentration distribution for a patch of dye, the variance is

$$\sigma_{rc}^2(t) \equiv \int_0^\infty r_e^2 S(t, r_e)\, 2\pi r_e dr_e \Big/ \int_0^\infty S(t, r_e)\, 2\pi r_e dr_e .$$

The spatial concentration distribution, S, is described by a two-dimensional Gaussian distribution, i.e.,

$$S(t, r_e) = \frac{M/D}{\pi\sigma_{rc}^2(t)} e^{-r_e^2/\sigma_{rc}^2(t)} .$$

where M/D is the total mass of dye per unit depth of mixed layer. In this case the variance is estimated from a plot of log S versus r_e^2. In another case S(t, r_c) is represented by a generalized exponential distribution:

$$S(t, r_e) = S(t, o)\, e^{-}(r_e/\sigma_{rc}(t))^m$$

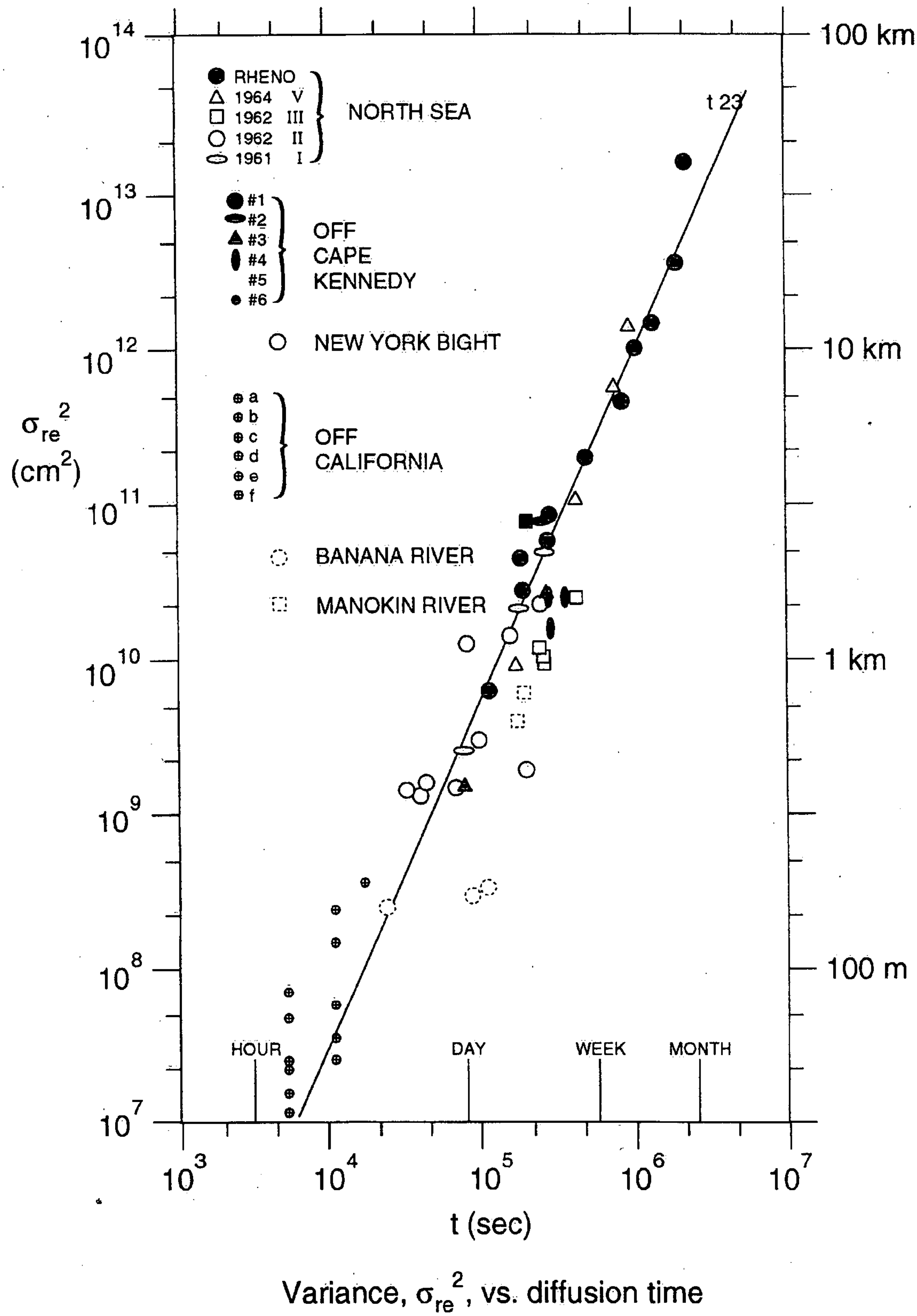
where S(t, o) is the peak concentration and m is a positive number. A plot of log S(t,o)/S(t, r_c) versus re gives the value of the variance and m.

By plotting the value of the variance against the time of diffusion, we get the diffusion diagram. A typical example is shown in Fig. 3.1.

In the following section the horizontal diffusion parameters in terms of oceanic parameters are discussed.

3.2 Horizontal Diffusion and Parameterization of its Parameters

The horizontal motions in the oceans are much greater than the vertical. Normally, it is assumed that the discharged pollutant is subject to horizontal diffusion within a thin homogeneous layer so that all vertical variations in both concentration and velocity is neglected. However, the vertical diffusion cannot be totally neglected. The horizontal concentration field c(x,y,t) within a diffusing patch varies irregularly in both



3.1 A typical example of diffusion diagram. (Okubo, 1971) space and time. The randomness from the observed concentration distributions can be removed by taking the average. The two important diffusion characteristics of a patch are the spread (standard deviations in three dimensions) and the maximum concentration. These two parameters are related through the conservation of mass. In predicting the dispersion of the pollutant patch, it is required to know the rate of growth of the diffusing patch under the coastal environmental conditions.

A log-log plot of the variance against diffusion time scale gives a straight line which defines the power law:

$$\sigma^2 = a t^m$$

By definition, the horizontal eddy diffusivity is written as:

$$K = \frac{1}{2}\frac{d\sigma^2}{dt}$$

From the above two equations we get

$$K = (ma/2)\, t^{(m-1)}$$

Eliminating t from the above equations

$$K = q\sigma^{\beta}$$

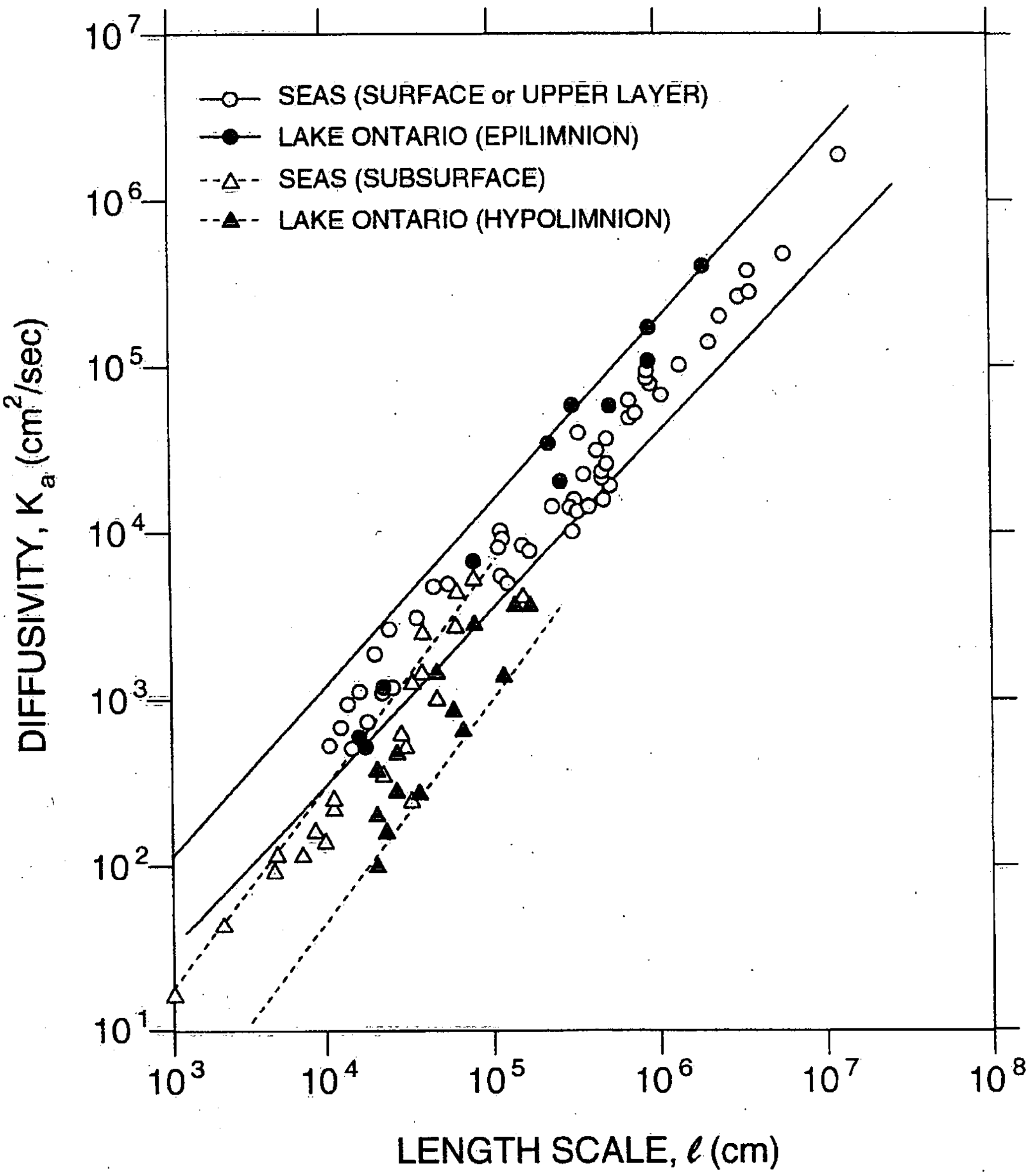
where

$$q = (m/2)\, a^{(1/m)}$$

$$\beta = \frac{2\,(m-1)}{m}$$

If m=1, the variance grows linearly with the diffusion time which corresponds to the Fickian diffusion model with a constant diffusivity. If m=2, the variance grows as the square of the diffusion time which corresponds to the linear length scale diffusion model. If m=3, the variance grows as the cube of the diffusion time corresponding to the inertial sub-range diffusion with the classical Richardson "four-thirds power law" dependence of eddy diffusivity on the length scale (Richardson, 1926). Figure 3.2 shows the horizontal eddy diffusivity as a function of the length scale of diffusion field (Murthy, 1977).

It is not always easy to conduct an experimental program in the marine environment. Dye and other tracer experiments are particularly difficult because of the large spatial and temporal scales that need to be considered. A number of considerations are important to the proper interpretation of experimental data. There will be a bias on fair weather in the data since experiments cannot be safely carried out under severe weather conditions. Also, the horizontal diffusivity varies considerably depending upon the environmental conditions, such as currents. An alternate way of computing the oceanic turbulence and diffusion parameters is by using the time series current meter data (Eulerian technique). Now the Eulerian technique to calculate horizontal diffusion parameters using time series current meter data will be discussed.



3.2 Horizontal eddy diffusivity as a function of length scale of diffusion field. (Murthy, 1977)

3.3 Eulerian Technique to Calculate Horizontal Diffusion Parameters

The coefficients are calculated using the time series current meter data by the well known Taylor's (1921) analysis. The following steps are involved in the calculation of oceanic turbulence and horizontal exchange parameters:

1. The alongshore and onshore/offshore components, u(t) and v(t) of the currents are computed. It becomes the basic data for calculating the horizontal exchange coefficients.
2. The mean flow and fluctuations are separated from the time series data - the numerical (low pass) filtering technique is more useful (kinetic energy spectra of currents provide the physical basis for the design of digital numerical filters).

3. The running mean values of u(t) and v(t) are subtracted from the instantaneous values u(t) and v(t) to get the fluctuations u'(t) and v'(t).

4. Calculate the variance

$$\overline{u'^2}(t) = \overline{[u(t) - \overline{u}(t)]^2}$$

   Measure the magnitude of velocity fluctuations. The overbar indicates the usual time averaging.

5. The Eulerian integral time scale characteristics of these fluctuations are calculated for u and v. This is obtained by computing the Eulerian autocorrelation coefficient $R_e(t)$ for u and v:

$$R_e(\tau) = \frac{\sum_{t=0}^{T-\tau} u'(t)\, u'(t+\tau)}{\left(\sum_{t=0}^{T-\tau} u'^2(t) \sum_{t=0}^{T-\tau} u'^2(t+\tau)\right)^{1/2}}$$

where T is the total time series record length.

The time scale T_e is given by

$$T_e = \int_0^{t_0} R_e(\tau)\, d\tau$$

where t_o is the time for the first zero crossing of the Eulerian correlogram.

The horizontal exchange coefficients K_x and K_y are calculated using the equation:

$$K_x = \beta\, \overline{u'^2_e} \int_0^{t} R_e(\tau)\, d\tau$$

For times $t > t_e$, the Eulerian correlation time scale, in the above equation will approach a constant T_e, the Eulerian integral time scale, in that case the horizontal exchange coefficient is

$$K_x = \beta\, \overline{u'^2_e} \cdot T_e$$

It is easy to calculate u_e and T_e from time series data, the factor beta is difficult to compute. Beta depends on the energy spectra of turbulent fluctuations, intensity of turbulence and the stability. Schott and Quadfasel (1979) reported a value for a factor similar to beta around 1.4 + or - 0.4 for an oceanic case based on simultaneous Lagrangian and Eulerian measurements in the Baltic. However, we assume beta = 1 for our calculations of exchange coefficients (it may be an under-estimation of coefficients). A plot of vertical variability of horizontal exchange coefficients calculated from time series current meter data for the Baltic Sea is shown as example in Fig. 3.3 (Gidhagen and Murthy, 1985).

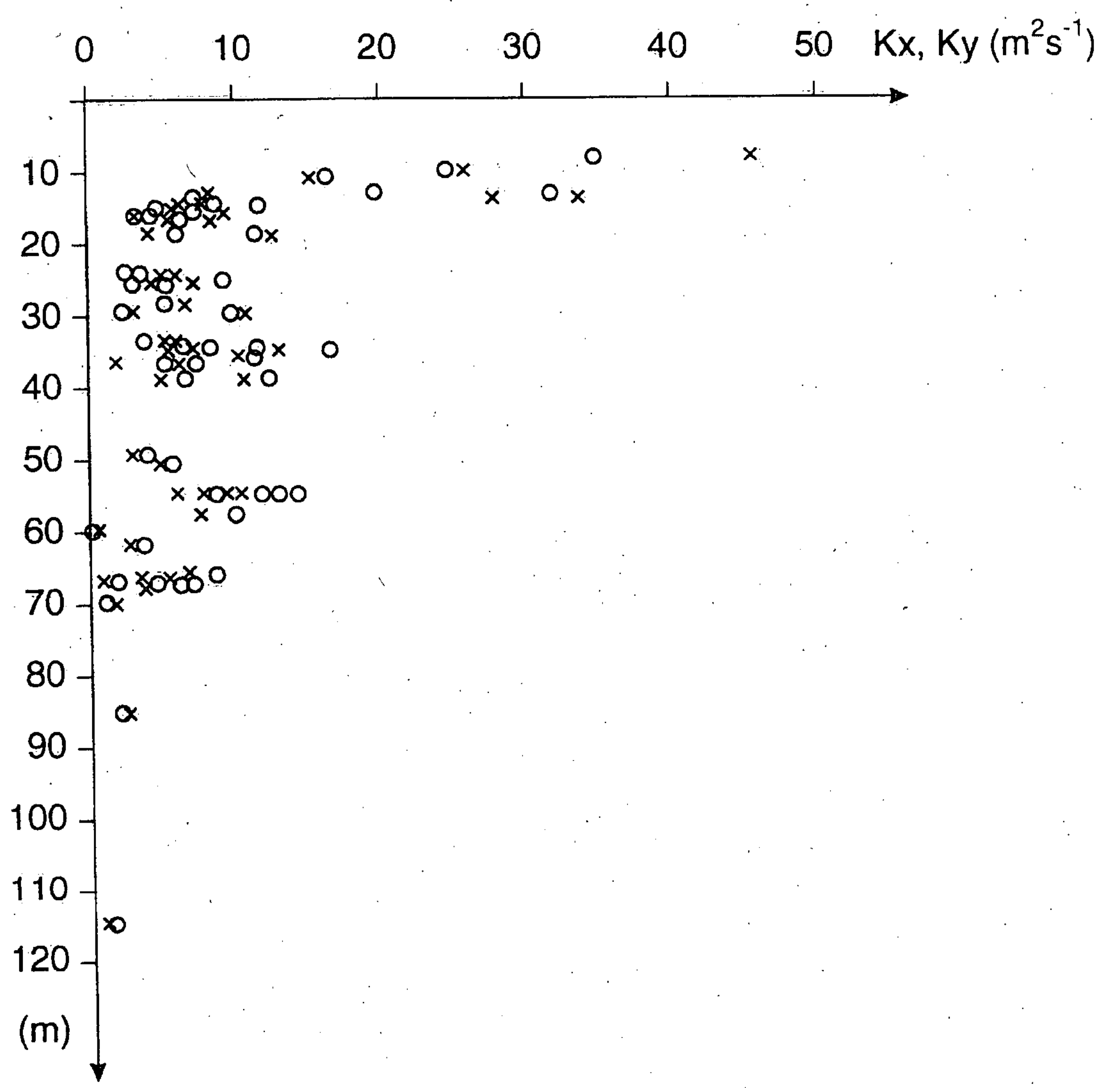
3.4 Vertical Diffusion

In contrast to the horizontal diffusion, the process of vertical diffusion is controlled by small scale motions characteristics of a stably stratified water column. The wind mixing plays an important role in providing turbulent energy down to the thermocline.

Kullenberg (1970) related the vertical diffusion coefficient to the stratification of water, current shear, and wind speed (wind stress). The formula is:

$$K_z = c\overline{W}^2 \overline{N}^{-2} \frac{d\overline{q}}{dz}$$

where c is a numerical constant, W^2 is a measure of the wind stress at the surface, N is the Brunt Vaisala frequency defined by



3.3 A plot of vertical variability of horizontal exchange coefficients for different stations. (Gidhagen & Murthy, 1985)

$$\overline{N}^2 = \frac{g}{\rho}\frac{d\overline{\rho}}{dz} \quad \text{and} \quad \frac{d\overline{\rho}}{dz}$$

is the absolute value of the mean current shear. For the winds greater than 5 m/sec, the vertical mixing in the upper zone is

$$K_z = (8)10^{-8}\overline{W}^2(\overline{N}^2)^{-1}\left|\frac{d\overline{q}}{dz}\right| \quad \text{where} \quad \overline{W}^2, \overline{N}^2, \quad \text{and} \quad \left|\frac{d\overline{q}}{dz}\right|$$

are the mean square of the wind speed, the mean Brunt Vaisala frequency, the mean current shear, respectively.

The vertical mixing for low and varying winds is governed by local processes. The source of energy is obtained from the kinetic energy of fluctuations. Then

$$K_z = 4.1x10^{-4}\overline{q}'^2(\overline{N}^2)^{-1}\left|\frac{dq}{dz}\right| \quad \text{where} \quad \overline{q}'^2 = \overline{u}'^2 + \overline{v}'^2$$

the kinetic energy of current fluctuations. The diagrams for the vertical diffusion characteristics, i.e., vertical eddy diffusivity (cm^2/sec) versus wind stress, stability parameter and current shear (cm^2/sec); and vertical eddy diffusivity (KN^2, $cm^2 \cdot sec^{-3}$) versus stability parameter, turbulent kinetic energy, and current shear ($cm^2 \cdot sec^{-3}$) corresponding to the above equations are drawn.

4. COASTAL TRANSPORT MODELS

Using the interpolated currents and the computed eddy diffusivity coefficients, the concentration distribution, by solving the mass balance or advection-diffusion equation can be computed. First the analytical solutions to the two dimensional advection-diffusion equation which works only in simple cases and later the numerical techniques are discussed.

4.1 Analytical Models

Analytical solution of the transport equation is not difficult for simple cases like Fickian diffusion, in which the eddy diffusivity and the mean current are constant. Suppose we instantaneously release effluent (t = 0) with strength 'Q' into the turbulent sea and take x axis along the constant current direction, (u = constant, v = w = 0), K = constant, but vary in each direction. Then the solution of diffusion equation is given by a three dimensional Gaussian distribution which is

$$c(x,y,z,t) = \frac{q}{(4\pi t)^{3/2}(K_x K_y K_z)^{1/2}} \exp\left[-\frac{1}{4t}\left(\frac{x^2}{K_x}+\frac{y^2}{K_y}+\frac{z^2}{K_z}\right)\right]$$

By integrating the above equation with respect to space and time one can obtain solutions for area or volume sources and the continuous point source, respectively.

Csanady (1973) described various types of solutions to predict the mean concentration distribution within diffusing instantaneous patches and continuous plumes in the coastal zone. Lam *et al.* (1986) illustrated some cases of steady-state analytical models.

The analytical models are useful in simple cases and also used as guidelines for the numerical models. For example, we consider a depth-integrated two dimensional cross-plume Gaussian distribution of concentration equation:

$$c(x,y) = \frac{QRe_x}{2\sqrt{2\pi}hux} \exp(-y^2 Re_x^2/2x^2)$$

where

$$Re_x = \frac{ux}{2K_x}$$

and h is the depth. By introducing $Q = c_o D$, where c_o = source concentration and D = the source discharge rate and the dilution factor $\eta = c/c_o$. Then

$$\eta = \frac{DRe_x}{2\sqrt{2\pi}hux} \exp(-y^2 Re_x^2/2x^2)$$

Under steady state conditions the mean current 'u' and eddy diffusivity K_x are controlling the dilution factor.

The frequency distribution of current speed and direction is used for calculating the mean dilution over a period longer than the time period over which the mean current is computed. A plot of calculated mean dilution contours, using the above equation is shown as an example in Fig. 4.1.

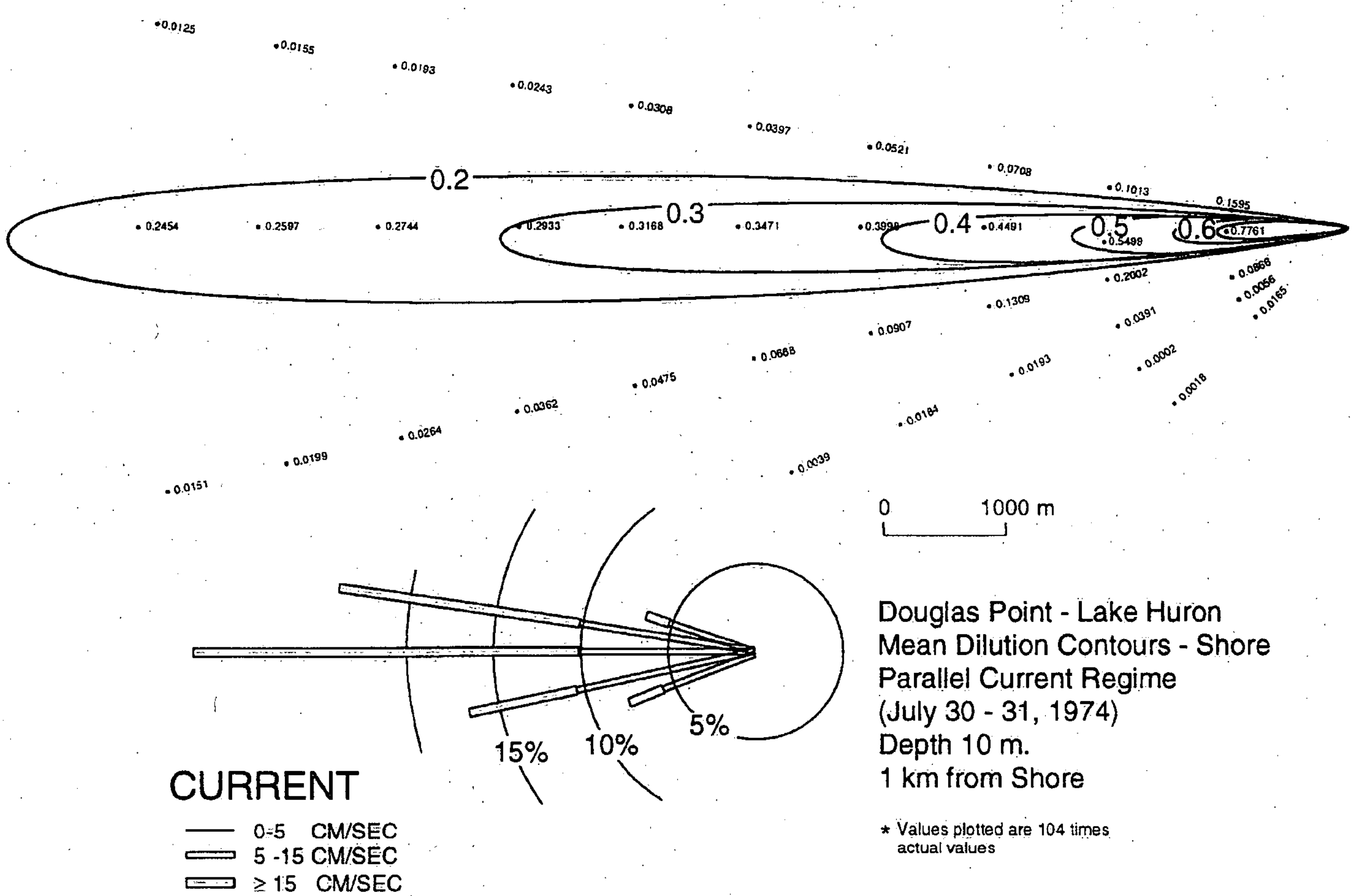
4.2 Outfall Diffusion Models

In a coastal region, when the material is discharged through a pipe line or dumped by ship, the concentration gradients of the contaminant is high near the discharge point and it varies spatially. This phase of mixing is called nearfield or initial mixing. If one moves away from the discharged point the concentration gradients decrease due to mixing and reduces the spatial variability. At this farfield stage the established wastefield drifts with the ocean currents which prevail in that region. Finally, the exchange rates on continental shelf scales and biological and chemical decay processes determine the long-term build up of contaminants.

Nearfield models deal with the calculation of concentration of contaminants in waters close to the disposal site for relatively short periods of time. The concentration distributions in the nearfield are influenced by the proximity of boundaries.

In the farfield models, a high spatial resolution is required to resolve the strong gradients and a lower resolution for more homogeneous areas.

In the vicinity of marine outfalls, the initial mixing takes place within a few minutes and at short distances and the effluents form a line source. The diffusion of this line source is governed by the prevailing coastal currents and their eddies. The dilution depends upon the location of the effluent plume within the coastal zone, current transport and dispersion characteristics of the area.



4.1 Simulated effluent concentrations using an analytical model for a shore-parallel current regime in Lake Huron. (Lam, et al., 1986)

In the numerical modelling, horizontal mixing means the differential advection on scales, either in time or space, and too small to be resolved in the model. This mixing is often represented as diffusion. The basic difficulty in all diffusion modelling problems is the determination of the appropriate eddy diffusivity and the incorporation of this quantity into the governing equations.

To predict two dimensional dilution contours of outfall discharge, we discuss Gaussian Cross-Plume Model (Kuehnel *et al.*, 1981). Consider the equation of advection and diffusion of a non-conservative material (Fischer *et al.*, 1979; Hinze, 1959) with an exponential decay rate in a homogeneous turbulence field

$$\frac{\partial c}{\partial t}+u\frac{\partial c}{\partial x}+v\frac{\partial c}{\partial y}+w\frac{\partial c}{\partial z}=\frac{\partial}{\partial x}\left(K_x\frac{\partial c}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y\frac{\partial c}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z\frac{\partial c}{\partial z}\right)-\lambda c$$

where $c(x,y,z)$ - the effluent concentration
u,v,w - velocities in x,y,z directions
K - eddy diffusivity
λ - the decay constant of the effluent

and make the following assumptions:

1. A steady and continuous effluent line source (diffuser) of length 'b' is kept perpendicular to a uniform and steady shore parallel current.

2. The effluent is diluted before releasing from the source.

3. The effluent field moves with the prevailing currents without disturbing the existing flow pattern of the coastal zone.

4. The diffusion in the flow direction is negligible compared to the advection.

5. The lateral eddy diffusivity is a function of the initial plume width.

6. The vertical diffusion is negligible and the effluent is uniformly distributed over the available water depths.

7. The outfall is located sufficiently far offshore so that the spread of effluent in the coastal zone is not restricted by the shore boundary.

Then the above equation becomes

$$\frac{\partial c}{\partial x}-K_y\frac{\partial^2 c}{\partial y^2}+\lambda c=0$$

After eliminating the decay constant (lambda) from the equation and applying assumption 5:

$$K\frac{\partial^2 C}{\partial y^2}=u\frac{\partial C}{\partial X}$$

The solution of this equation can be obtained using standard integral techniques (Hildebrand, 1965):

$$c(x,y)=C(x,y)\,e^{-\lambda x/u}=C(X,y)\,e^{-\lambda x/u}$$

$$=\frac{C_0 e^{-\lambda x/u}}{2}\left(erf\left[\frac{(y+b/2)}{\sqrt{4KX/u}}\right]-erf\left[\frac{(y-b/2)}{\sqrt{4KX/u}}\right]\right)$$

Before using the above equation, we must specify the functional relationship between X and x. According to Brooks (1960) the functional relationship is as follows:

$$\frac{4KX}{u}=\frac{b^2}{6}\left[\left(1+\frac{1}{n}\left(\frac{4Kx}{u}\right)\frac{6}{b^2}\right)^{n}-1\right]$$

where n = 1,2,3 for Fickian, lateral shear, and inertial sub-range diffusion models, respectively.

By introducing the dilution factors the above equation is written as

$$\eta_{(}x,y)=\frac{1}{2}\eta_{so}e^{-\lambda x/u}\left(erf\left[\frac{(y+b/2)}{\sqrt{4KX/u}}\right]-erf\left[\frac{(y-b/2)}{\sqrt{4KX/u}}\right]\right.$$

where $n = c/c_s$ = effluent field to source dilution factor.

$n_{so} = c_o/c_s$ = jet or nearfield to source dilution factor

In the extreme farfield, the line source approaches a point source and the limit of the above equation reduces to:

$$\eta(x,y) = \eta_{so} \cdot e^{-\lambda x/u} \frac{b}{\sqrt{4\pi KX/u}} \cdot e^{-y^2/(4KX/u)}$$

This model can be applied to calculate the average effluent concentration in the variable current speed and plume direction using polar coordinate system. Based on the described speed-direction histogram and the above equations the average dilution factor at any (r,θ) is:

$$\eta_{(r,\theta)} = \sum_{mn} f_{mn} \eta_{(r,\theta,U_m,\phi_n)}$$

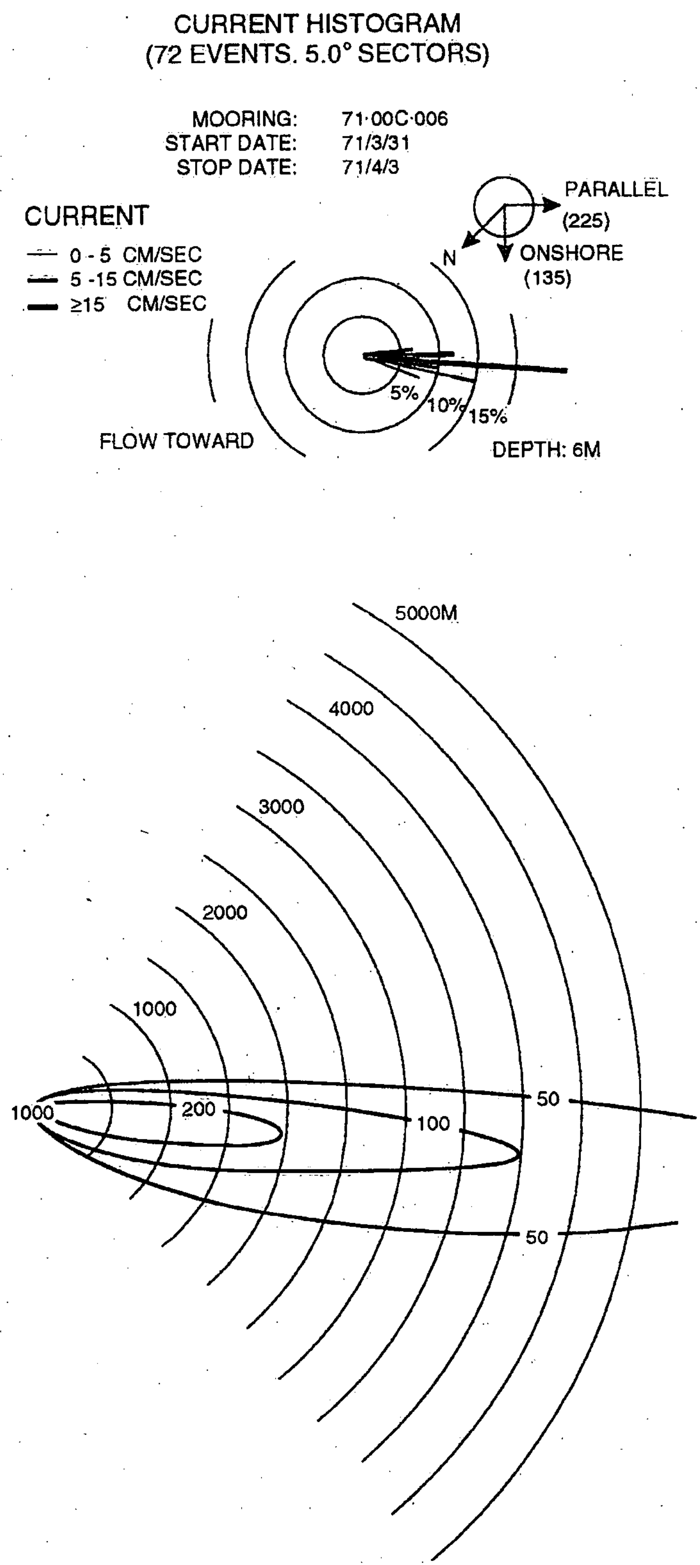
$$\eta_{(r,\theta,u_m,\phi_n)} = \eta_{(x,y)}$$

and f_{mn} = the speed - direction frequency distribution of a current episode.

This analysis describes single current episode of an identifiable flow regime. If more data is available, the average concentration field of each current episode belonging to the flow regime can be calculated.

The input parameters to be used in this model to calculate the outfall dilution are: eddy diffusivity, discharge rate, discharge speed, initial dilution, diffuser depth, diffuser width and distance from shore. Typical predicted mean dilution contours for an outfall diffuser system are shown in Fig. 4.2 (Kuehnel *et al.*, 1981).

Roberts (1991) reviewed the methods for predicting dispersion and environmental impact of wastewater discharged from ocean outfalls. Initial dilution and



4.2 Predicted mean dilution contours for outall-diffuser system in Lake Ontario. (Murthy & Kuehnel, 1988) wastefield formation, the process occurring within about 10 minutes after release from the outfall diffuser was discussed.

As pointed out by both Okubo (1971) and Murthy (1977), there is no framework to include environmental factors into the data analysis. The experimental data are useful for doing numerical models. However, mean flow quantities, such as the circulation patterns and prevailing winds and turbulence quantities such as intensity, length scales and rates of energy dissipation, all need to be considered.

To get the dilution contours from a diffuser outfall it is suggested the steps given below should be followed:

1. Determine the initial dilution due to the jet mixing.

2. Classify the current episodes according to the speed and direction ranges.

3. Divide each episode into hourly speed and direction events.

4. Calculate the farfield dilution or the total dilution including the initial dilution for each hour at all points of a (polar) grid.

5. Repeat the procedure for other hourly events and then average the results over the whole episode.

6. Short duration current episodes, where the plume length is limited by advection rather than diffusion should be included in the analysis.

7. Decrease the current direction segments of the current episodes to improve the accuracy of diffusion field calculations (if the model is more sensitive to the current direction).

4.3 Coastal Transport Models for Conservative and Non-Conservative Substances

The prediction of the rate and direction of transport of a conservative contaminant (which does not react chemically or biologically but dissolves in the receiving environment) requires both the hydrodynamic model for water circulation and the dispersion model for advection and diffusion of the contaminant. The hydrodynamical model can be either a simple average circulation derived from observations or complex two and three dimensional numerical models. The hydrodynamical model is used as a foundation to derive the concentration field of the contaminant.

If the conservative contaminant is released in the estuary which mixes instantaneously and there is not exchange with the sea, then the farfield concentration in the estuary can be determined from the mass of the contaminant and volume of the estuary. The nearfield mass concentration is simply the maximum concentration of the contaminant. If the estuary is stratified, either vertically or horizontally, a one or higher dimensional model is required.

If the contaminants are not passive and non-conservative the particulate material is lifted from the sea bed carried with the water and settles under gravity. The amount transported depends upon the speed of the water flow and the turbulence intensity of that flow. Hence, to determine the distribution of sediment particles and the distribution of the contaminant, a sediment transport model is also required together with the hydrodynamic model. The latter is used to determine the transport of the contaminant within the water and also to determine the bed stress which is used as a driving force for the sediment transport model.

For many coastal problems, the output from a two-dimensional model averaged over depth is the appropriate input to the sediment transport model.

5. REMARKS

The following points should be considered for developing the coastal transport modelling capability at the Coastal Ocean Space Utilization Section, National Institute of Oceanography, Dona-Paula, Goa.

1. The data base, for coastal climatology, which includes bathymetry, meteorological data, time series oceanographic data on currents, stratification, turbulence and diffusion parameters, should be developed.

2. Collaboration with National Water Research Institute, Canada, and the Indian Institutes, like Centre for Atmospheric Science, IIT, New Delhi, Ocean Engineering Division, IIT, Madras, and CMMACS, Bangalore is necessary to develop national capability in coastal transport modelling of pollutants.

3. Coastal transport models described in this report with some modifications can be applied to the site specific studies using the existing meteorological and Oceanographic climatological data base at NIO to predict the fate of the pollutants discharged into the coastal waters along the Indian coasts.

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