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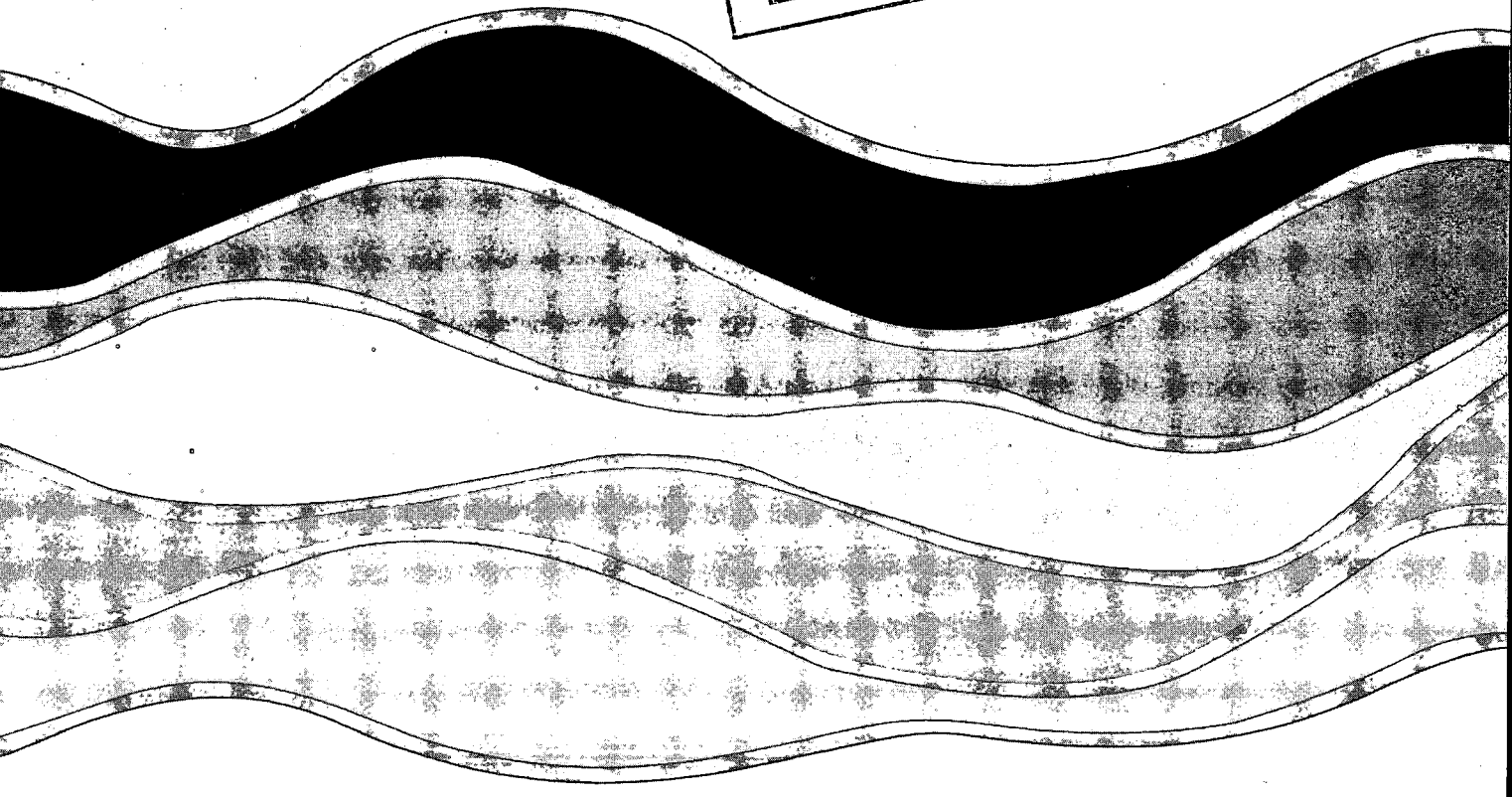

# PHYSICAL PROCESSES OF POLLUTANT TRANSPORT IN THE AQUATIC ENVIRONMENT

Y.L. Lau

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# PHYSICAL PROCESSES OF POLLUTANT TRANSPORT IN THE AQUATIC ENVIRONMENT

by

Y.L. Lau

Rivers Research Branch
National Water Research Institute
Canada Centre for Inland Waters
Burlington, Ontario

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## MANAGEMENT PERSPECTIVE

This report contains the notes from an invited lecture given at a workshop on Environmental Management and Technology held in Hong Kong in September, 1990. The lecture provided a description of the physical processes which govern the transport of contaminants in various aquatic environments and was designed for an audience from a wide range of disciplines. It should be a useful introduction for those who are interested in physical transport processes.

## PERSPECTIVES DE GESTION

Le présent rapport renferme les notes recueillies lors d'un exposé par un conférencier invité à un atelier de travail sur la gestion et la technologie environnementales tenu à Hong Kong en septembre 1990. La conférence portait sur les processus physiques qui régissent le transport des contaminants dans divers milieux aquatiques et elle s'adressait à un auditoire appartenant à une vaste gamme de disciplines. Ce rapport devrait constituer une introduction très utile pour tous ceux qui s'intéressent aux processus du transport physique.

ABSTRACT

An introduction into the various physical mechanisms which govern the transport of material in the aquatic environment is given. These processes are shown to be part of the mass conservation equation which is used for the analysis of mixing problems. Special considerations for different environments such as rivers, lakes and estuaries are described. The role of sediments in contaminant transport is briefly discussed.

RÉSUMÉ

On donne une introduction aux divers mécanismes physiques qui régissent le transport de matières en milieu aquatique, en montrant que ces mécanismes interviennent dans l'équation de conservation de masse, utilisée pour les problèmes de mélange. On décrit les caractéristiques spéciales pour différents milieux, comme les rivières, les lacs et les estuaires. Le rôle des sédiments dans le transport des contaminants est brièvement examiné.

## INTRODUCTION

Surface water has long been used as a vehicle for the disposal of industrial and municipal wastes. In most instances, the waste discharges contain unacceptably high concentrations of pollutants and the receiving water body is used as a means of diluting these discharges. In order to achieve standards of water quality which would not be detrimental to the aquatic environment, it is necessary for the pollutant concentration to be reduced to acceptable levels within certain distances from the discharge. This leads to the concept of "mixing zone" which is used by some regulatory agencies. Outside of this zone, established water quality criteria must be met. The zone is thus a limited area within which the initial dilution can occur. As the dilution rate is controlled by the physical processes of mixing and dispersion in the receiving water body, it is important for designers of discharges as well as for the regulatory authority to be knowledgable in the mixing processes in order to assess whether discharges can comply with mixing zone criteria and standards. This knowledge is also required for water quality modelling, for designing of monitoring and surveillance programmes and for assessing the effects of accidental spills.

While the mixing zone concept can be applied to concentrated sources of discharge, pollutants can also enter the aquatic environment through diffuse sources such as agricultural runoff or atmospheric deposition. Assessing the effects of such sources also requires knowledge of the transport and mixing processes. Indeed,

sound environmental management requires an understanding of all the physical, chemical and biological processes in the aquatic environment which all need to be taken into account for the proper assessment of the impact of various waste discharges.

This lecture is an introduction to the various physical mechanisms which govern the transport and mixing of pollutants in the aquatic environment. The intention is to provide the audience, who may come from many different disciplines, an overview of the basic processes involved; of the special considerations for various aquatic environments such as rivers, lakes and estuaries; and of the approaches which may be useful for the assessment of dilution under different circumstances. Hopefully, it will help the audience to achieve an understanding of the physics of the process which will be necessary in an integrated approach to problems of environmental management.

## THE TRANSPORT MECHANISMS

The principal mechanisms for the transport of material in a flow field are advection and diffusion. Advection refers to the movement of material by the mean motion of the fluid and diffusion refers to the transport either by molecular motion cr by the turbulence associated with the flow. These two mechanisms are responsible for the distribution of material in the environment, whether it be in rivers, lakes or estuaries. If we

have, complete, quantitative information about these mechanisms, we would be able to predict the movement and the spreading of any waste discharge exactly. However, information on these mechanisms are incomplete and simplifying assumptions usually have to be made.

Advection

As advection is the transport by the mean current, the flux of material due to advection is simply the product of the mean velocity and the concentration, i.e.

$$J = uc \qquad (1)$$

in which c is the time-mean concentration, u is the time-mean velocity and J is the advective flux per unit area per unit time in the direction of the mean velocity.

Evaluating the advective flux therefore requires knowledge of the whole velocity field. This can range from a fairly simple steady, uniform flow situation in a straight canal to quite complex tidal flows in stratified estuaries. However, as we shall see later on, the three-dimensional velocity field is often either not completely known or is not necessary.

Molecular Diffusion

Molecular diffusion is the transport due to the motion of the molecules of the fluid in collision with one another and with molecules of the tracer in suspension. The collision rate

depends upon the fluid temperature, density and the properties of the tracer. Even though the motion of the molecules is random, a net transfer of the molecules of the tracer will take place from the region of higher concentration to the region of lower concentration. This is because there are more tracer molecules in the region of higher concentration so that, on the average there are more of these molecules moving into than out of the region of lower concentration.

Transport by moleculer diffusion was expressed quantitatively by Fick, who used an analogy between this process and the process of heat transfer by conduction. According to Fick, the rate of transfer of the diffusing substance through a unit cross sectional area is proportional to the concentration gradient measured normal to the section, i.e.

$$F=-D\frac{\partial c}{\partial x} \qquad (2)$$

in which x is the direction and F is the amount of substance diffusing per unit area per unit time in the x direction. The proportionality constant D is called the molecular diffusivity and it is a property of the diffusing substance and the fluid in which it is diffusing.

Turbulent Diffusion

The spreading of a substance due to the random turbulent fluctuations in the flow field is termed turbulent diffusion. In the case of molecular diffusion, the molecules perform the random motions which transport the tracer. In turbulent diffusion, it is the fluid particles which are performing the random motions. Mathematically, this transport is represented by the time average of the product of the fluctuating components of velocity and concentration. Experimental evidence has supported the assumption that turbulent diffusion transport is proportional to the gradient of the mean concentration. Therefore, by analogy with molecular diffusion, a turbulent diffusivity is introduced and the transport is written as

$$j=\overline{u'c'}-\varepsilon\frac{\partial c}{\partial x} \qquad (3)$$

in which j is the turbulent diffusive transport, u' and c' are the fluctuating components of velocity and concentration, respectively, the overbar refers to time averaging and $\varepsilon$ is the turbulent diffusion coefficient in the x direction. Unlike the molecular diffusivity, which is a property of the fluid and the diffusing substance, the turbulent diffusivity is a property of the flow field and changes with direction and location.

The spreading of a substance by turbulent diffusion is much more rapid than that by molecular diffusion. The value of the molecular diffusivity for many solutes in water is of the order of $10^{-5}$ $cm^2/s$.

The turbulent diffusivity for most natural flows are several orders of magnitude larger. Therefore, even though molecular diffusion is always present, it can safely be neglected in comparison with turbulent diffusion when considering the spreading of pollutants in the environment.

Shear Flow Dispersion

The spreading of materials in the aquatic environment is often enhanced by a process known as "shear dispersion" which comes about because of the shear or non-uniformity of the currents in the horizontal or vertical directions. This effect can be very important in rivers or estuaries which have significant velocity variations over their widths[11] or secondary flows due to non-uniform cross sections and also in lakes and coastal environments when the diffusing cloud is large enough so that the mean velocities are quite different between the leading and trailing edges. Because of the velocity differences, different parts of the diffusing cloud are advected at different rates and the shape of the cloud becomes distorted. This distortion results in increased concentration gradients which lead to increased transport by turbulent diffusion and the growth rate of the cloud can be very much greater than what it would be in a uniform current. This process is usually referred to as dispersion.

Figure 1 presents a qualitative demonstration of the enhancement of spreading by dispersion.

When the transport by current shear can be quantified, it is of course desirable to consider it separately from the other transport mechanisms. However, it is often not possible to do this in practice and the effect of shear is usually lumped together with the diffusion process. The resulting turbulent mixing coefficient then embodies the effect of both turbulent diffusion and shear flow dispersion.

## THE MASS CONSERVATION EQUATION

The mechanisms responsible for the transport of material in a water body have been described in the previous sections. These descriptions can help us understand the mixing process but are not sufficient as a tool for analyzing mixing problems. Nearly all mathematical analysis of the mixing process are based on the application of the principle of conservation of mass. Considering an arbitrary control volume, the principle requires that the sum of the transport of material into and out of the control volume due to advection by the total instantaneous velocity and due to molecular diffusion must be equal to the change in the mass of material in the control volume, resulting in the equation

$$\frac{\partial C}{\partial t}+U.\nabla C=D\nabla^2 C \qquad (4)$$

in which U and C are the instantaneous three-dimensional velocity vector and concentration, respectively.

Because the instantaneous velocity is generally not available, equation (4) cannot be applied in practice. To obtain a useable equation, we write the velocity U, as the sum of a time-averaged velocity plus a fluctuating component. The instantaneous concentration is likewise split into two parts. Substituting these into equation (4) and applying the Reynolds' Rules of Averaging, we obtain the so called advective diffusion equation. In Cartesian coordinates, this is written as

$$\frac{\partial c}{\partial t}+\frac{u\partial c}{\partial x}+\frac{v\partial c}{\partial y}+\frac{w\partial c}{\partial z}=-\frac{\partial \overline{u'c'}}{\partial x}-\frac{\partial \overline{v'c'}}{\partial y}-\frac{\partial \overline{w'c'}}{\partial z} \qquad (5)$$

in which c is the time-mean concentration; c' is the fluctuating

component of the concentration; u, v and w are the time-mean velocities in the x, y and z directions, respectively; and u', v' and w' are the corresponding fluctuating components of velocity. As shown in equation (3), the transport by turbulent diffusion is assumed to be proportional to the gradient of the mean concentration. Using this assumption, and neglecting the molecular diffusion term, equation (5) is reduced to

$$\frac{\partial c}{\partial t}+\frac{u\partial c}{\partial x}+\frac{v\partial c}{\partial y}+\frac{w\partial c}{\partial z}=\frac{\partial}{\partial x}(\varepsilon_x\frac{\partial c}{\partial x})+\frac{\partial}{\partial y}(\varepsilon_y\frac{\partial c}{\partial y})+\frac{\partial}{\partial z}(\varepsilon_z\frac{\partial c}{\partial z}) \quad (6)$$

Equation (6), usually after simplification by various assumptions, is the basis of most mathematical analysis of pollutant transport. It should be kept in mind that the above formulation is limited to conservative substances which undergo no process other than dilution. Processes such as production and decay, chemical reactions and transformations etc. have not been considered.

## MIXING IN THE NEAR FIELD

For effluents which are discharged into the receiving waters through a pipe or some other type of outfall, there is a region in the immediate vicinity of the outfall in which the mixing of the effluent is controlled largely by the characteristics of the discharge. In this region, the turbulence created by the

momentum and the buoyancy of the discharge dominates the mixing process. Further away from the discharge, when the excess momentum and buoyancy have been dissipated, the mixing is governed by the flow and the turbulence in the receiving water. These regions are often referred to as the "near-field" and the "far-field" respectively. The difference in the characteristics of the effluent plume in these two regions results in different types of analyses being used to calculate the pollutant mixing.

The extent of the near-field can vary greatly depending on the type of discharge. For a large ocean outfall, this region can extend for hundreds of metres with significant dilution of the discharge. For many small municipal and industrial effluents, the momentum and buoyancy are so small that the near-field is practically non-existent and the effluent mixing can be considered to be entirely governed by the ambient conditions.

In the near field, where the effluent is discharged into the water in the form of a jet or a series of jets, the shear which is generated between the discharge and the surrounding fluid creates eddies which entrain ambient fluid into the jet and dilutes the discharge. Often, the effluent is less dense than the ambient water and the plume will rise towards the water surfaces until it has reached the surface or until the excess buoyancy is too small to push the plume through a barrier such as a thermal stratification. The plume will then spread laterally. Normally, the most important information required are the level of rise of the plume- whether it will remain submerged or will

reach the surface- and the thickness of the plume at that point which will give an indication of the amount of dilution. Analysis of the mixing in the near field relies heavily on the theory of buoyant jets and plumes. The methods used range from simple dimensional analysis to sophisticated turbulence modelling.[38,41] The former tries to establish, through dimensional reasoning, power law relationships between the dependent variables such as centreline velocity and plume width and relevant parameters such as mass flux, momentum flux or buoyancy flux. The latter tries to solve the mass conservation equation together with the equations of motion, using some form of turbulence closure relationships.[40]

As the topic of outfall design will be discussed in the upcoming lecture on "ocean disposal of wastewater", I shall not go into any more detail about mixing in the near field. However, it is pertinent to point out that the problem of initial dilution is one in which the designer of the discharge does have considerable control because it is affected by the jet discharge geometry such as nozzle diameter, spacing, exit velocity etc., in addition to external conditions such as water depth, density stratification and current velocity.

## MIXING IN THE FAR FIELD

As one moves away from the source, the excess momentum and buoyancy of the effluent discharge becomes dissipated and the spreading of the plume becomes independent of the discharge

conditions. At this point, the current and the turbulence in the receiving water control the mixing and spreading of the plume. The mechanisms which are responsible for the mixing process have already been described and they are the same for all types of receiving waters, whether it be rivers or lakes or estuaries. However, the different hydrodynamic conditions which exist in these environments often lead to different methods of analysis. Assumptions which are generally acceptable for analyzing river plumes may not be appropriate for lakes. Therefore, the different types of receiving waters will be discussed separately.

River Mixing

Consider a river receiving a constant source of discharge as shown in Figure 2. At a certain distance from the discharge, the effluent would have been mixed fairly well throughout the depth of the river. From there on the spreading takes place across the width until a point downstream where the effluent is well mixed across the whole cross section. It is instructive to compare the distance required for vertical mixing, $L_v$, with the distance required for mixing across the cross section, $L_m$. By assuming that the vertical eddy diffusivity is equal to the average vertical momentum diffusion coefficient and making use of an experimentally determined lateral mixing coefficient, the ratio between these two distances can be written as[8]

$$\frac{L_m}{L_v} \approx 0.45 \left(\frac{W}{h}\right)^2 \tag{7}$$

in which W is the width and h is the depth.

Because rivers are typically much wider than they are deep, the ratio W/h is usually no less than twenty to thirty and $L_m$ is normally at least a few hundred times larger than $L_v$. Therefore, for most natural streams, a tracer will have been well mixed throughout the depth before it has spread very much across the width. As a result, analysis of mixing in rivers and streams can usually be simplified by neglecting any vertical variations and considering only the changes in the depth-averaged value of the concentration across stream and downstream. For the problem of a steady discharge, the normal procedure is to integrate the mass conservation equation, equation (6), over the depth to obtain the following equation for the depth-averaged quantities in which the double overbar denotes depth-averaged value of a quantity

$$\frac{\partial}{\partial x}(huc) + \frac{\partial}{\partial z}(hwc) = \frac{\partial}{\partial z}\left(h\bar{\bar{\varepsilon}}_z \frac{\partial \bar{\bar{c}}}{\partial z}\right) - \frac{\partial}{\partial z}\left(h\overline{\overline{w'c'}}\right) \tag{8}$$

and $w'$ and $c'$ refer to the deviations of w and c, respectively,

from their depth-averaged values. The turbulent diffusion term in the x direction has been neglected because it is small in comparisonwith the advection term.

The term $w^y c^y$ represents the transport by shear dispersion which was described previously. There is no method of separating its effect from the transport by turbulent diffusion and we have no recourse but to lump the two together by the following expression

$$(\bar{\bar{e}}_z \frac{\partial \bar{\bar{C}}}{\partial z} - \overline{\overline{w^y c^y}}) = e_z \frac{\partial \bar{\bar{C}}}{\partial z} \tag{9}$$

The coefficient $e_z$ is the lateral turbulent mixing coefficient which includes the effects of both diffusion and shear dispersion.

Using the above definition of the lateral mixing coefficient, equation (8) can be written as

$$\frac{\partial}{\partial x}(huc) + \frac{\partial}{\partial z}(hwc) = \frac{\partial}{\partial z}(e_z \frac{\partial c}{\partial z}) \tag{10}$$

It should be noted that, for natural streams, there is almost always a secondary velocity in the lateral direction. This advective transport in the lateral direction should not be lumped together with the dispersion term. Otherwise, one would not be

able to explain such phenomena as the narrowing of a dye plume in the downstream direction as shown in Figure 3.

Because the velocities and depths usually vary from point to point, equation (10) has to be solved numerically. The data which are required for computing the concentration profiles are the depth averaged velocities and depths at a number of cross sections, an upstream concentration distribution and the value of the lateral mixing coefficient.

In order to take into account stream curvature and to eliminate the need to measure or calculate the transverse velocity, a general curvilinear coordinate system, as shown in Figure 4, can be used together with a streamtube concept to transform equation (10) in the following simpler equation[5]

$$\frac{\partial c}{\partial x}=\frac{\partial}{\partial q}\left(E_x\frac{\partial c}{\partial q}\right) \qquad (11)$$

in which $m_x$ is a metric coefficient, $E_x=uh^2m_xe_x$ is a dispersion factor and q us a cumulative discharge coordinate defined by

$$q=\int_0^z hum_x\,dz \qquad (12)$$

Equation (11) includes all the physical mechanisms contained in equation (10) and has the advantage of incorporating the stream curvature plus being simpler in form. It has been most often used for calculating steady state concentration distributions from continuous sources.

The lateral mixing coefficeint, $e_z$, which is a required input to the solution of equation (10) or (11), is the most difficult piece of information to obtain. There is no theoretical basis on which one can predict the value of this parameter and the best way to ensure an accurate value is to conduct a dye test on the actual river reach in question and use the dye concentration data to evaluate $e_z$.[5] If a dye test is not feasible, then it is necessary to select a value based on our knowledge of how $e_z$ varies with river geometry and flow conditions.

Because the turbulence in a river is generated primarily by the bed shear stress and the size of the largest turbulent eddies are of the order of the flow depth, the mixing coefficient should scale with the shear velocity $U_*$ and the depth h. Data gathered by various researchers have shown that the dimensionless mixing coefficient, $e_z/U_*h$, varies between approximately 0.25 for relatively straight uniform channels to 1.0 or larger for very sinuous reaches.[*6] The sinuosity of a reach appears to have a fairly large influence, possibly because of its influence on the secondary circulation and the shear dispersion.

If a pollutant source is not continuous but is introduced into the river all at one time, such as in the case of an accidental spill, the pollutant patch will spread laterally and longitudinally, as depicted in Figure 5. Before the pollutant cloud has travelled the mixing distance, $L_F$, where it will have been fairly well mixed across the whole cross section, the concentration has to be calculated from the two dimensional equations with, of course, the addition of the time derivative term.[16,31] After the cloud has mixed fairly well across the cross section, it has been shown that its longitudinal spread can be modelled as a gradient diffusion process and the cross sectional average concentration can be described by the equation

$$\frac{\partial \hat{C}}{\partial t} + \hat{U}\frac{\partial \hat{C}}{\partial x} = D_L \frac{\partial^2 \hat{C}}{\partial x^2} \qquad (13)$$

in which the ^ refers to a cross-sectional average and $D_L$ is called the longitudinal mixing coefficient.

The analytical solution to equation (13) for a mass M released instantaneously throughout the cross section of area, A, is

$$C = \frac{M}{2A\sqrt{\pi D_L t}} \exp\left[-\frac{(x-\hat{U}t)^2}{4D_L t}\right] \qquad (14)$$

From this solution, it can be deduced that the peak concentration should decrease as $x^{-0.5}$ and that the variance of the time-concentration curve at a given cross section should increase linearly with x.

To apply this one-dimensional longitudinal dispersion equation, one must have a value for the coefficient $D_L$ as well as an estimate of how far downstream one must go before this equation is applicable. Unfortunately, there are huge variations in the published values of the dimensionless dispersion coefficient,[8] making the field determination of $D_L$ almost a necessity. The downstream distance, $L_F$, required for the onset of one-dimensional mixing has been given as[9]

$$L_F = \frac{1.8\ell^2 u}{u_* h} \qquad (15)$$

in which $\ell$ is taken as the distance from the point of maximum velocity to the farthest bank. However, it has been pointed out that, for most engineering applications, the region of interest is shorter than $L_F$, making it necessary to use a two-dimensional analysis or some modified form of one-dimensional analysis which take into account the non-Fickian behaviour.[2]

## LAKE AND RESERVOIR MIXING

Mixing problems in lakes and reservoirs are more complicated than those in rivers mainly because the hydrodynamics are more complicated. While gravity drives a river's flow and its turbulence is mainly generated by the bottom shear stress, factors affecting lake hydrodynamics include wind stress, wave action, periodic oscillations, inflows, outflows and, in particular, thermal stratification.

The annual cycle of temperature stratification plays an important part in lake and reservoir dynamics. Looking at a lake in a temperate region in spring, one would find that the whole lake would be at a uniform temperature of about 4°C. As the weather warms, the surface layer is warmed up and currents set up by the wind generate mixing and lead to the downward transport of heat.

As summer approaches, this heating causes the water to be divided into an active upper layer of more or less uniform temperature, termed the *epilimnion*, and a deep, cold, relatively undisturbed region termed the *hypolimnion*. These two regions are separated by a relatively narrow layer in which the temperature decreases rapidly with depth, termed the *thermocline*. This structure is maintained through the summer months until the weather begins to cool in the autumn. The cooling of the upper layer meads to a steady increase of the thickness of the epilimnion until it eventually includes the whole depth. The whole lake is then at

the same temperature and is freely circulating. This is called the fall overturn. This condition prevails until the onset of spring when the cycle is repeated.

Many different processes contribute to mixing in lakes and reservoirs.[11] During calm conditions, the diurnal heating and cooling lead to mixing by natural convection in which the cooled surface water sinks as a plume downward and warmer water rises. Winds create surface waves, producing turbulence which gets transported to the lower parts of the epilimnion. Increasing wind stress induces a circulating current in both the epilimnion and the hypolimnion, causes the thermocline to tilt and creating downwelling of surface water and upwelling of bottom water at the upwind and downwind shores. The oscillations or seiching caused by the periodic wind action can also create turbulence at the boundaries. Inflows which have a higher density can travel along the bottom, right into the hypolimnion, producing turbulent shear and mixing. In general, one would find a two-layered system with the epilimnion being well mixed vertically by the wind stress and by natural convection and a lower layer of much smaller mean motion. This two-layered structure with a thermocline is very significant as far as the mixing processes are concerned. The density stratification associated with the thermocline inhibits downward diffusion because the stable density gradient suppresses turbulence. This kind of structure has to be considered when designing intakes and discharges. For instance, it may be

advantageous for power plants to locate the inlet for cooling water at the hypolimnion while discharging the heated waste water at the epilimnion. In oceanic coastal zones, submerged sewage outfalls are often used to discharge wastes at some distance from the shore, with the objective of trapping the effluents below the thermocline so that further dilution can take place before the effluent plume reaches the surface. In lakes, however, this may not be a practical strategy. Because dispersion in the hypolimnion is relatively weak, the frequent upwelling of coastal waters may bring very high waste concentrations to the surface close to the shore.

Because so many processes contribute simultaneously to the transport and mixing, it is very difficult to account for their effects separately. Therefore, it is usual to consider their combined effect in terms of an effective diffusion coefficient and relate this coefficient with some physical parameter. In our previous discussion on river mixing, it was shown that the eddy diffusivity depends only on the turbulence and has a constant value for a particular flow. This is because the eddy size is essentially limited by the depth of the river. In large bodies of water, e.g., in the open ocean, there may not be any natural limit to the size of eddies and the diffusivity depends not only on the turbulence but also on the size of the diffusing cloud itself. This consideration leads to the well known Richardson's 4/3 law[39], in which the diffusivity increases as the 4/3 power of

the length scale of diffusion. In lakes and reservoirs, diffusion coefficients will increase with the length scale, although not necessarily according to the 4/3 law.

Because the horizontal scales of motion in lakes are much larger than the vertical scales, their effects can be considered separately and it is often assumed that a pollutant which is introduced is subject to horizontal mixing within a relatively thin layer in which all vertical variations in concentration and velocity can be neglected. Using this approach, the eddy diffusivities have been obtained from a large number of dye patch diffusion experiments in the Great Lakes in Canada. The results, shown in Figures 6 and 7, demonstrate that the horizontal turbulence is anisotropic. The diffusivity in the along-flow direction is much larger than that in the cross flow direction. In these figures, the along-flow and the cross-flow length scales, $L_x$ and $L_y$, are taken as equal to three times the variance of the concentration distribution in those directions. What is also evident is the difference between the epilimnion and the hypolimnion, with the diffusivities in the hypolimnion being an order of magnitude smaller.

Because of the variability of the flow field as well as the length scale dependence of the eddy diffusivities, detailed predictions of concentration distributions usually require numerical solution of the two-dimensional mass conservation equation, with the velocity field provided by some hydrodynamic

model. However, in some relatively simple situations, analytical solutions can be used to obtain good qualitative estimates of dilution of continuous effluent plumes in steady, uniform currents.

Considering a source with concentration $C_o$ and discharge rate Q, the depth-average concentration in the steady state plume can be given by the equation

$$C=\frac{C_oQ}{4h\sqrt{\pi K_y xu}}\exp\left(\frac{-y^2u}{4K_yx}\right) \qquad (16)$$

in which x is the direction of the mean current and $K_y$ is the eddy diffusivity in the cross plume direction, assumed constant.

By making use of climatological data, one can determine the joint current speed and direction frequency and use equation (16) to calculate the mean dilution contours for specified current "episodes"[26], e.g., shore-parallel currents or weak current regimes. A couple of examples are shown in Figures 8 and 9. These calculations, though lacking the sophistication of numerical models incorporating diffusivity-length scale dependence, can nevertheless provide good first order estimates.

ESTUARY MIXING

Mixing processes in estuaries are extremely complicated owing to the many factors which affect the hydrodynamics. Estuary flows are driven by water surface slope as well as wind stress, and internal density variations. In addition, it is oscillatory in nature. The mean velocity contains fluctuations of varying periods. The resulting flows may be in different directions at different depths or at different sides. Often the velocity is not aligned with the channel axis. The interaction of advection and diffusion in such flows makes the analysis of mixing very complicated. In general, the mixing can be related to the action of the wind or the tide or can be caused by the river flow.[11]

Mixing caused by the wind is usually important only in wide estuaries or embayments. A constant wind stress exerted over a wide, shallow basin of non-uniform depth will generate a large scale circulation, with the flow primarily in the direction of the wind on the shallow side and against the wind on the deep side. This circulating current is a large scale mixing mechanism. The interaction of this circulating current with the tidal flow also causes additional mixing.

The tide causes mixing through the turbulence generated by bottom friction as the tidal flow moves over the channel bottom. This mixing mechanisms is similar to the turbulent diffusion occurring in steady river flows. At the same time, the tidal wave also

interacts with the bathymetry and generates large scale circulations. These circulating currents will lead to shear flow dispersion plus mixing caused by tidal "pumping" and "trapping". The shear flow dispersion effect is the same as that discussed previously for steady river flows. However, in estuaries this effect is usually smaller because the oscillatory nature of the flow somehow reverses the effect of the velocity shear. It is of consequence only when the period of the tidal flow is similar to the time required for cross sectional mixing.

Tidal pumping refers to the net residual circulation that is superimposed on the back and forth tidal flow. It can be caused by the earth's rotation which deflects flows to the right in the northern hemisphere, or it can be a result of the interaction of the tidal flow with the bathymetry. An example of this interaction is the flow at a narrow inlet to a wide bay. The inflow is concentrated at the centre, much like a jet entering a big basin while the ebb flow is more distributed all around, like a flow into a sink. Thus there will be a net inflow at the centre and an outflow at the sides of the bay. These currents cause mixing in the same way as the wind and gravity induced currents. The phenomenon is called tidal pumping to indicate that it derives its energy from the tide.

Tidal trapping occurs when there are side channels and small embayments. In the main channel, tidal elevations and velocities

are usually not in phase because of the momentum of the water which causes the current to continue moving in the same direction even after the water level has dropped. In the side channels, these are more in phase. A parcel of water moving upstream in a flood current can have a portion moving into a side channel. As the water level drops, this portion can come back into the main channel while the rest of the parcel in the main channel is still moving upstream. These parcels will now be separated, creating a dispersion effect.

The discharge of fresh water by the river into the estuary represents a source of buoyancy and this buoyancy flux, together with the kinetic energy of the tidal flow, determine the amount of density stratification in the estuary. The density gradient creates a pressure gradient which drives an internal circulation current. There will be a net upstream transport along the bottom and a net downstream transport along the surface. In a cross section of non-uniform depth, a transverse circulation will be set up which will enhance the transverse mixing. The velocity gradient across the width of the channel can create large shear flow dispersion effects.

Any or all of the processes described above can contribute simultaneously to the mixing in an estuary. Therefore, mixing coefficients defined for estuaries would contain the combined effects of all these advection and diffusion mechanisms, making

it very difficult to establish the magnitudes of these coefficients based on bulk channel parameters. Measurements of the transverse mixing coefficient show that the dimensionless coefficient, $e_z/U_*h$, to vary around 1.0.[48]

For some estuaries which are long and narrow and not strongly stratified, it is possible to use a one-dimensional analysis and consider the velocity, concentration and salinity to be a function of only the longitudinal distance. All the other mixing mechanisms and cross sectional variations are lumped together into a longitudinal dispersion coefficient, K. This coefficient may be used in the one-dimensional equation

$$A\frac{\partial C}{\partial t}+Q_f\frac{\partial C}{\partial x}=\frac{\partial}{\partial x}\left(KA\frac{\partial C}{\partial x}\right) \qquad (17)$$

in which $Q_f$ is the fresh water discharge and the time derivative represents the change per tidal cycle.

The dispersion coefficient K can be obtained from an equation expressing the balance of salt for a steady state condition in the estuary. In steady state, the downstream advection of salt by the fresh water discharge is balanced by the upstream transport by all other mechanisms. This is written as

$$\frac{Q_f}{A}S=K\frac{\partial S}{\partial x} \qquad (18)$$

in which S is the salinity and $Q_r/A$ represents the net downstream velocity of the freshwater flow. Using equation (18), the value of K can be calculated based on salinity measurements. Many observed values of K are in the order of several hundred meters squared per second, which is smaller than the longitudinal dispersion coefficients observed in rivers of comparable size.[11]

For those types of estuaries in which the one-dimensional approach is applicable, the salt balance is a very useful tool for many engineering estimates such as the average dilution of a given pollution loading or the approximate mean retention time of a tracer inside the estuary. However, it must be kept in mind that the analysis should only be used for estuaries which are not

significantly stratified and which have retention times much longer than the time required for mixing across the width.

When the one-dimensional approach is not applicable, estuary studies have to rely on either numerical modelling or physical modelling, both of which require considerable skill on the part of the modeller as they are sometimes more of an art than an exact science.

## TRANSPORT BY SEDIMENTS

It would be inappropriate to discuss pollutant transport mechanisms without some consideration of the transport by

sediments. Many contaminants are adsorbed onto suspended sediments, especially those finer sediments in the silt and clay size ranges, and are transported in the particulate phase instead of in the dissolved phase. For most metals, for phosphorous, as well as for a number of synthetic organic compounds[25], it has been shown that transport by the particulates can be a high percentage of the total load. Therefore, unless the sediment load is negligible, analysis of pollutant transport or water quality modelling must take into account the transport by sediments. This means that, in addition to an equation for the mass conservation of the dissolved phase, one would need to solve another similar conservation equation for the particulate phase which is attached to the sediments. The particulates undergo advection and diffusion similar to the dissolved contaminants but, in addition, they possess a settling velocity which allows them to settle out of suspension and be lost to the water column. At the same time there is also the mechanism of resuspension which brings deposited material back into the flow. These processes must be included in the mass conservation equation. Of course, the exchange between the dissolved phase and the particulate phase also needs to be accounted for.

The settling of cohesive sediments is rather complicated because of the process of flocculation. The amount of flocculation depends upon the rate of collision of the particles and their ability to adhere to one another after collision.[17] In natural

flows, the rate of collision is largely governed by the fluid shear. The floc size is continually changing through aggregation and disaggregation which makes it difficult to assign a value for the settling velocity. Sometimes, the settling velocity is obtained through settling experiments in the laboratory. However, because the floc size is dependent on the turbulence in the flow, there is no guarantee that the settling velocity determined in the laboratory will resemble that occurring in the field. A floc may be able to settle through the water column but may not be able to deposit on the bed because the more intense turbulent shear near the bed can break up the floc so that the particles are re-entrained back into the flow.

In many water bodies, the bottom sediments have accumulated large quantities of contaminants. These contaminants can be brought back into the water column through resuspension brought about by increased turbulence at the sediment-water interface. This may occur because of increased discharge in river flows or increased wave action in shallow waters. In estuaries, there may be resuspension during flood flow and deposition during slack water. There are no reliable methods for calculating the depositional or resuspension fluxes. Field measurements of concentrations cannot separate these two phenomena. Therefore, the net effect of these two processes are usually lumped together in most analysis.
Analysis of pollutant transport to include the transport by sediments requires the simultaneous solution of the equations for

the conservation of dissolved and particulate concentrations.[35] This almost always requires numerical modelling. However, it must be kept in mind that many of the transport mechanisms for cohesive sediments are still poorly understood and that there are very few reliable expressions for settling velocities or deposition or erosion rates, especially if organic material is present.

## SUMMARY

A review of the physical mechanisms responsible for the transport of contaminants in the aquatic environment has been presented. The major mechanisms of advection, diffusion and shear dispersion are each shown to be a component of the mass balance equation which is the basic tool used for the analysis of pollutant transport. The different aquatic environments such as rivers, estuaries and lakes and reservoirs all possess certain distinct hydrodynamic characteristics. The mixing processes in these environments are each described and possible simplifications to the mass conservation equation are discussed. The role of fine sediments in the transport of contaminants and the difficulties involved with its analysis are briefly reviewed.

## SELECTED BIBLIOGRAPHY

1. Abraham, G., et al. 1981. Mathematical modelling of flows and transport of conservative substances: requirement for pedictive ability. In Transport Models for Inland and

Coastal Waters, H.B. Fischer (ed), Academic Press, New York.

2. Beltaos, S. 1980. Longitudinal dispersion in rivers. ASCE J. Hydraul. Div., 106(HY1), 151-172.

3. Beltaos, S. and Day, T.J. 1978. A field study of longitudinal dispersion. Can. J. Civil Eng., 5(4), 572-585.

4. Bowden, K.F. 1963. The mixing processes in a tidal estuary. Int. J. Air water Pollut., 7, 343-356.

5. Bowden, K.F. 1978. Mixing processes in estuaries. In Estuarine Transport Processes, B. Kjerfve (ed), Belle W. Baruch Library in Marine Science Number 7, Univ. of South Carolina Press, Columbia, South Carolina.

6. Csandy, G.T. 1973. Turbulent Diffusion in the Environment, D. Reidel, Boston.

7. Elder, J.W. 1959. The dispersion of marked fluid in turbulent shear flow. J. Fluid Mech., 5, 544-560.

8. Elhadi, N., et al. 1984. River mixing- a state-of-the-art report. Can. J. Civ. Eng., 11(3), 585-609.

9. Fischer, H.B. 1967. The mechanics of dispersion in natural streams. J. Hydraul. Div. ASCE, 93, 187-216.

10. Fischer, H.B. and Holley, E.R. 1971. Analysis of the use of distorted hydraulic models for dispersion studies. Water Resources Res., 7(1), 46-51.

11. Fischer, H.B., et al. 1979. Mixing in Inland and Coastal Waters. Academic Press, New York.

12. Hansen, D.V. and Rattray, M. 1965. Gravitational

circulation in straits and estuaries. Mar. Res., 23, 104-122.

13. Harden, T.O. and Shen, H.T. 1979. Numerical simulation of mixing in natural rivers. J. Hydraul. Div. ASCE, 105(HY4). 393-408.

14. Holley, E.R. 1971. Transverse mixing in rivers. Report No. S-132, Delft Hydraulic Laboratory, Delft, The Netherlands.

15. Holley, E.R. and Usseglio-Polatera, J.. 1984. Dispersion simulation in two-dimensional tidal flow. J. Hydraul. Eng. ASCE, 110(7), 905-926.

16. Holly, F.M. Jr. 1975. Two dimensional dispersion in rivers. Hydrology paper No. 78, Colorado State University, Fort Collins.

17. Hunt, J.R. 1982. Self-similar particle size distributions during coagulation: theory and experimental verification. J. Fluid Mech., 122, 169-185.

18. Imberger, J. 1976. Dynamics of a horizontally stratified estuary. Proc. Coastal Eng. Conf. ASCE, Honolulu, Hawaii, Vol. 4, 3108-3123.

19. Imberger, J. and Patterson, J.C. 1981. A dynamic reservoir simulation model-DYRESM:5 In Transport Models for Inland and Coastal Waters, H.B. Fischer (ed), Academic Press, New York.

20. Koh, R.C.Y. and Brooks, N.H. 1975. Fluid mechanics of waste water disposal in the ocean. Ann. Rev. Fluid Mech. 7,187-211.

21. Kraus, E.B. 1977. Modelling and Prediction of the Upper Layer of the Ocean. Pergaman Press, Oxford.

22. Krishnappan, B.G. and Lau, Y.L. 1983. User's manual for model RIVMIX. National Water Research Institute, Environment Canada, Burlington, Ontario.

23. Kuehnel, R.O.W., et al. 1981. A coastal dispersion model for effluent plumes. National Water Research Institute Report, Environment Canada, Burlington, Ontario.

24. Kullenberg, G. 1971. Vertical diffusion in shallow waters. Tellus, 23, 129-135.

25. Kuntz, K.W. and Warry, N.D. 1983. Chlorinated organic contaminants in water and suspended sediments of the lower Niagara River. J. Great Lakes Res., 9, 241-248.

26. Lam, D.C.L. and Murthy, C.R. 1978. Outfall diffusion models for the coastal zone. Proc. 16th Coastal Eng. Conf., Hamburg, Germany, ASCE, New York, 2584-2597.

27. Lam, D.C.L., et al. 1981. An inverse problem approach to modelling coastal effluent plumes. Adv. Water Res., 4,to 185- 190.

28. Lau, Y.L. 1985. Mixing coefficient for ice-covered and free-surface flows. Can. J. Civil Eng., 12(3), 521-526.

29. Lau, Y.L. and Krishnappan, B.G. 1977. Transverse dispersion in rectangular channels. J. Hydraul. Div. ASCE, 103(HY10), 1173-1189.

30. Lau, Y.L. and Krishnappan, B.G. 1981. Modelling transverse mixing in natural streams. J. Hydraul. Div. ASCE, 107(HY2),

209-226.

31. Luk, G., et al. 1989. Modelling river mixing with unsteady pollutant source. J. Envirnm. Eng. ASCE, 116(1), 125-143.

32. Lick, W. 1982. Entrainment, deposition and transport of fine-grained sediments in lakes. Hydobiologia, 91, 31-40.

33. Murthy, C.R. 1976. Horizontal diffusion characteristics in Lake Ontario. J. Phy. Ocean., 6, 76-84.

34. Mehta, A.J. and Partheniades, E. 1975. An investigation of the deposition properties of flocculated fine sediments. J. Hydraul. Res., 13(4), 361-381.

35. Onishi, Y. 1981. Sediment-contaminant transport model. J. Hydraul. Div. ASCE, 107(HY9), 1089-1107.

36. Okubo, A. 1971. Oceanic diffusion diagrams. Deep-Sea Res., 18, 789-802.

37. Okubo, A. 1976. Remark on the use of diffusion diagrams in modelling scale-dependent diffusion. Deep-Sea Res., 23, 1213-1214.

38. Rajaratnum, N. 1976. Turbulent Jets. Elsevier, Amsterdam. The Netherlands.

39. Richardson, L.F. 1926. Atmospheric diffusion shown on a distance neighbour graph. Proc. Roy. Soc. London, Ser. A, 110, 709-737.

40. Rodi, W. 1980. Turbulence models and their application in hydraulics. State-of-the-art paper. Int. Assoc. for Hydraul. Res., Delft, The Netherlands.

41. Rodi, W., et al. 1982. Buoyant Jets and Plumes. Pergamon

Press, Oxford.

42. Sayre, W.W. 1986. Dispersion of mass in open-channel flow. Hydraul. Paper No. 3, Colorado State Univ., Fort Collins.

43. Taylor, G.I. 1921. Diffusion by continuous movements. Proc. London Math. Soc. Ser. A., 20, 196-211.

44. Taylor, G.I. 1953. Dispersion of soluble matter in solvent flowing slowly through a tube. Proc. Roy. Soc. London Ser. A, 219, 186-203.

45. Taylor, G.I. 1954. The dispersion of matter in turbulent flow through a pipe. Proc. Roy. Soc. London Ser. A, 223, 446-468.

46. Thatcher, M. and Harleman, D.R.F. 1972. A mathematical model for the prediction of unsteady salinity intrusion in estuaries. R.M. Parsons Laboratory Rep. No. 144, Massachusetts Institute of Technology, Cambridge, Massachusetts.

47. Valentine, E.M. and Wood, I.R. 1977. Longitudinal dispersion with dead zones. J. Hydraul. Div. ASCE, 103(HY9), 975-990.

48. Ward, P.R.B. 1976. Measurements of estuary dispersion coefficient. J. Environm. Eng. Div. ASCE, 102, 855-859.

49. Yotsukura, N. and Cobb, E.D. 1972. Transverse diffusion of solutes in natural streams. USGS Professional Paper 582-C.

50. Yotsukura, N. and Sayre, W.W. 1976. Transverse mixing in natural channels. Water Resour. Res. 12(4) 695-704.

51. Zimmerman, J.T.F. 1978. Topographic generation of residual

circulation by oscillatory (tidal) currents. Geophys. Astrophys. Fluid Dynam., 11, 35-47.

LIST OF CAPTIONS

Figure 1. Increased spreading caused by shear flow dispersion.

Figure 2. Plume resulting from a continuous effluent in a river.

Figure 3. Concentration profiles in a river plume. Note the narrowing of the plume due to transverse advection. (from Lau and Krishnappan, 1981).

Figure 4. Natural curvilinear coordinate system.

Figure 5. Spreading of a dye patch released into a river.

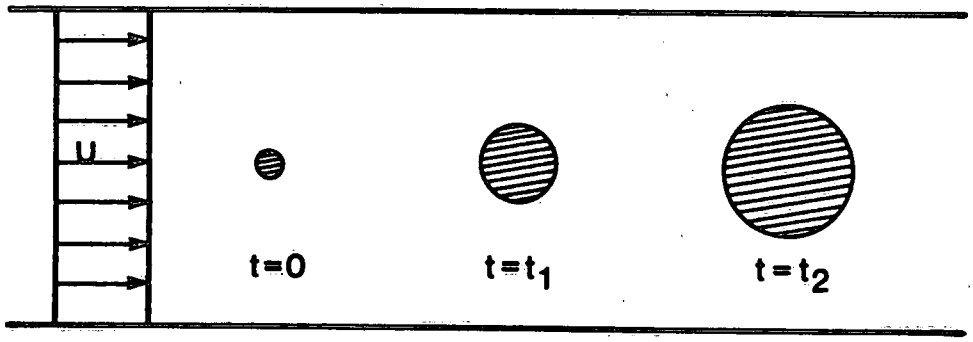
Figure 6. Variation of eddy diffusivity $K_x$ with length scale. (from Murthy, 1976).

Figure 7. Variation of eddy diffusivity $K_y$ with length scale. (from Murthy, 1976).

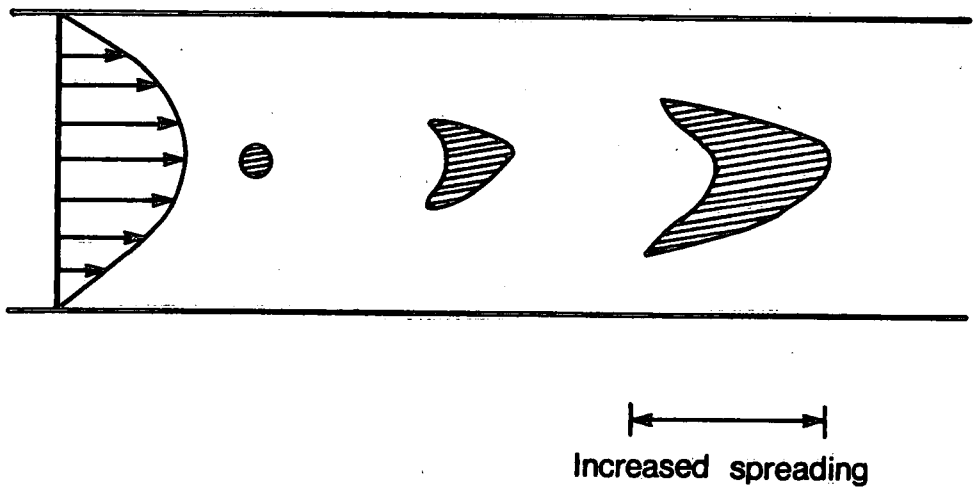
Figure 8. Simulated concentration contours for a shore-parallel current regime in a lake. (from Lam and Murthy, 1978).

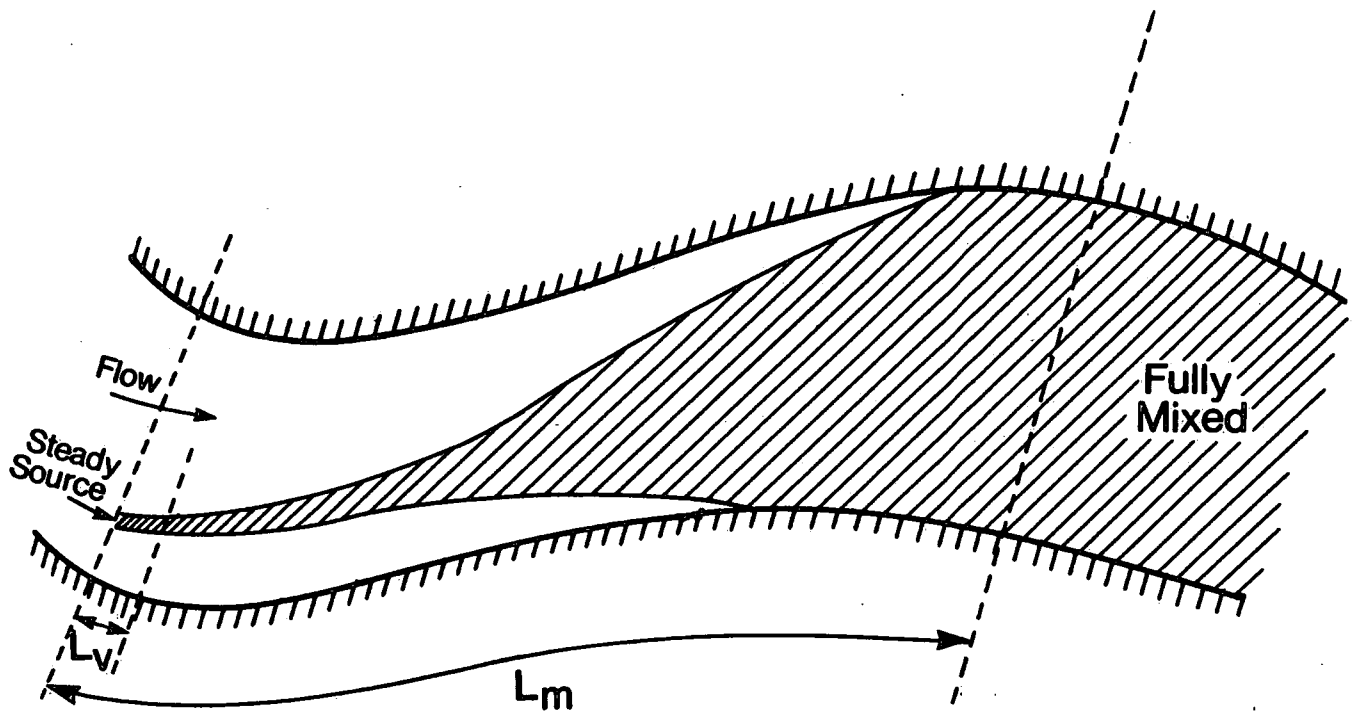
Figure 9. Simulated concentration contours for a weak current regime in a lake. (from Lam and Murthy, 1978).

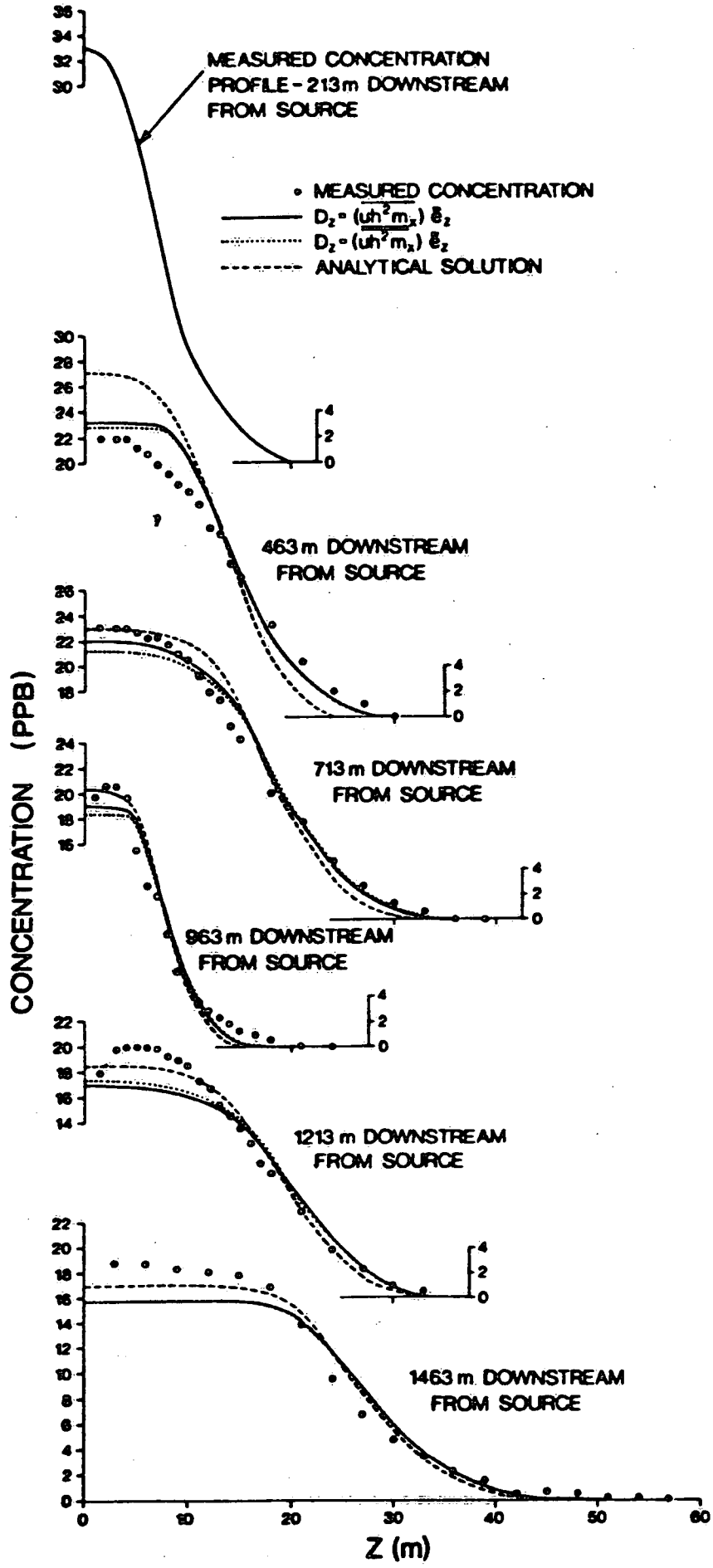
## Uniform Advection & Diffusion



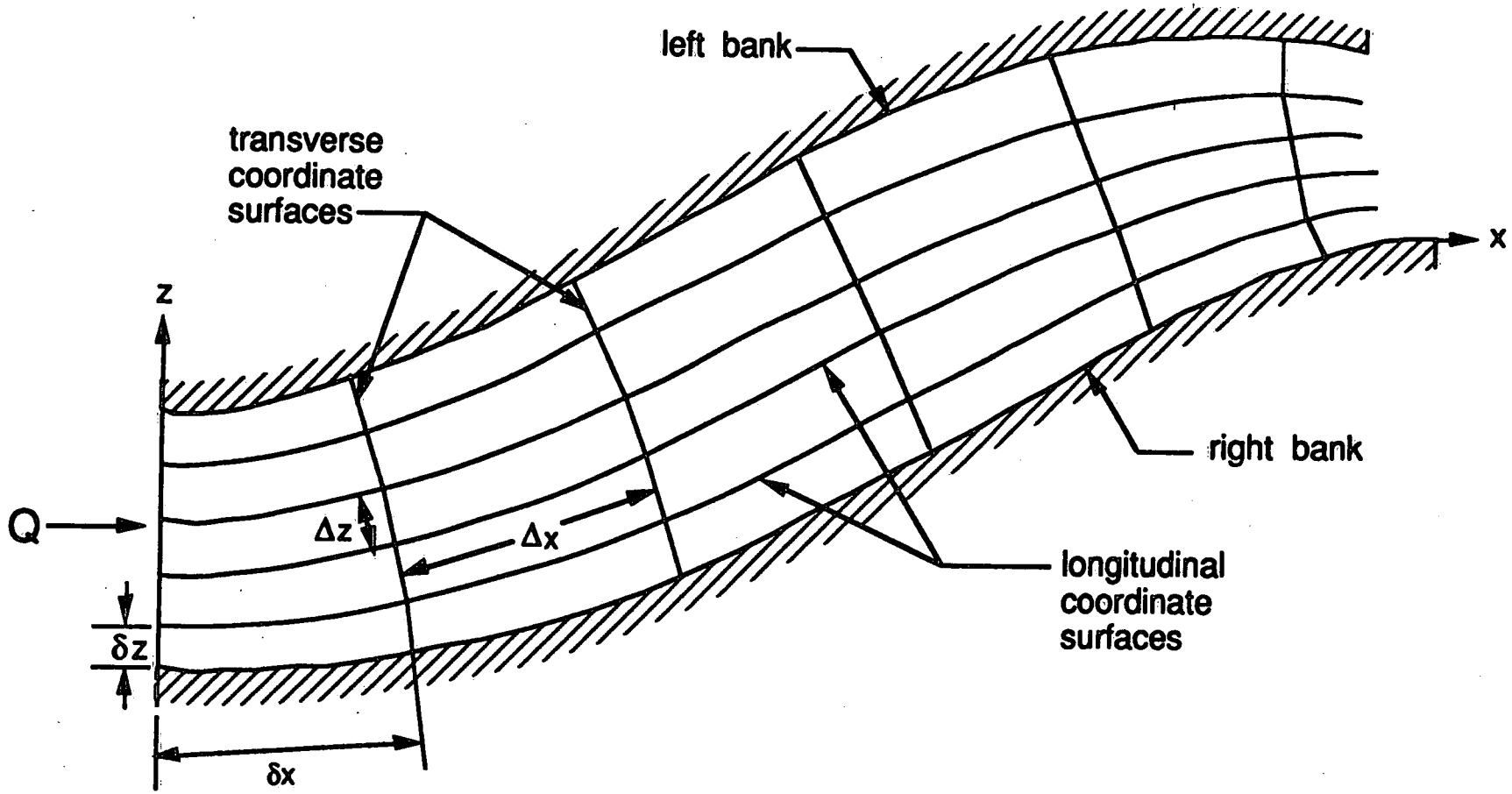

## Velocity Shear & Diffusion




Flow
Steady
Source
Fully
Mixed
$L_v$
$L_m$

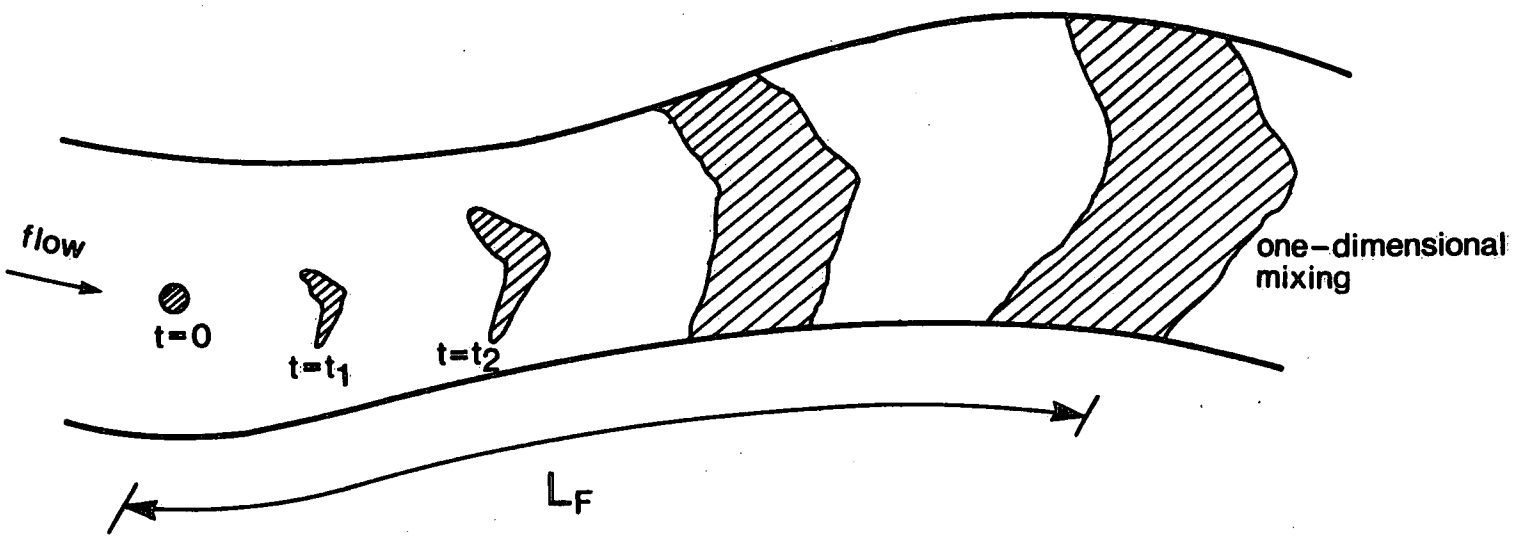

MEASURED CONCENTRATION PROFILE - 213m DOWNSTREAM FROM SOURCE
• MEASURED CONCENTRATION
$D_z = (\overline{uh^2 m_x})\,\bar{\varepsilon}_z$
$D_z = (uh^2 m_x)\,\bar{\varepsilon}_z$
ANALYTICAL SOLUTION
463 m DOWNSTREAM FROM SOURCE
713 m DOWNSTREAM FROM SOURCE
963 m DOWNSTREAM FROM SOURCE
1213 m DOWNSTREAM FROM SOURCE
1463 m DOWNSTREAM FROM SOURCE
CONCENTRATION (PPB)
Z (m)

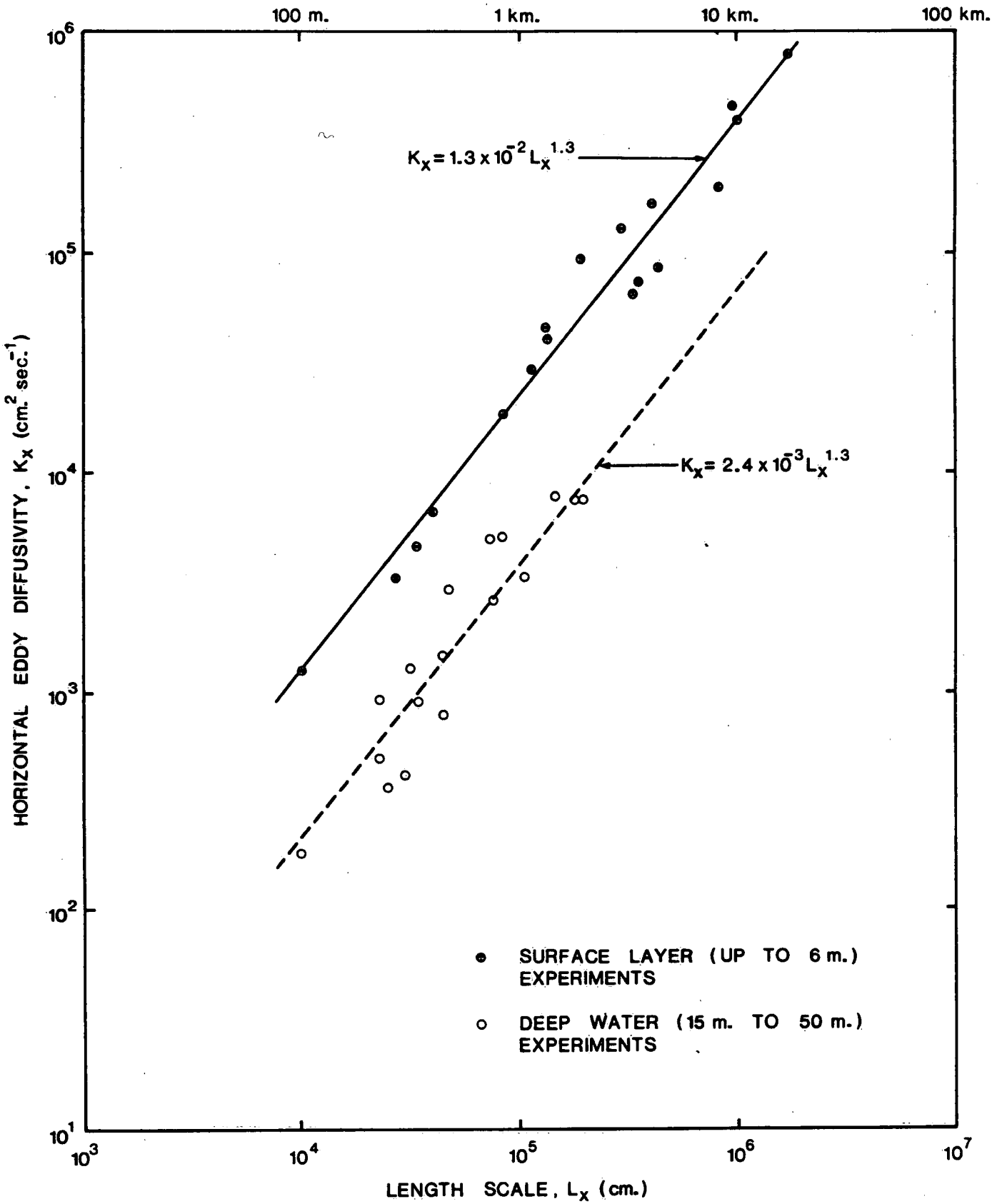
-193

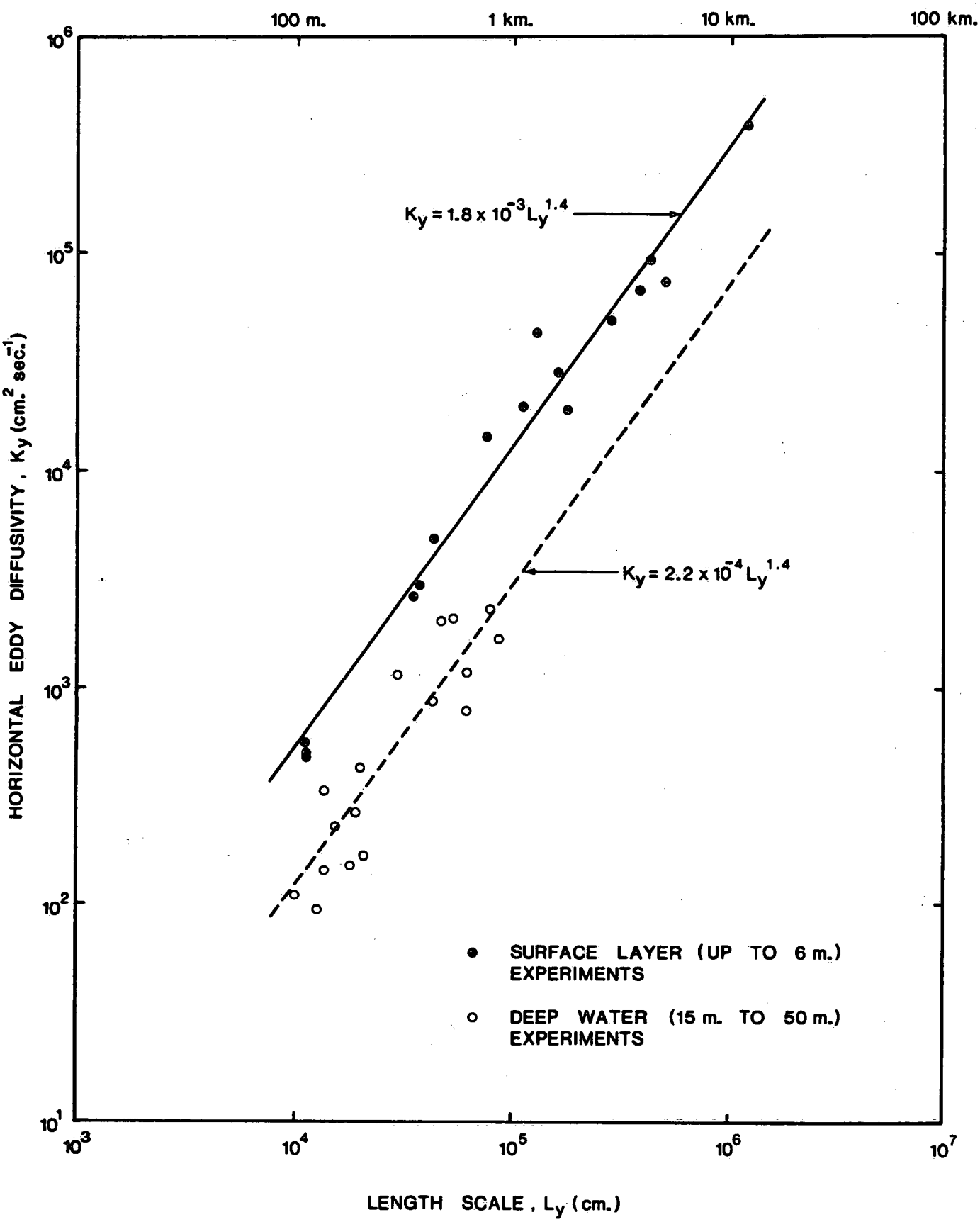


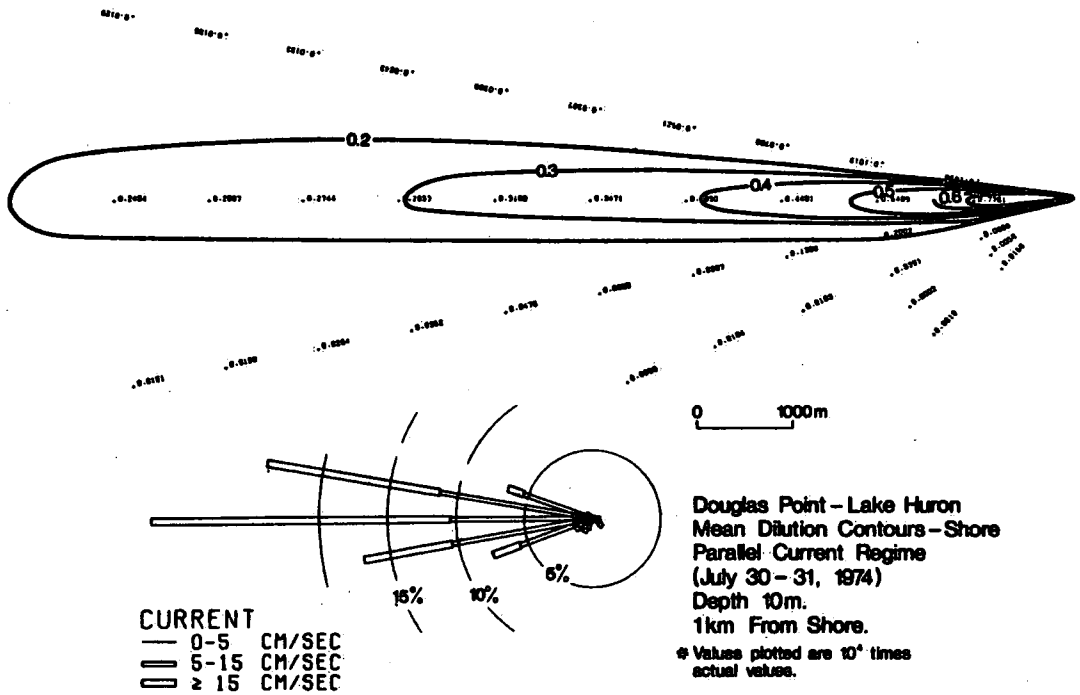

$$\Delta x = m_x \delta x$$

$$\Delta z = m_z \delta z$$


flow
t=0
t=t1
t=t2
one-dimensional
mixing
LF

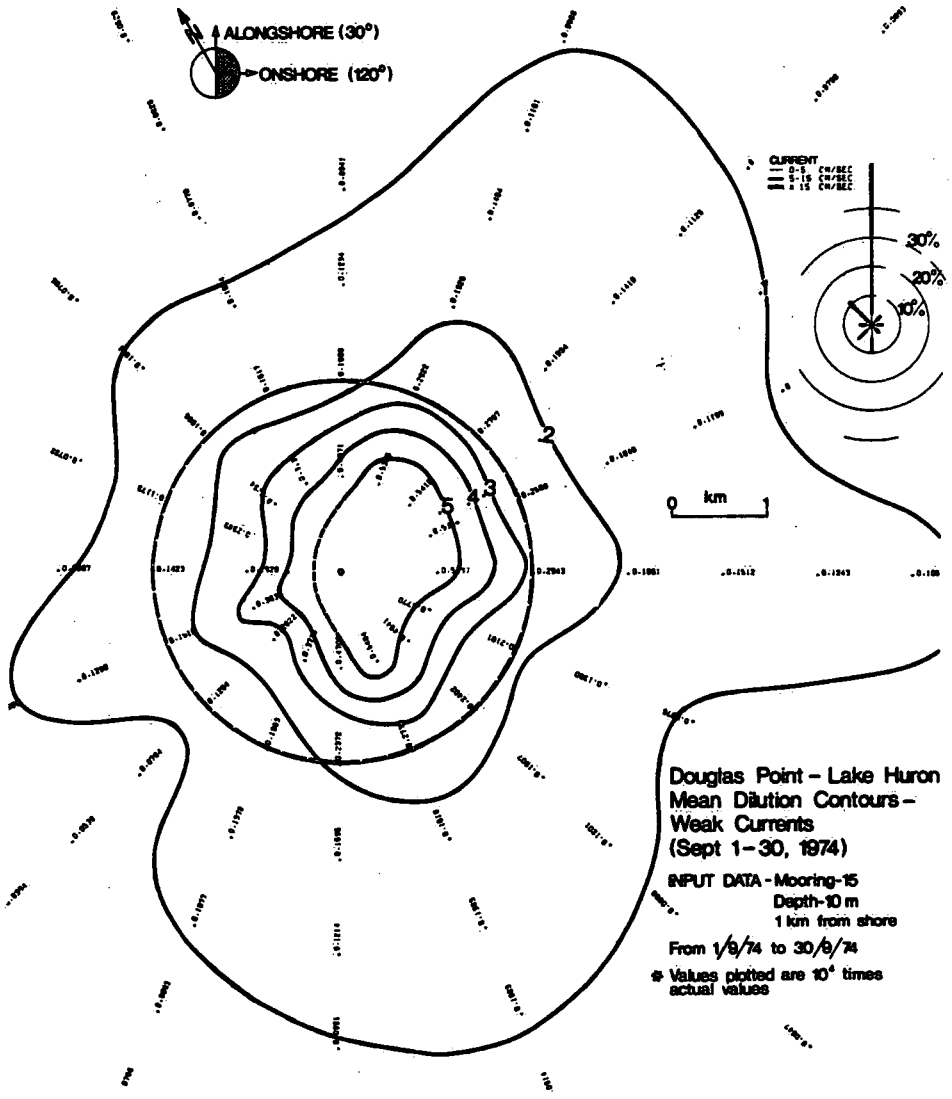

100 m.
1 km.
10 km.
100 km.
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$K_x = 1.3 \times 10^{-2} L_x^{1.3}$
$K_x = 2.4 \times 10^{-3} L_x^{1.3}$
HORIZONTAL EDDY DIFFUSIVITY, $K_x$ ($cm.^2 sec.^{-1}$)
SURFACE LAYER (UP TO 6 m.) EXPERIMENTS
DEEP WATER (15 m. TO 50 m.) EXPERIMENTS
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
LENGTH SCALE, $L_x$ (cm.)

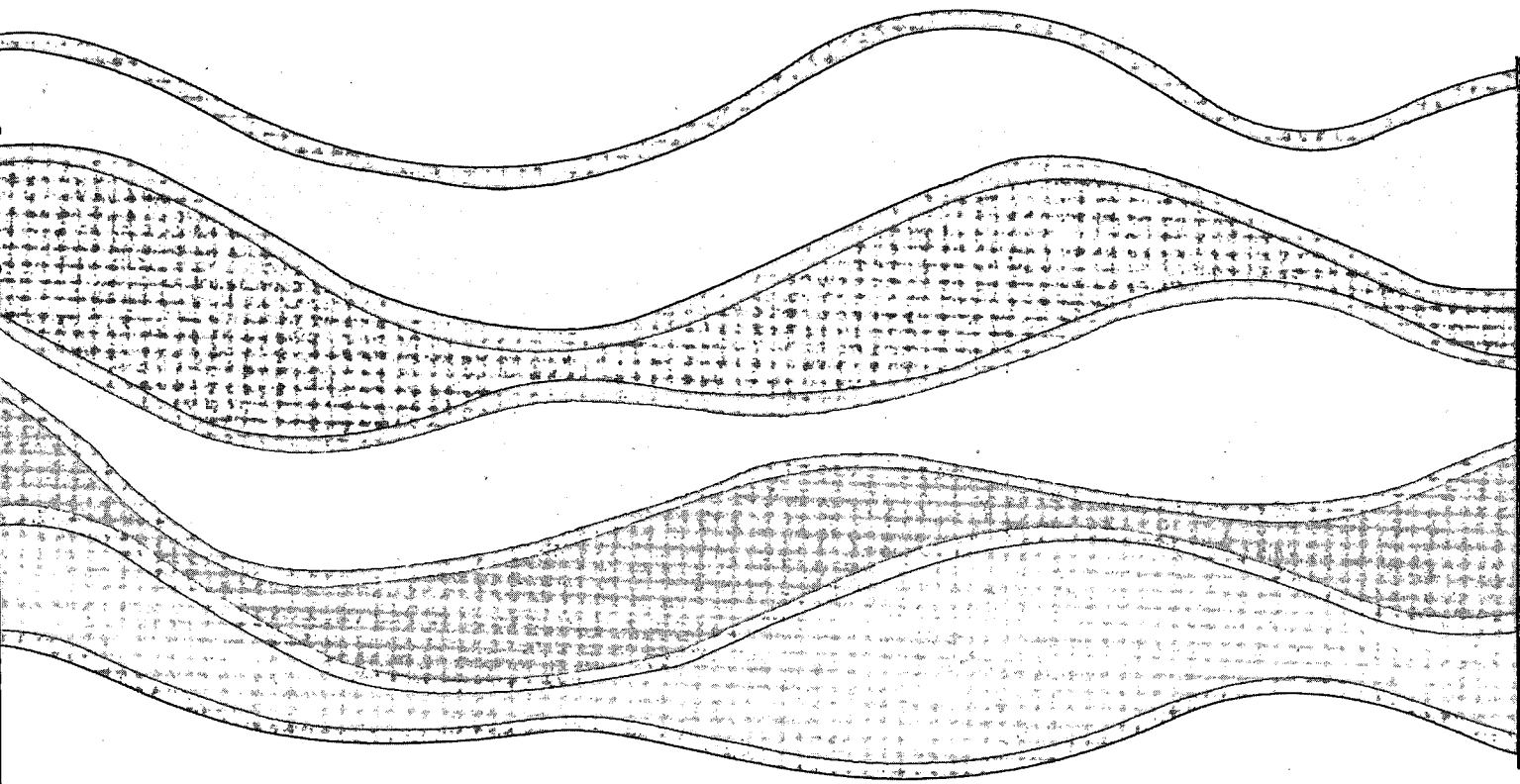

100 m.
1 km.
10 km.
100 km.
$10^6$
$10^5$
$10^4$
$10^3$
$10^2$
$10^1$
$K_y = 1.8 \times 10^{-3} L_y^{1.4}$
$K_y = 2.2 \times 10^{-4} L_y^{1.4}$
SURFACE LAYER (UP TO 6 m.) EXPERIMENTS
DEEP WATER (15 m. TO 50 m.) EXPERIMENTS
HORIZONTAL EDDY DIFFUSIVITY, $K_y$ (cm.$^2$ sec.$^{-1}$)
$10^3$
$10^4$
$10^5$
$10^6$
$10^7$
LENGTH SCALE, $L_y$ (cm.)




Douglas Point – Lake Huron
Mean Dilution Contours – Shore
Parallel Current Regime
(July 30 – 31, 1974)
Depth 10m.
1km From Shore.

* Values plotted are $10^4$ times actual values.


ALONGSHORE (30°)
ONSHORE (120°)
CURRENT
0-5 CM/SEC
5-15 CM/SEC
> 15 CM/SEC
30%
20%
10%
0 km 1
2
3
4
5
Douglas Point - Lake Huron
Mean Dilution Contours -
Weak Currents
(Sept 1-30, 1974)
INPUT DATA - Mooring-15
Depth-10 m
1 km from shore
From 1/9/74 to 30/9/74
* Values plotted are 10⁴ times actual values



NATIONAL WATER RESEARCH INSTITUTE
P.O. BOX 5050, BURLINGTON, ONTARIO L7R 4A6

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INSTITUT NATIONAL DE RECHERCHE SUR LES EAUX
C.P. 5050, BURLINGTON (ONTARIO) L7R 4A6