

A FIELD INVESTIGATION OF THE LATERAL
TURBULENT DIFFUSION COEFFICIENT IN
THE OTTAWA RIVER

by

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ABSTRACT

An account of the theories relating to the turbulent lateral diffusion coefficient in open channels is given. A literature survey of the field studies carried out to measure this coefficient was conducted. The author develops an Idealized Gradient Diffusion Model to simulate gradient diffusion in open channels.

Dye diffusion studies were conducted on a reach of the Ottawa River over a range of Reynolds numbers varying from 0.7×10^6 to 2.0×10^6 . The continuous sampling method used has not been used previously in any reported field study of this scale. The author's study is reported and the results are analyzed.

It was found necessary to apply a constraint to the Idealized Gradient Diffusion Model to get meaningful results. An expression results to estimate the depth-averaged lateral turbulent diffusion coefficient from the hydraulic parameters of the flow.

Recommendations are made for improved field procedure and for future research needs.

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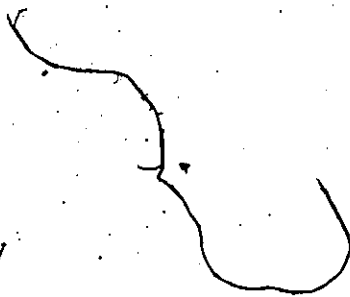
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LIST OF SYMBOLS

- a = area
- b = top width of the channel
- c = instantaneous concentration
- \bar{c} = time averaged concentration
- c' = fluctuating concentration
- $\bar{\bar{c}}$ = spatial average of the time averaged concentration
- d = total depth of flow
- E_L = Eulerian length scale for vertical mixing
- E_T = Eulerian time scale for vertical mixing
- Fr = Froude Number
- g = acceleration due to gravity
- i = index
- k = constant
- K = coefficient of eddy diffusion
- l = dimensionless longitudinal distance
- L = mean size of eddies causing diffusion
- L_T = Lagrangian time scale of turbulence
- m = constant
- M = mass of tracer
- n = constant
- p = constant
- r = constant
- Re = Reynolds Number
- R_T = Lagrangian correlation coefficient



- s = hydraulic gradient
- t = time
- u = instantaneous velocity
- \bar{u} = time averaged velocity
- $\bar{\bar{u}}$ = spatial average of the time averaged velocities
- u' = fluctuating velocity
- u* = shear velocity
- W = weight of tracer
- x = coordinate in the longitudinal direction
- y = coordinate in the vertical direction
- z = coordinate in the lateral direction
- Δ_z = width of a lateral segment
- ϵ = energy dissipation per unit volume
- μ = dynamic viscosity of the fluid
- v = variance coefficient
- ρ = mass density of fluid
- γ = unit weight of tracer
- σ^2 = variance
- τ = delay time
- τ_0 = bed shear stress

CHAPTER 1

INTRODUCTION

1.1 Transport of Pollutants in Rivers

Considerable amounts of pollutants are dumped into our waterways yearly. It is very evident that many of these waterways are not capable of assimilating these pollutants. Much of the damage done to these waterways and their ecosystems could have been avoided had there been greater understanding of the effects caused by the pollutants. Presently, environmentalists are trying to identify and assess the broad range of effects these pollutants have on ecosystems. It is hoped that with this greater understanding major disruptions in our ecosystems will be avoided by more discriminate pollutant disposal programmes.

It was with this objective in mind that an integrated study involving the University of Ottawa and the National Research Council of Canada was set up in 1971. This study is focussed on assessing and accounting for the levels of mercury and certain organochloride compounds in a particular reach of the Ottawa River. It is planned to accomplish this from knowledge of mass inflow rates, uptake and release rates of these pollutants by biota, movements between physical and biotic elements and mass transport through the system as a whole.

The principal component of the ecosystem effective in mass transport of the pollutants is water. Transport by water is affected by convection and diffusion. Diffusion results from turbulent velocity fluctuations which are manifestations of the turbulent eddies. These velocity fluctuations cause an interchange of fluid particles between neighbouring zones. With the interchange of these particles a simultaneous interchange of all properties associated with them occurs. Thus with time the turbulent eddies cause the pollutants contained in the water to be diffused. This is known as turbulent diffusion. Turbulent diffusion occurs in all directions.

1.2 Object of Study

The object of this work is to investigate lateral turbulent diffusion in the study reach and to quantify it in terms of the hydraulic parameters describing the flow.

CHAPTER 2

LITERATURE REVIEW

2.1 Theoretical Considerations

It can be shown (3) that the conservation of mass equation for a soluble conservative substance undergoing turbulent diffusion at any point can be written as

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_i \frac{\partial \bar{c}}{\partial x_i} = - \frac{\partial}{\partial x_i} (\overline{u_i' c'}) \quad (1)$$

where $\frac{\partial \bar{c}}{\partial t}$ is the time rate of change of the time averaged concentration,

\bar{u}_i is the time averaged velocity in the i th direction,

and $\overline{u_i' c'}$ is the time averaged velocity-concentration covariant,

where the instantaneous velocity and concentration are composed of a time average and a fluctuation, i.e.,

$$u_i = \bar{u}_i + u_i'$$

and
$$c_i = \bar{c}_i + c_i'$$

Molecular diffusion is neglected in Eq. 1 as it is relatively insignificant in turbulent flows.

The Boussinesq Hypothesis (15) states that the flux of a diffusing substance in any direction is proportional to the concentration gradient of the substance in

that direction. The Reynolds Analogy () states that the transport of mass and momentum are analogous. These two widely accepted conditions are expressed respectively in the following mathematical form:

$$K_1 = \frac{-\overline{u_1'c'}}{\partial \bar{c} / \partial x_1} = \frac{-\rho \overline{u_1'u_1'}}{\partial \rho \bar{u}_x / \partial x_1} \quad (2)$$

where K_1 is the turbulent diffusion coefficient for the i direction,

$\overline{u_1'u_1'}$ is the time averaged velocity covariant and the subscript 1 refers to the principal direction of flow ρ is the density of the fluid.

The first equality in Eq. 2 is a definition of the turbulent diffusion coefficient. The turbulent diffusion coefficient, thus defined, completely describes the effect of turbulence on a soluble substance contained in the flow. It has units of L^2/T . The term $\overline{u_1'c'}$ is the transport of solute due to turbulence in the i th direction.

Eq. 1 can now be written as

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_1 \frac{\partial \bar{c}}{\partial x_1} = \frac{\partial}{\partial x_1} K_1 \frac{\partial \bar{c}}{\partial x_1} \quad (3)$$

There are four principal mathematical approaches used to estimate the lateral turbulent diffusion coefficient K_z .

2.1.1 The Semi-empirical Fickian Diffusion Theory

Nearly all estimations of K_z are based on this theory. The following two basic assumptions are made:

1. There is no net velocity in the vertical or the lateral direction,
2. There is complete homogeneity of turbulence throughout the flow field.

With these two assumptions made, Eq. 3 can be written as

$$\frac{\partial \bar{c}}{\partial t} + \bar{u}_1 \frac{\partial \bar{c}}{\partial x} = K_1 \frac{\partial^2 \bar{c}}{\partial x_1^2} \quad (4)$$

Eq. 4 implies that diffusion in each of the three directions is independent of the diffusion in the other two directions. Hence the joint probability density function is equal to the product of the three one-dimensional probability density functions. The one-dimensional probability density function is assumed to follow normal probability law (5). If it is assumed that a tracer is mixed completely throughout the depth then, downstream of an instantaneous injection of a tracer, the probability density functions can be used to estimate the concentration of tracer at any point in the flow, given by the coordinates, x and z , at any time t as follows:

$$c(x, z, t) = \frac{W}{\gamma d} f(x, t) f(z, t) \quad (5)$$

where W = weight of the tracer injected at source
 γ = unit weight of the tracer
 d = mean depth of flow
and f = is the probability density function.

For large distances downstream of a continuous steady injection of tracer the concentration at any point can be shown to be (26)

$$c(x,z) = \frac{qC_0}{u_x d} f(z,x) \quad (6)$$

where q = rate of injection of the tracer,
and $\bar{u}_x = \bar{u}_1$
 C_0 = concentration of the tracer at the source.

The variance corresponding to Eq. 6 is σ_z^2 where

$$\sigma_z^2 = 2 Kz \frac{x}{u_x} \quad (7)$$

Hence from a study of the rate of change of the variance of the tracer plume under steady state conditions Kz can be estimated. This method has been successfully used in almost all tracer studies. It provides little insight into the mechanisms of turbulent diffusion.

Recently, Cleary (2) introduced a term into Eq. 4 to describe the instantaneous tracer source. By recording concentrations, spatial coordinates and times after injecting the dye the best fit values for Kx , Ky and Kz are found by an optimum search method.

2.1.2 Taylor's Analysis

Taylor (27) gives a realistic description of turbulence based on its statistical properties. He based his theory on the properties of continuously varying random variables. The correlation coefficient R_τ for the velocity of a particle in the direction i at times t and $t+\tau$ is written as

$$R_{\tau i} = \frac{\overline{u_i'(t) u_i'(t+\tau)}}{\overline{u_i'^2(t)}} \quad (8)$$

The wavy overbar indicates that the average is taken over a large number of fluid particles. As τ gets large $R_{\tau i}$ approaches zero. Consequently

$$\lim_{t \rightarrow \infty} \int_0^t R_{\tau i} d\tau = L_{t i} \quad (9)$$

$L_{t i}$ is a constant and is called the Lagrangian time scale for turbulence in the i direction. Taylor showed that for homogeneous stationary turbulence the variation of displacements from the initial position of particles undergoing turbulent diffusion in the direction i after large times is given by the following equation:

$$\sigma_i^2 = 2 \overline{u_i^2} \int_0^T \int_0^t R_\tau d\tau dt = 2 \overline{u_i^2} T L_{t i} \quad (10)$$

It can be seen that by comparing Eq. 7 and Eq. 10 that the turbulent diffusion coefficient can be written as

$$K_1 = \overline{u_1^2} L_{t1} \quad (11)$$

To estimate K_2 using Eq. 11 poses the problem of measuring the velocity fluctuations of the same particles at different times. Recently (6,19,21) hot wire anemometry has made it possible to measure longitudinal velocity fluctuations at fixed points. This gives a measure of what is known as the Eulerian correlation coefficient. No theory exists relating this to the Lagrangian correlation coefficient. McQuivey and Keefer (21) using results of some previous flume experiments obtained values for L_{tz} .

2.1.3 Orlob's Analysis

The Kolmogoroff Similarity Principle (15) for turbulent systems led Orlob (22) to give another mathematical description of lateral turbulent diffusion based on the mechanisms of the eddies causing the turbulence. Turbulence is composed of low frequency large eddies and high frequency small eddies. Energy enters the system through the larger eddies and is passed by inertial action down to the smaller eddies. Due to increasing viscous effects the small eddies dissipate the energy in the form of heat. For large Reynolds numbers there exists a range of high frequency eddies which Kolmogoroff terms the universal equilibrium range. In this range turbulence is deemed to be statistically steady and independent of the external conditions. It can

be shown that the character of the turbulence is determined by the mean rate of energy dissipation per unit volume ϵ , and the kinematic viscosity, ν . This led to the determination of a length scale for turbulence which from dimensional considerations is written as

$$\ell = \left(\frac{\nu^3}{\epsilon}\right)^{1/4} \quad (12)$$

Orlob using an analogy between molecular and eddy diffusion replaced μ with the eddy diffusion coefficient K and wrote

$$K_i = \text{constant } \epsilon^{1/3} L_i^{4/3} \quad (13)$$

where L_i is the mean size of the eddies participating in the diffusion process in the i direction. The analogy is questionable insofar as it implies a constant relationship between the scale of the large eddies and the scale of the eddies in the universal equilibrium range. Eq. 13 has not been proven.

2.1.4 Elder's Analysis

Elder (5) using the Reynolds analogy and assuming complete vertical homogeneity of turbulence proved that the vertical turbulent diffusion coefficient is proportional to $d u_*$ where u_* , the shear velocity, is defined as $\left(\frac{\tau_o}{\rho}\right)^{1/2}$. τ_o is the bed shear stress. From this he assumed that the lateral turbulent diffusion coefficient is also proportional to $d u_*$. This describes turbulence as being completely dependent on the transfer of momentum within the flow.

2.2 Laboratory Studies

Elder (5) was the first to measure the lateral turbulent diffusion coefficient in an open channel. He studied the spread of a drop of dye on the water surface of a laboratory flume. He found that the dimensionless diffusion coefficient, K_z/du_* , was equal to 0.23. Numerous other studies have since been conducted in laboratory flumes (6,22,25,26). Dye and floating particles were used as tracers. Reported dimensionless diffusion coefficients range from 0.17 to 0.36. Considering that the data comes from many different sources the value of 0.23 gives a very good estimate of the dimensionless diffusion coefficient. All these studies were conducted in shallow flumes with Reynolds numbers ranging approximately from 10^4 to 10^5 .

Measurements of velocity fluctuations in a laboratory flume indicate an increase in the longitudinal turbulent diffusion coefficient with depth beneath the water surface (21). The same pattern would be expected in the lateral turbulent diffusion coefficient. No observations of this type are reported for natural channels. This is because it is not experimentally possible to measure velocity fluctuations in natural channels reliably.

2.3 Field Studies

2.3.1 General Description of Methods

Continuous point injection at the water surface was used for most of the reported studies (9,14,18,23,33). Dye was allowed to spread across the complete width of the channel in practically every reported field study. Point samples were taken at different stations across at least two sections. Methods of sampling and location of the stations varied. For details of these it is best to refer to the individual original report. The cross section geometry and the velocity profile or the discharge velocity were measured. A river bed characteristics or the hydraulic gradient was also measured.

2.3.2 Results

Table 2.1 summarizes the results of reported field studies of the measurement of K_z . Due to the many different conditions under which these studies were conducted and due to their having been conducted by different investigators there is likely to be considerable variation in the results.

Figure 2.1 shows the dimensionless coefficients K_z/du_* plotted against the Reynolds number, Re . It appears that K_z/du_* tends to increase with increasing Re . This might indicate that Elder's treatment does not fully explain turbulent lateral diffusion in flows with large Re . Further experimental data is necessary before this could be verified. Figure 2.2 shows.

Table 2.1 Summary of Previous Field Studies

Investigator	Channel Description ¹	K_z (m^2/s)	$K_z/d\bar{u}_x$	K_z/du^*
Fischer (9)	Atrisco Feeder Canal, very straight and uniform. $b = 16$ m $d = 0.61$ m $\bar{u}_x = 0.57$ m/s $(\bar{u}_x/u^*) = 10.3$ $Re = 4.4 \times 10^5$	0.012	0.035	0.24
Fischer ² (11)	Green and Duwamish Rivers, winding and very non- uniform $b = 23$ m $d = 1.1$ m $\bar{u}_x = 0.37$ m/s $(\bar{u}_x/u^*) = 7.4$ $Re = 3.4 \times 10^5$	0.10+0.185	.03+.037	.175+.320
Yotsukura, Fischer and Sayre (33)	Missouri River, gently meandering and very nonuniform $b = 185 \rightarrow 230$ m $d = 2.8$ m $\bar{u}_x = 1.75$ m/s $(\bar{u}_x/u^*) = 23$ $Re = 3.7 \times 10^6$	0.127	0.026	0.60
Glover (14)	Columbia River, gradual s-bend and very nonuniform $b = 310$ m $d = 5.2 \rightarrow 7.4$ m Hyd. radius = 3.1 m $\bar{u}_x = 1.35$ m/s $(\bar{u}_x/u^*) = 16$ $Re = 5.2 \times 10^6$	0.23	0.028	0.72

Table 2.1 continued

Investigator	Channel Description ¹	K_z (m^2/s)	$K_z/d\bar{u}_x$	K_z/du_x^*
Patterson and Gloyna (23)	Colorado River, middle of S bend weeds in suspension and varying roughness b = 74 m d = 1.85 m $\bar{u}_x = 0.85$ m/s $(\bar{u}_x/u_x^*) = 11$ Re = 1.2×10^6	0.065	0.041	0.39
Reported in Ref. (34)	South River, very rough bed water plants and clumps in the reach b = 13 + 19 m d = 0.3 + 0.45 m $\bar{u}_x = 0.185$ m/s $(\bar{u}_x/u_x^*) = 4.6$ Re = 5.5×10^4	0.005	0.08	0.30
Reported in Ref. (34)	Bernardo Conveyance Channel, straight, uniform plain bed b = 20 m d = 0.7 m $\bar{u}_x = 1.26$ m/s $(\bar{u}_x/u_x^*) = 20$ Re = 6.7×10^5	0.015	0.017	0.30

Table 2.1 concluded

Investigator	Channel Description ¹	K_z (m ² /s)	$K_z/d\bar{u}_x$	K_z/du_*
Holley and Abraham (8)	<p>Issel River, curved, nonuniform groins along both sides $b = 70-85$ m (between groins) $d = 4.0$ m $\bar{u}_x = 1.0$ m/s $(\bar{u}_x/u_*) = 13$ $Re = 3.1 \times 10^6$</p>	0.16	0.04	0.52
Holley and Abraham (18)	<p>Waal River, straight, reasonably uniform, groins along both sides $b = 265-300$ m $d = 4.7$ m $\bar{u}_x = 0.8$ m/s $(\bar{u}_x/u_*) = 14.3$ $Re = 2.9 \times 10^6$</p>	0.10	0.025	0.35

¹The temperature is assumed to be 10°C except for the Columbia River Study. A temperature of 35°C was assumed because the radionuclide tracers were in a heated effluent.

²Fischer cautions that his analysis is likely to give erroneous results on account of the paucity of the data.



a plot of the dimensionless coefficient K_z/\bar{u}_x against Re . K_z/\bar{u}_x appears to have a random variation with Re . From the data in Table 1 the mean value of K_z/\bar{u}_x is approximately 0.03.

Figure 2.3 shows a plot of K_z/\bar{u}_x against the relative roughness (\bar{u}_x/u_*). There is a trend for the dimensionless coefficient to decrease with increasing (\bar{u}_x/u_*).

As the South River is very similar to those channels which are best described using Elder's process its high value for K_z/\bar{u}_x is omitted from the averaging process.

Attempts to relate K_z/\bar{u}_x and K_z/u_* to the width-depth ratio were unsuccessful (1,17). It would be expected that for wide channels these coefficients would be almost independent of the width-depth ratio due to the relatively small amount of lateral restraint on the turbulence.

2:3.3 Observations Reported in Field Studies

1. Effect of River Curvature

The presence of net lateral velocities due to river curvature was detected and its effect was approximated in the Issel River Test (18). In this case it had the effect of altering the measured K_z by $\pm 25\%$ of the actual K_z .

2. Littoral Regions

Fischer (11) reports larger values for K_z in the littoral regions than in the mid-stream regions. He does,

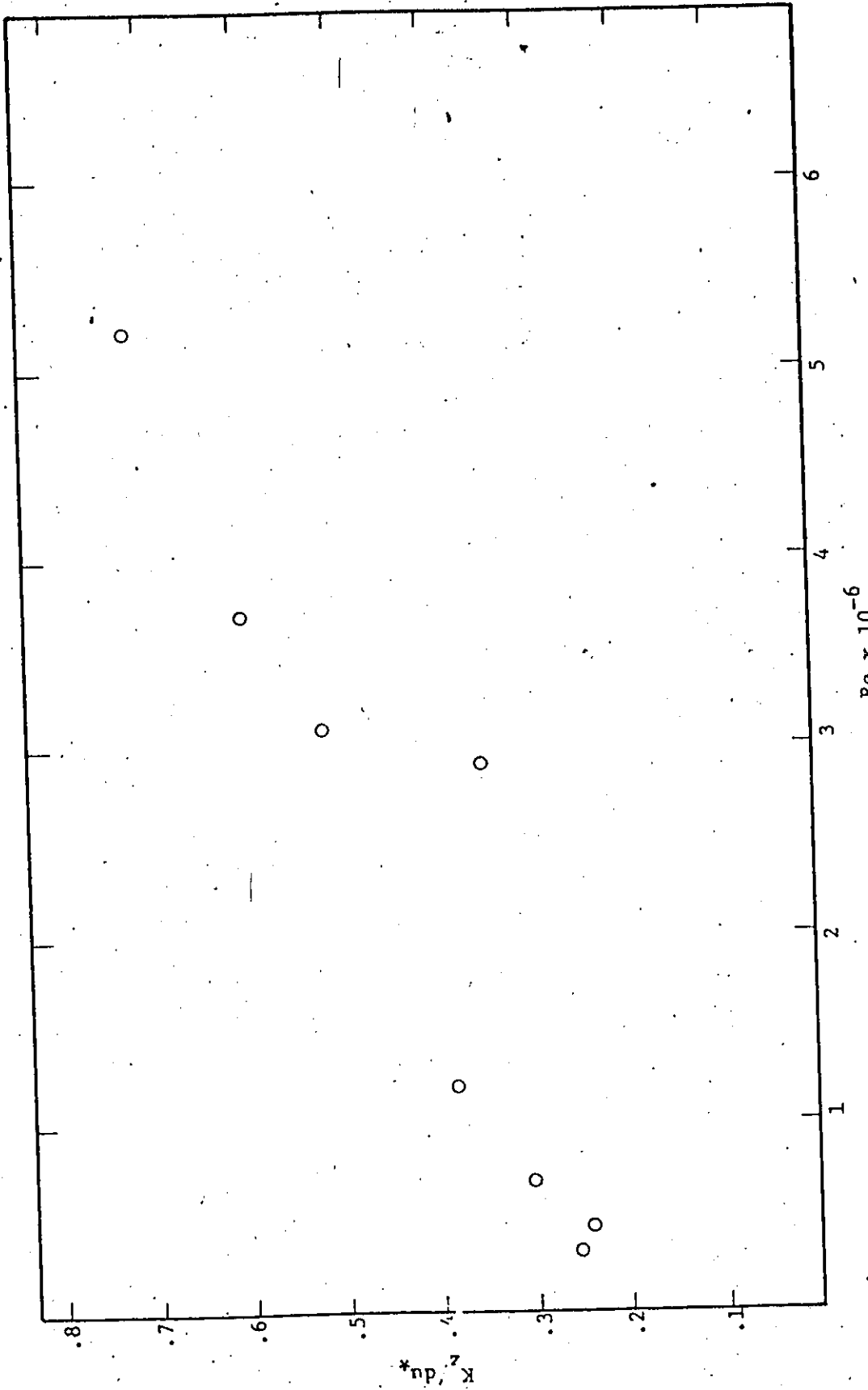


Fig. 2.1 K_z/du_* versus the Reynolds Number

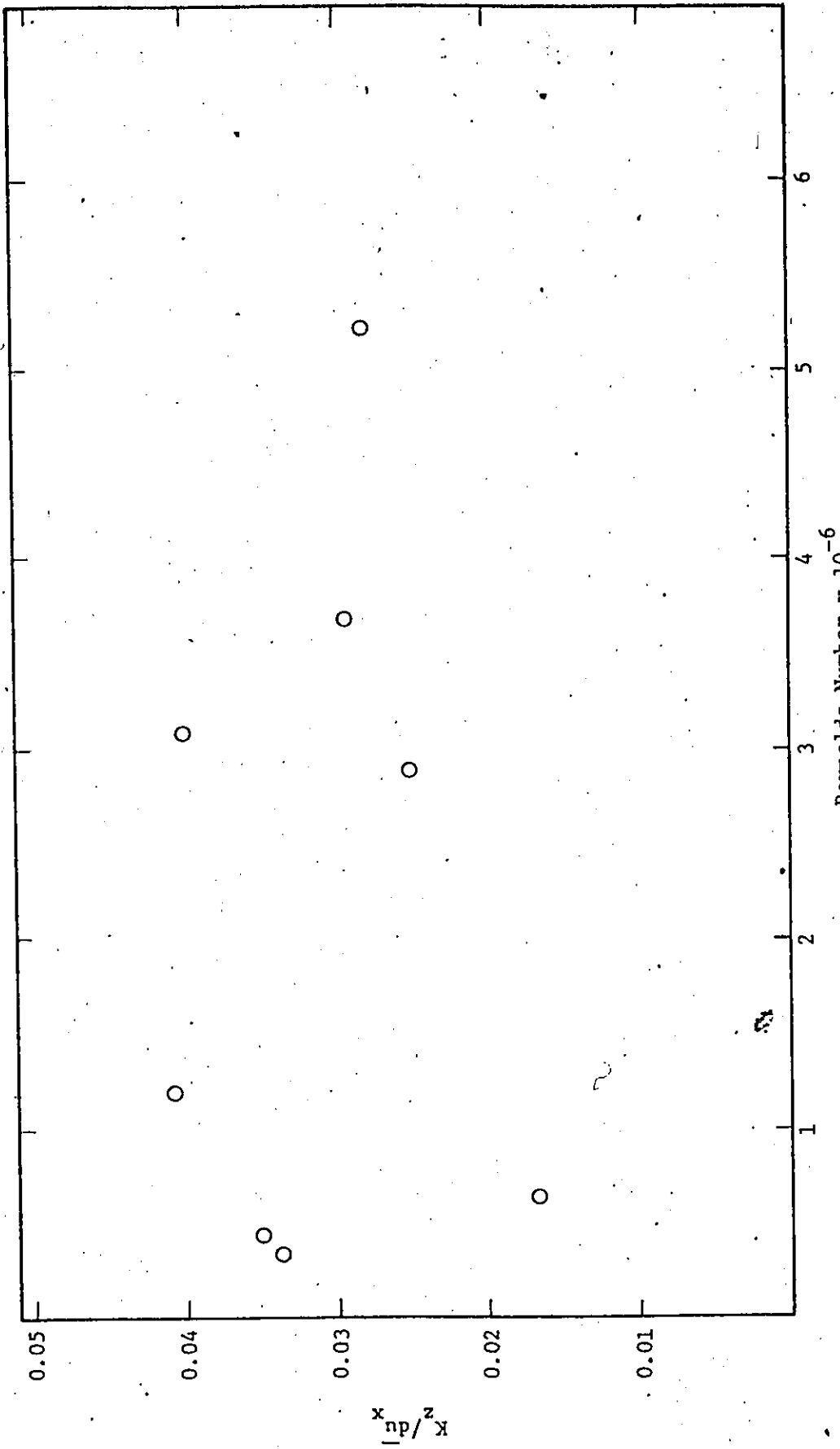


Fig. 2.2 K_z/du_x versus the Reynolds Number

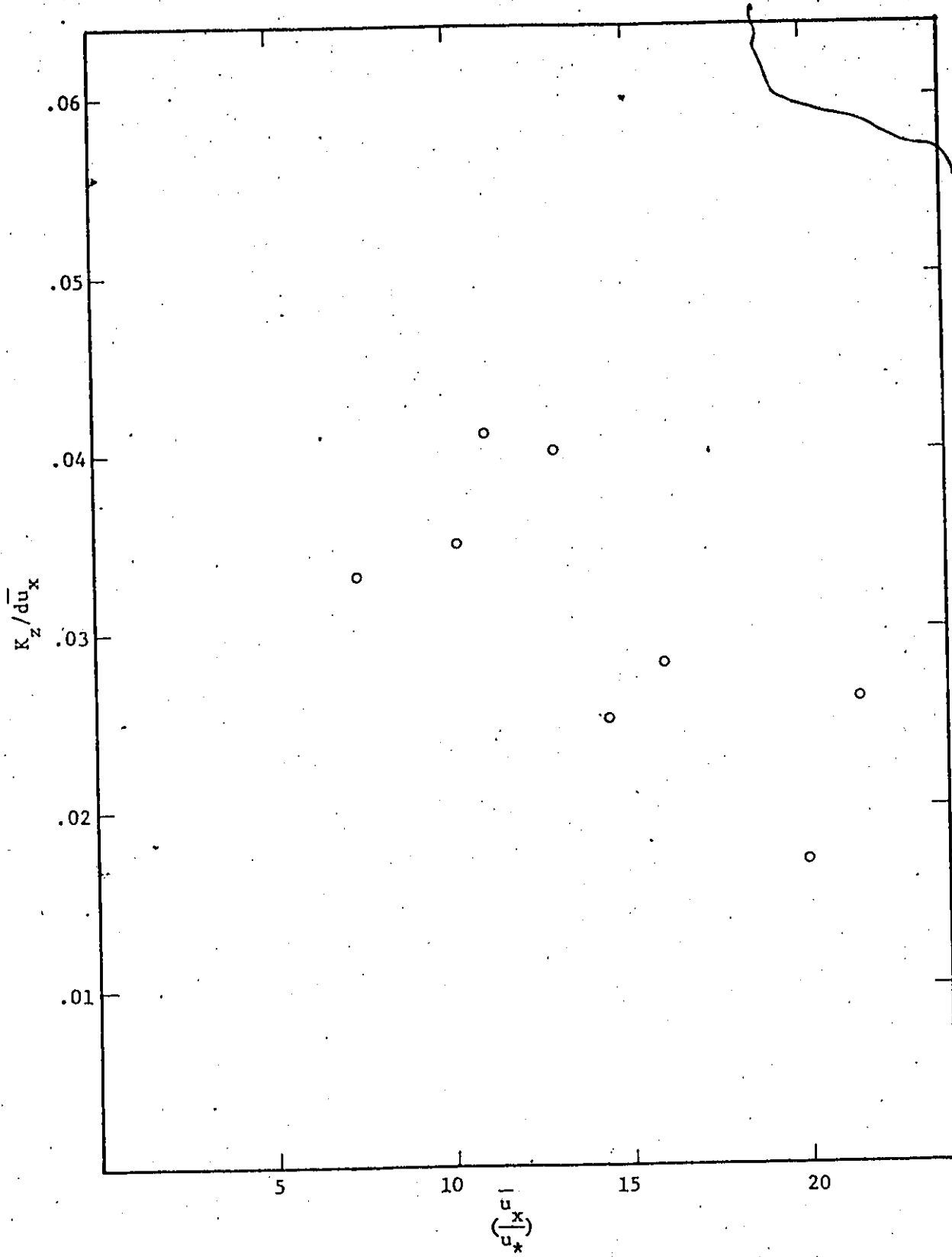


Fig. 2.3 $\frac{K_z}{\frac{du_x}{dz}}$ versus $\frac{u_x}{u_*}$

however, caution us that his method of analysis is likely to give erroneous results. No field study has given reliable measurements of any lateral variation in K_z . The existence of lateral variation in K_z undermines, to some extent, the use of an average value for K_z when applied to the complete width of the channel.

3. Unsteadiness in Concentrations

Holley and Abraham (18) noticed considerable unsteadiness in concentrations measured within 2.5 km of the injection. They cite the turbulence caused by the groins along the side of the river as being the probable cause of this. It is evident from their data, however, that the unsteadiness is most prominent at the low concentration portion of the plume. This portion is furthest from the groins. It is this author's opinion that these time variations were caused by lack of uniform vertical dye mixing in these regions..

CHAPTER 3

AUTHOR'S MATHEMATICAL THEORY

3.1 Introduction

When dye is injected continuously into a flow from a point source the downstream concentration is only steady at stations where the dye is vertically mixed. The concentrations at the outer edges of the dye plume will tend to be unsteady with time. The author in this chapter develops a method by which the concentrations at the outer edges of the plume can be excluded from the calculation of K_z .

3.1.1 The Idealized Gradient Diffusion Model

Consider a dye-containing control volume partitioned by vertical planes parallel to the flow streamlines. Two such planes are labelled 1 and i in Figure 3.1. The upstream and downstream boundaries of the control volume are vertical planes orthogonal to the streamlines. Vertical plane 1 corresponds to the position of maximum dye concentration, i.e., the centre line of the dye plume. As net turbulent transport is proportional to the concentration gradient the net transport of dye across vertical plane 1 is zero. Therefore the difference between the convective inflow and the convective outflow of dye in the portion of the control volume between

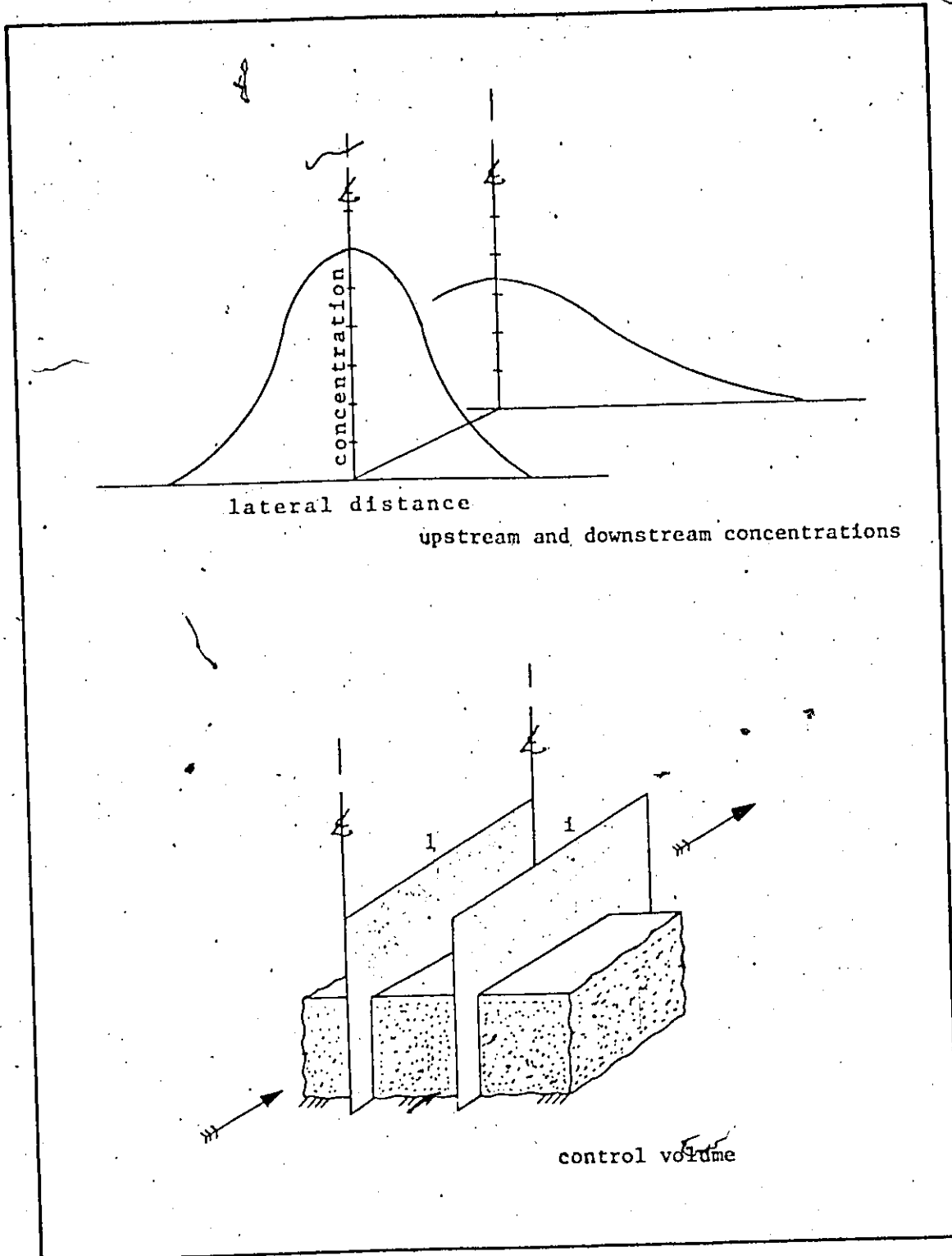


Fig. 3.1 Dye Flow Schematic

plane 1 and plane i is equal to the net transport of dye across plane i. This transport is due solely to lateral turbulent diffusion. This principle can be used to express the lateral turbulent diffusive transport of dye across any plane using the following equation:

$$\dot{M}_i = (\bar{u}_u a_u \bar{c}_u - \bar{u}_d a_d \bar{c}_d)_{1+i} \quad (14)$$

where \dot{M}_i = the time rate of transport due to turbulent diffusion across any vertical plane i,

\bar{u} = the spatial average of the time averaged velocities,

a = the cross sectional area of water

\bar{c} = the spatial average of the time averaged concentrations,

subscripts u and d denote the upstream and downstream ends of the control volume, and $()_{1+i}$

denotes the average between plane 1 and plane i.

For flow in which the streamlines are parallel a_u is equal to a_d .

The term $\bar{u}_z'c'$ in Eq. 2 can be replaced by $\frac{\dot{M}_i}{a_i}$ for any longitudinal vertical section i where a_i is the area of the longitudinal vertical plane i between the upstream and the downstream ends of the control volume. Eq. 2 now can be written as

$$\dot{M}_i = a_i K_{zi} \left(\frac{\partial \bar{c}}{\partial z} \right)_i \quad (15)$$

The term $(\frac{\partial \bar{c}}{\partial z})_1$ is the average slope of the lateral concentration profile in the control volume at the plane 1. As long as the dye is vertically mixed, then K_z can be calculated for any lateral position within the plume using Eq. 14 and Eq. 15.

The data necessary to use this model are the upstream and downstream section geometry, velocity distributions and concentration profiles.

This model is based upon the simplifying assumption that lateral turbulence is homogeneous with depth. As stated in Chapter 2 variations in the turbulence properties throughout the depth of flow of a laboratory flume are reported. It is reasonable therefore to expect some variations in the turbulence properties throughout the depth of flow of a natural channel. Consequently it is important to remember that the value of K_z which results from using this model is only an estimate of the depth-averaged value of K_z .

3.1.2 Estimation of the Portion of the Dye Plume in

Which the Dye is Vertically Mixed

Statistically the highest concentration of dye at every downstream section will be found in the streamtube into which the dye was injected. For some distance downstream of the injection the concentration distribution at any section is described by elliptical isoconcentration lines with their centroids at the streamline of injection (4). The shape of the ellipses is governed by the relationship between K_z and K_y . At a certain distance downstream of the injection dye reaches the water surface and the river bed and is reflected back towards mid stream. At a greater distance downstream this re-

flection will cause the dye concentration to become uniform with depth. Because of the initial elliptical shape of the isoconcentration lines this will first occur at the centre of the dye plume. This distance is called the Eulerian length scale for vertical mixing, E_L . It depends solely on the depth and the characteristics of the turbulence. It is assumed for simplicity that these characteristics, along with the depth, do not vary. At distances further downstream the dye becomes uniformly mixed throughout the depth at stations which are laterally displaced from the plume centreline. Figure 3.2 gives a schematic representation of the foregoing description.

Appendix A gives the development of the following formula for estimating the Eulerian length scale for vertical mixing:

$$E_L = 4.26 d \frac{\bar{u}_x}{u_*} \quad (16)$$

Appendix B gives the development of the following formula for estimating the width of the plume at any section in which the dye is vertically mixed:

$$w = 0.055 (\ell - 1)^{0.7} \quad (17)$$

where w = the width of the portion of the plume in which the dye is vertically mixed divided by the Eulerian length scale,

and ℓ = distance from the injection divided by the Eulerian length scale.

Close to the banks the lateral homogeneity of turbulence breaks down due to the proximity of the boundary. This would cause w in Eq. 17 to become asymptotic to the dimensionless width of the river. As all the experiments in this study were confined to regions out from the banks this effect is not considered consequential.

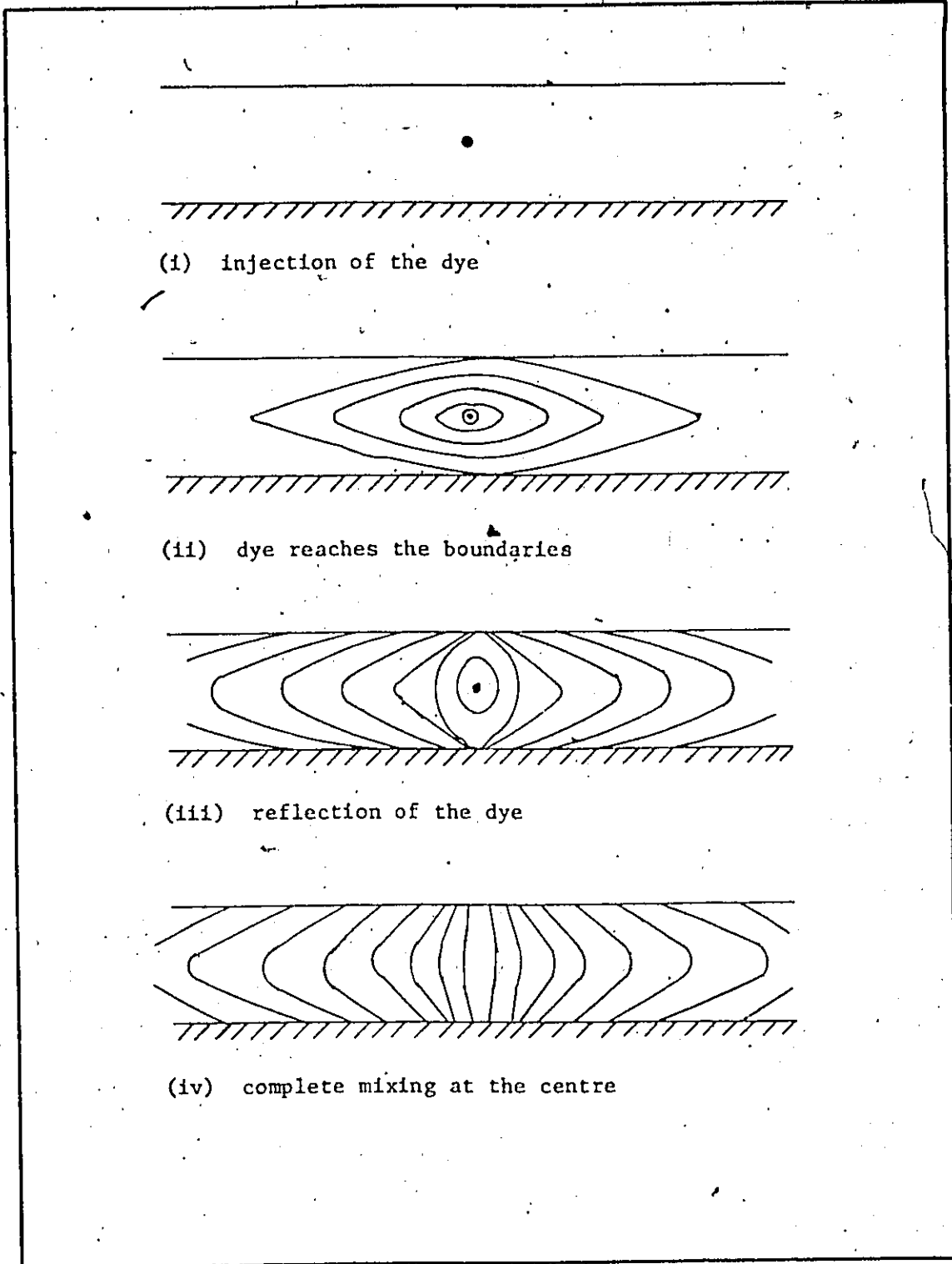


Fig. 3.2 Isoconcentration Line Development

CHAPTER 4

STUDY AREA AND EQUIPMENT

4.1 Description of the Study Area

The Ottawa River extends approximately 1,100 kilometers from the drainage system of Lake Temiscamisque to the St. Lawrence River. The total drainage area for this basin is 145,000 square kilometers. The average yearly flow is about 2,500 cubic meters per second. The reach selected for study by the N.R.C.-University of Ottawa group stretches for roughly 5 kilometers downstream of the Central Ottawa-Hull region. This reach is shown in Figure 4.1.

Field work on the diffusion study commenced in May 1973 and continued until November 1973. Initial experiments were conducted in an area of width 850 m and maximum depth of 9 m. This area is indicated by section 52 on Figure 4.2. Few of these earlier experiments are reported as few were successful. From the end of June onwards all experiments were conducted further downstream in the channel beside the Green Creek Pollution Control Centre. This channel was chosen for the following reasons:

1. good uniformity of depth throughout,
2. the proximity of the shore to mid stream made it easier to survey accurately,

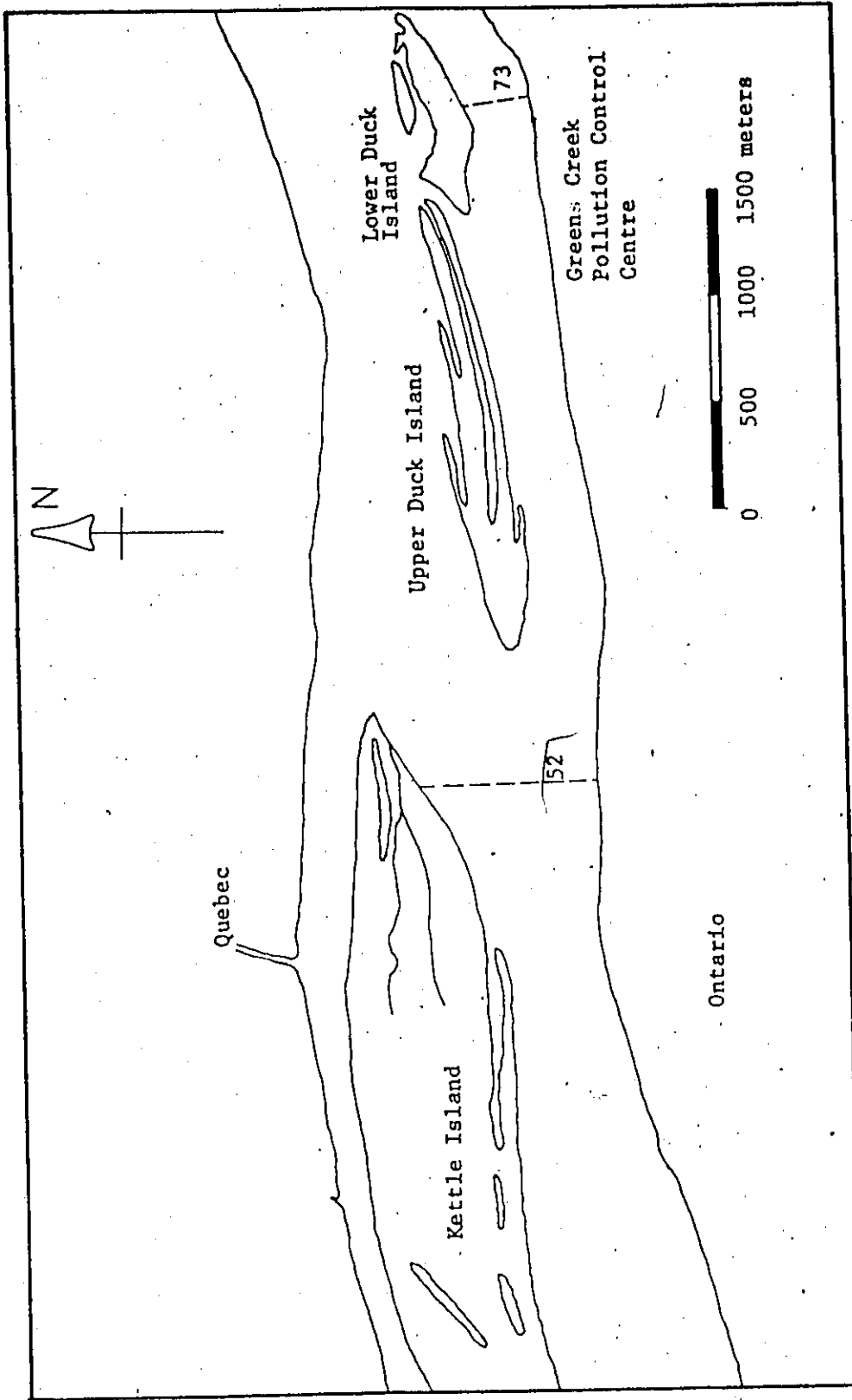


Fig. 4.1. University of Ottawa-N.R.C. Study Area, Ottawa River

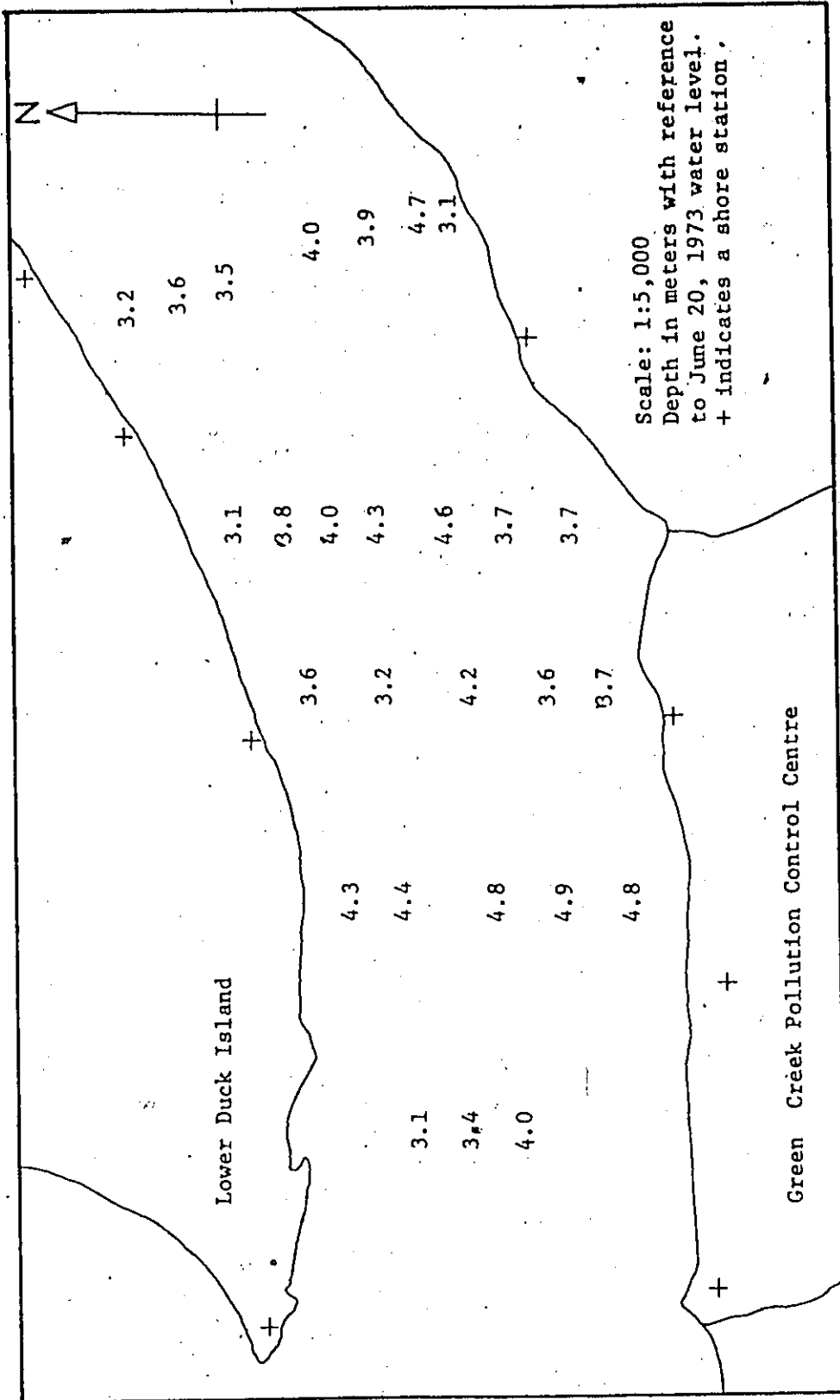


Fig. 4.2 Study Reach near the Green Creek Pollution Control Centre

3. less dye had to be used because the river was shallow.

A plane of the Green Creek study area is given on Figure 4.2. The shore stations were surveyed using sextant readings onto charted landmarks. Depth soundings were made using a weight suspended from a rope marked off in equal lengths.

The bed is fine and silty towards the Ontario shore. In the mid-stream region and towards Lr. Duck Island the bed material is a medium to coarse sand. The bed is covered with a layer of wood chips. This layer is estimated to be 100 mm thick. Runs with a sonic echo sounder showed that dunes were not present.

Figure 4.3 shows a picture of this reach taken from the Ontario shore.

4.2 The Dye

Rhodamine B fluorescent dye was used as the tracer in this study. It was chosen for the following reasons:

1. quantities of the dye were already available,
2. it is less expensive than other fluorescent dyes used for tracer studies,
3. it is detectable at low concentrations,
4. it had been used successfully in other reported studies,

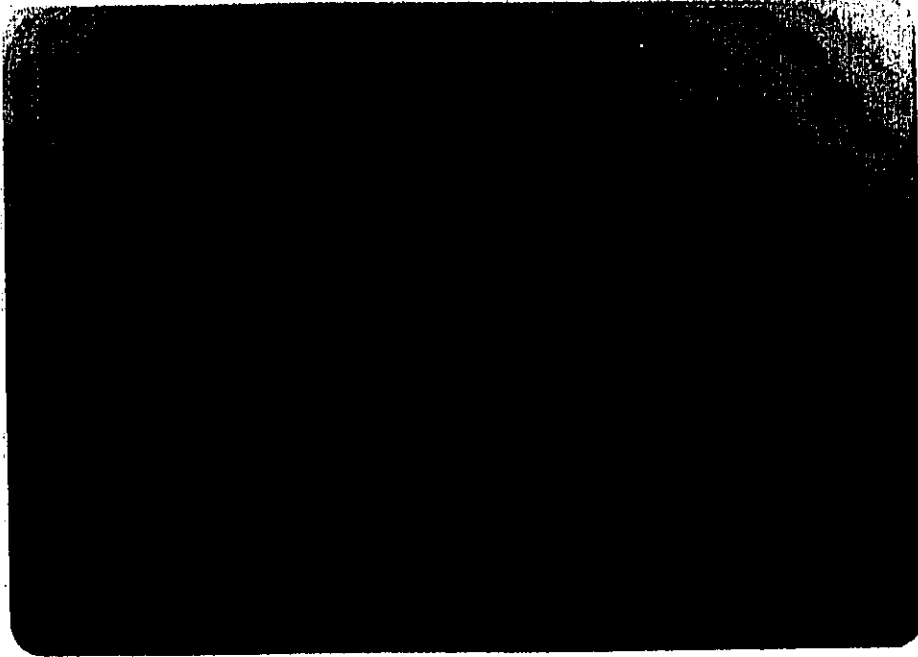


Fig. 4.3 Study Reach near Green Creek Pollution Control Centre.

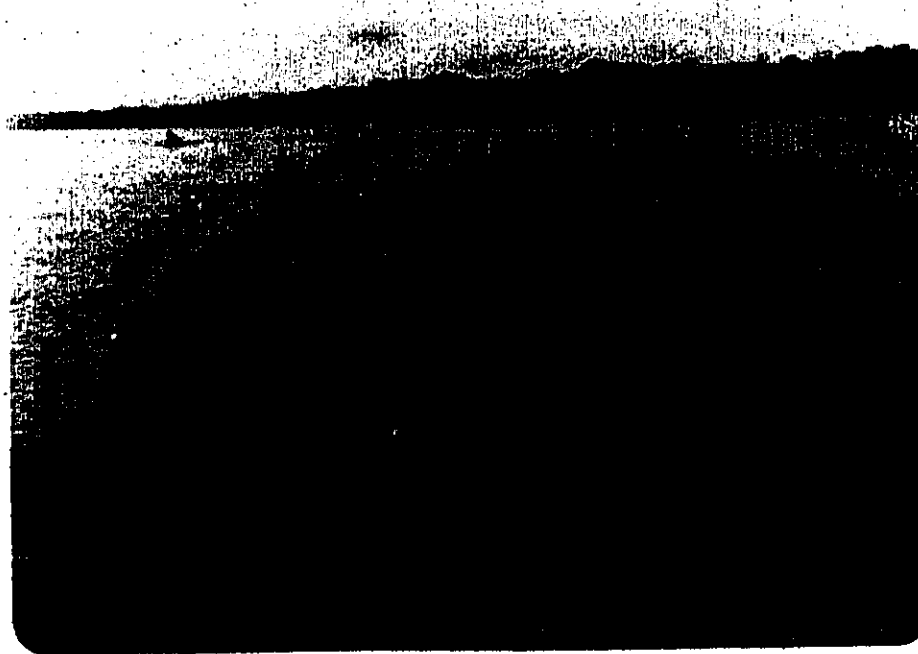


Fig. 4.4 The Continuous Dye Injection System

5. no natural background of the dye could be detected in the study region.

The dye is purchased in 20-litre containers in the form of a 40% solution in acetic acid. The relative density of the solution was measured at 1.25. Ethanol at a measured relative density of 0.52 was added to make a combined relative density of 1.00. Water was added to dilute the mixture to any desired concentration. Any temperature variations were deemed insignificant in causing alterations of these relative densities.

4.2.1 Dye Injection

The device used for the continuous injection of the dye is shown diagrammatically in Figure 4.5. It comprises a 20-litre Nalgene bottle with a syphon system. To start the syphon the air tube was pinched and pressure was applied using the squeeze bulb. When it was apparent that dye was entering the water the pressure application was ceased and the air tube was freed. Dye continued to flow at a constant rate until the level inside the bottle dropped below the bottom of the air tube. The rate of emission was regulated using a screw clamp on the output tube. It was found necessary to free this clamp completely to start the system efficiently. Consequently a separate setting had to be made for each experiment. To do this it was necessary to observe the falling rate of the level of dye in the bottle for some

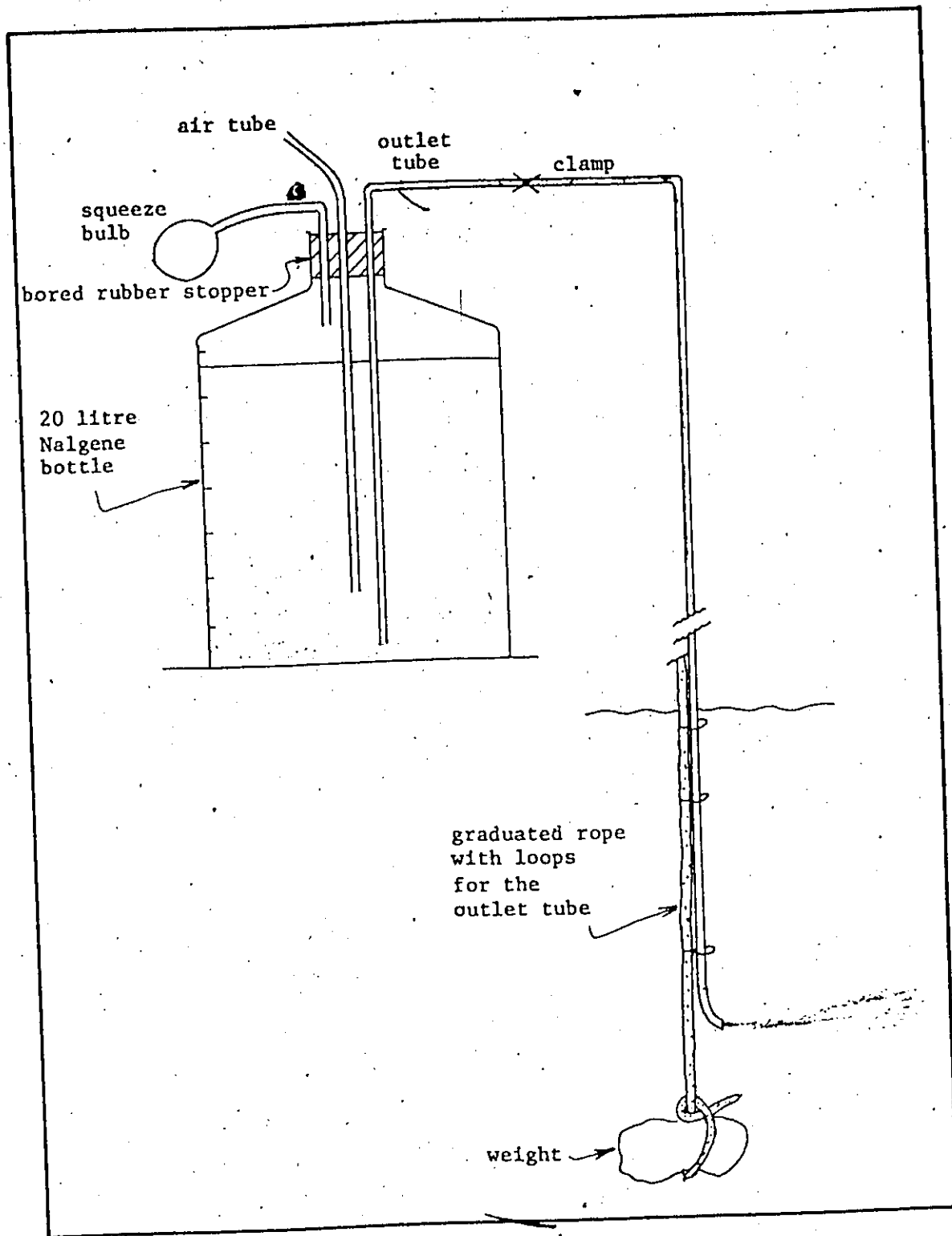


Fig. 4.5 Schematic of the Continuous Injection System

time before setting the clamp finally. The rate of flow was not recorded. The outlet tube was trained down into the water to approximately mid depth through loops in a weighted rope tied to the boat. A picture of the injection system is given in Figure 4.4.

4.3 Equipment

4.3.1 The Fluorometer

A Turner Model III Fluorometer was used to measure the concentration of the dye. It operates on the principle that the intensity of fluorescent light emitted by a sample under constant input light intensity is directly proportional to the concentration of the fluorescent substance. The constant input light source is an ultraviolet lamp. The intensity of the lamp can be varied. The maximum optical absorbance of Rhodamine B dye occurs at a wavelength of 550 m μ and the maximum fluorescence intensity at 570 m μ (7). As recommended (29) narrow pass filters of colour specification #546 and #590 were used as primary and secondary filters respectively.

Appendix C gives the details of the calibration of the fluorometer. Using the light intensity denoted by 30x there was linearity throughout the range of experimental concentrations. Using the light intensity denoted by 10x there was linearity throughout also except for very low concentrations. The 30x intensity was used almost completely throughout.

The continuous flow door attachment was used with the fluorometer for the field tests as it was required to observe the sample concentration continuously.

4.3.2 The Recorder

To record the observations, a Perkins-Elmer Millivolt Recorder was connected to the voltage output of the fluorometer. A range setting of 20 mV was used on the recorder. This was sufficient to give a good chart range and linearity between the dial reading and the chart reading.

4.3.3 Pumping Equipment

The sample was pumped to the fluorometer through 6 mm Tygon tubing by a 100 mm high, 100 mm diameter immersible pump. A nylon strainer prevented dirt from entering into the impeller. This pump was fixed at the end of a 2.5 m long steel pole (see Figure 4.6). The pole was attached to the boat using two C-clamps. With the pole in this position a 3.5 m long tube was used. When it was required to unclamp and lower the pump an 8.0 m length of tube was used. The pump delivered at an average rate of 0.31 litres per minute through the shorter tube and at 0.28 litres per minute through the longer tube. The delivery rate varied by as much as 10% from day to day. This was most likely due to unreliable generator performance. The discharge rate

Fig. 4.6 The Pump

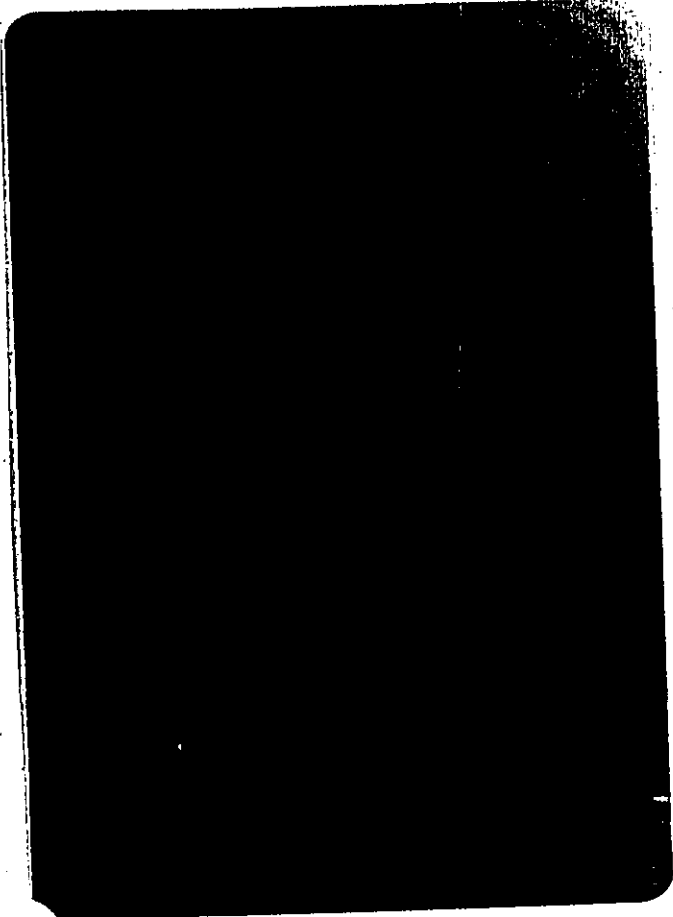
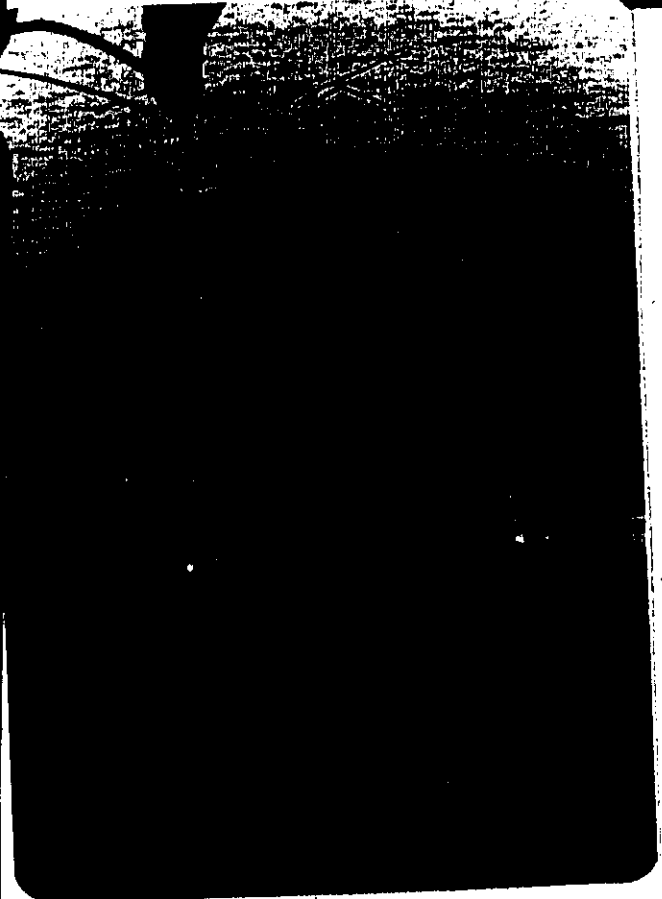


Fig. 4.7 The OTT Propeller Meter



was measured before and after sampling each day and the average rate was used.

4.3.4 Ancillary Equipment

A 2.5 kW portable gasoline A.C. generator was used as a power source for the fluorometer, the recorder and the pump. It provided 115 V and 60 cycles. Because the output voltage fluctuated it was necessary to connect the instruments through a voltage regulator.

Two boats were used for this study. A 4 m boat was used to support the injection system. The 5 m boat in Figure 4.9 was used to make measurements. An 18 HP out-board motor was used to drive this boat.

Figure 4.8 shows a schematic of the equipment arrangement adopted. Figure 4.10 shows a picture of the equipment on the 5 m boat.

4.3.5 Velocity Measurement Equipment

Velocities were measured using an OTT-propeller meter. A picture of this instrument is shown in Figure 4.7. The instrument aligns itself parallel to the direction of the flow. The number of propeller revolutions given by the revolution counter is calibrated against the flow velocity. The instrument is weighted with a 10 kg weight. A rope was used to lower the meter into the water. The rope was marked at equal length intervals.

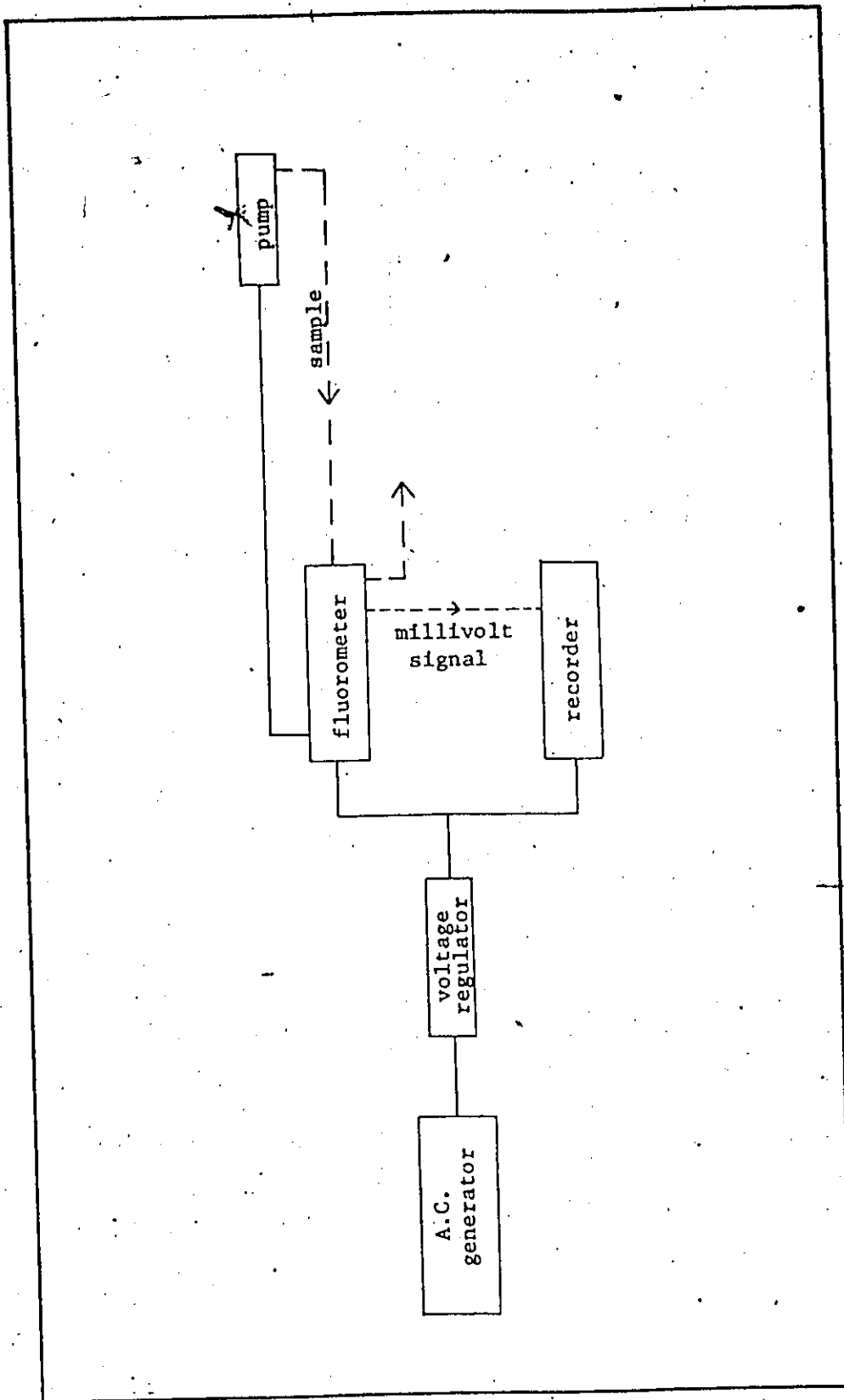


Fig. 4.8 Schematic of the Equipment Arrangement

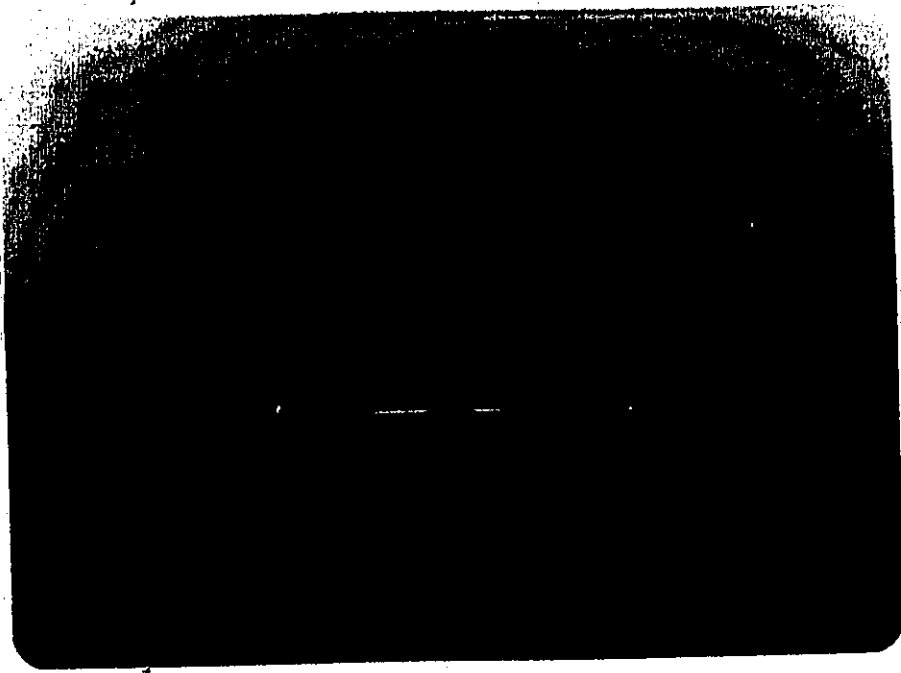


Fig. 4.9 The 5M Boat

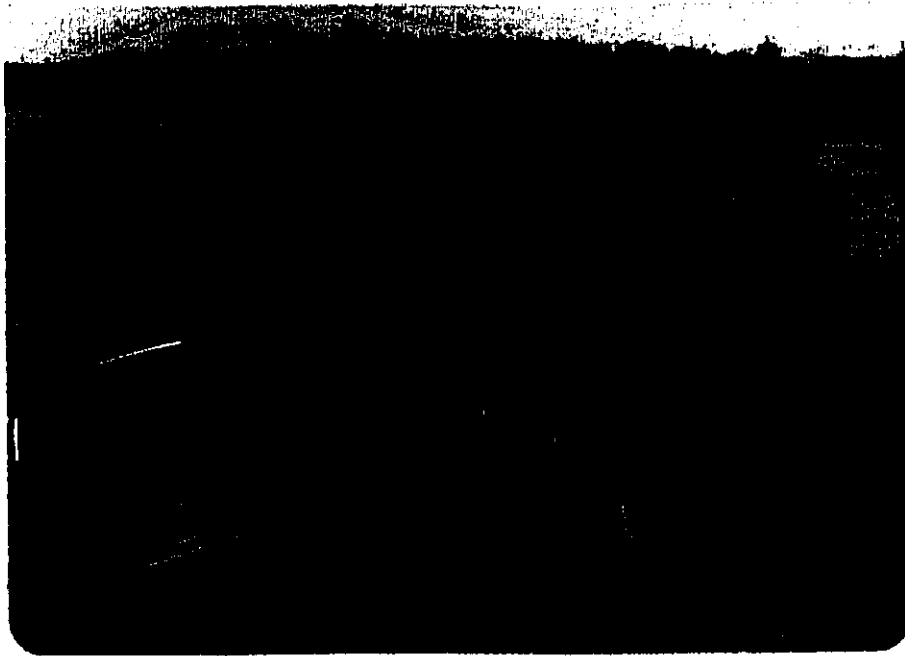


Fig. 4.10 Equipment on the Boat

CHAPTER 5

FIELD PROCEDURE

5.1 Surveying, Dye and Velocity Measurements

For each lateral diffusion experiment two section lines at apparent right angles to the flow were set out from a plan of the study area. These two sections were marked using two ranging poles on the Ontario shore at each section. A common downstream section was used for most of the experiments. Two markers were dropped from the boat approximately 100 m apart in the mid-stream region at each section to settle as closely as possible to the section line. A marker consisted of an anchored coloured bottle held in position on the surface by a weight at the river bed at the end of a line. These markers were not permanent.

The 4 m boat was anchored upstream and the dye injection rate was regulated. The distance from the injection to the first section varied from 550 m to 1750 m. Times varying up to 80 mins were allowed for establishing steady state conditions at the first section. To get the lateral concentration profile a number of traverses were then made with the pump, clamped onto the boat, pumping water from about 1.5 m below the water surface through the fluorometer. The boat operator kept as constant a speed as possible, and kept on line with the marker nearer the Ontario shore and the two ranging poles. The recorder chart paper was marked

passing each marker. The same procedure was carried out at the second section after a steady state had been established there. The markers were surveyed from the shore points using a sextant.

When all the traverses were completed the boat was anchored at a number of stations, usually three, on both sections in the region where the dye had passed. At each station velocities were measured at different depths using the Ott propeller meter. The stations were surveyed using sextant readings onto the shore points.

Where vertical concentration profiles were taken the boat was initially anchored. It was sometimes necessary, especially in windy conditions, to use two anchors to keep the boat steady. Then the pump was started and lowered slowly down into the water. The time to complete the lowering was noted. The chart was marked at the beginning and at the end of the lowering. The chart was allowed to run for a sufficiently long time after lowering to allow for the travel time of the water sample which was 50-60 secs.

When it was possible, experiments were conducted in the morning when the weather was calm. This was done for a number of reasons:

1. The wind created currents which caused the dye plume to shift.
2. The recorder performed poorly when the boat was rocking.

3. It was easier to control the boat in calm weather.
4. An early start made it possible to complete sampling, velocity measurements and survey work in one day.

A minimum of two people was needed to carry out the field operations.

The water temperature data was obtained from co-workers on the Ottawa River study.

5.2 Stage Measurements

A staff gage was set up at a point about 6 km upstream of the Green Creek Pollution Control Centre. This was read at approximately the same time as each dye study was conducted. Another staff gage was set up at the Green Creek Pollution Control Centre and it was read before and after each study. By interpolating the downstream water level corresponding in time to the upstream water level the true surface slope was not found. This was due most likely to the nonlinear nature of the water level fluctuations.

Data was subsequently obtained from two stage recorders belonging to the Water Survey Division, Environment Canada. These stage recorders were located at Hull, P.Q. and at Cumberland, Ontario. They were 26 km apart and the reach between them contained the study area. As there was no time lag between the two in the trend of the average daily water levels the average daily figures were used to estimate the water surface slope.

CHAPTER 6

RESULTS AND OBSERVATIONS

6.1 Concentration Profiles

The measured lateral concentration profiles at the upstream and downstream sections for each lateral diffusion experiment are shown in Figure 6.1. Some profiles are omitted due to obvious faulty boat handling and due to traverses having been made when the concentration distribution was obviously not steady. Figure 6.1 is plotted looking upstream. The peak positions frequently did not match when located from the boat speed and the marker location. This was most likely due to the boat speed not being constant throughout the traverse. On Figure 6.1 the peaks are superimposed.

In some cases there was considerable variation in the magnitude of the peak concentrations. Attempts to correlate this phenomenon with the boat speed were unsuccessful. This can be seen in Appendix D. It can be concluded from this that there was some unsteadiness in either the river flow or in the dye injection rate. Since measurements of the injection rate were not made during the experiments it is not possible to find out what caused the variation in the magnitude of the peak concentrations.

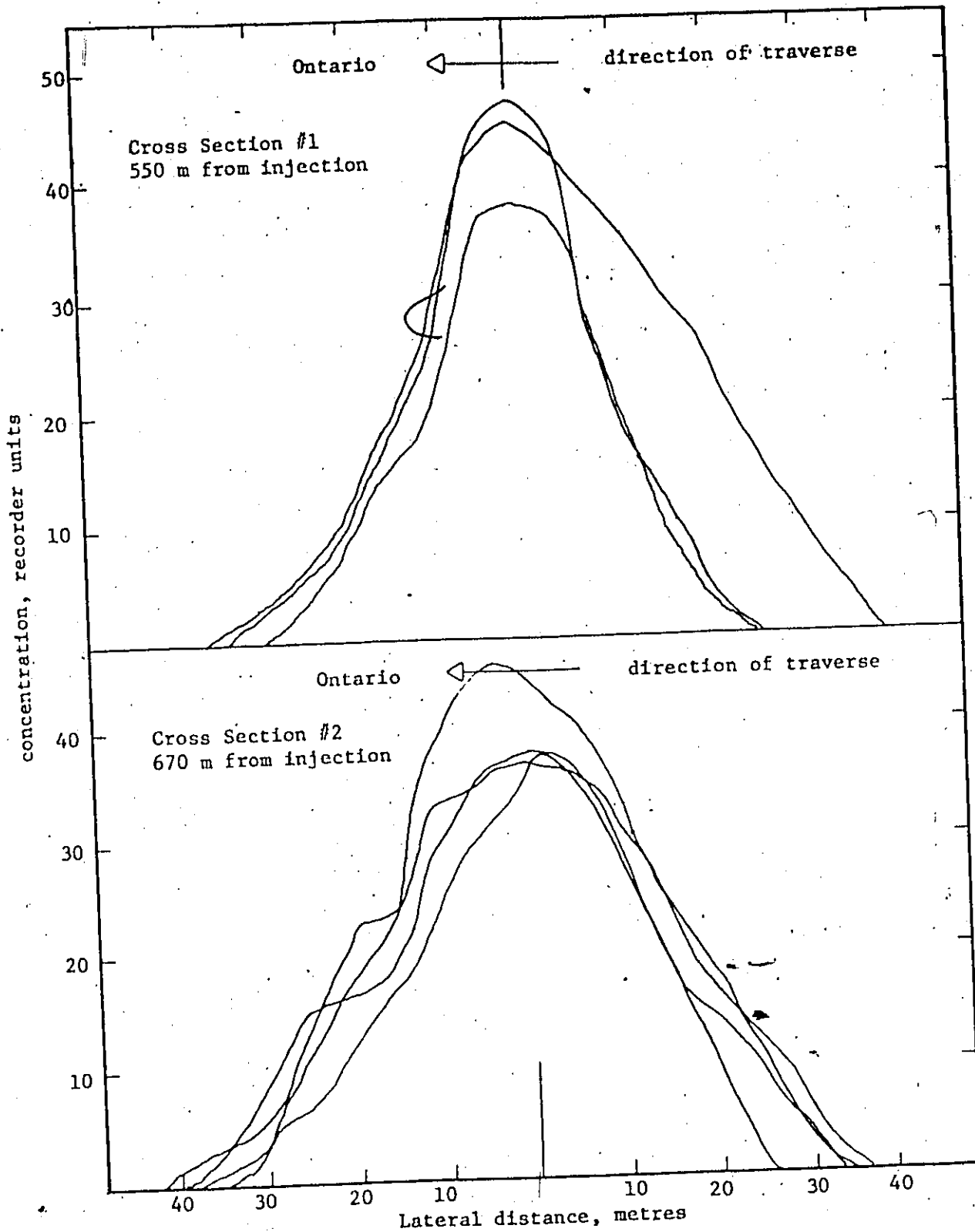


Fig. 6.1(A) Concentration Profiles - June 12

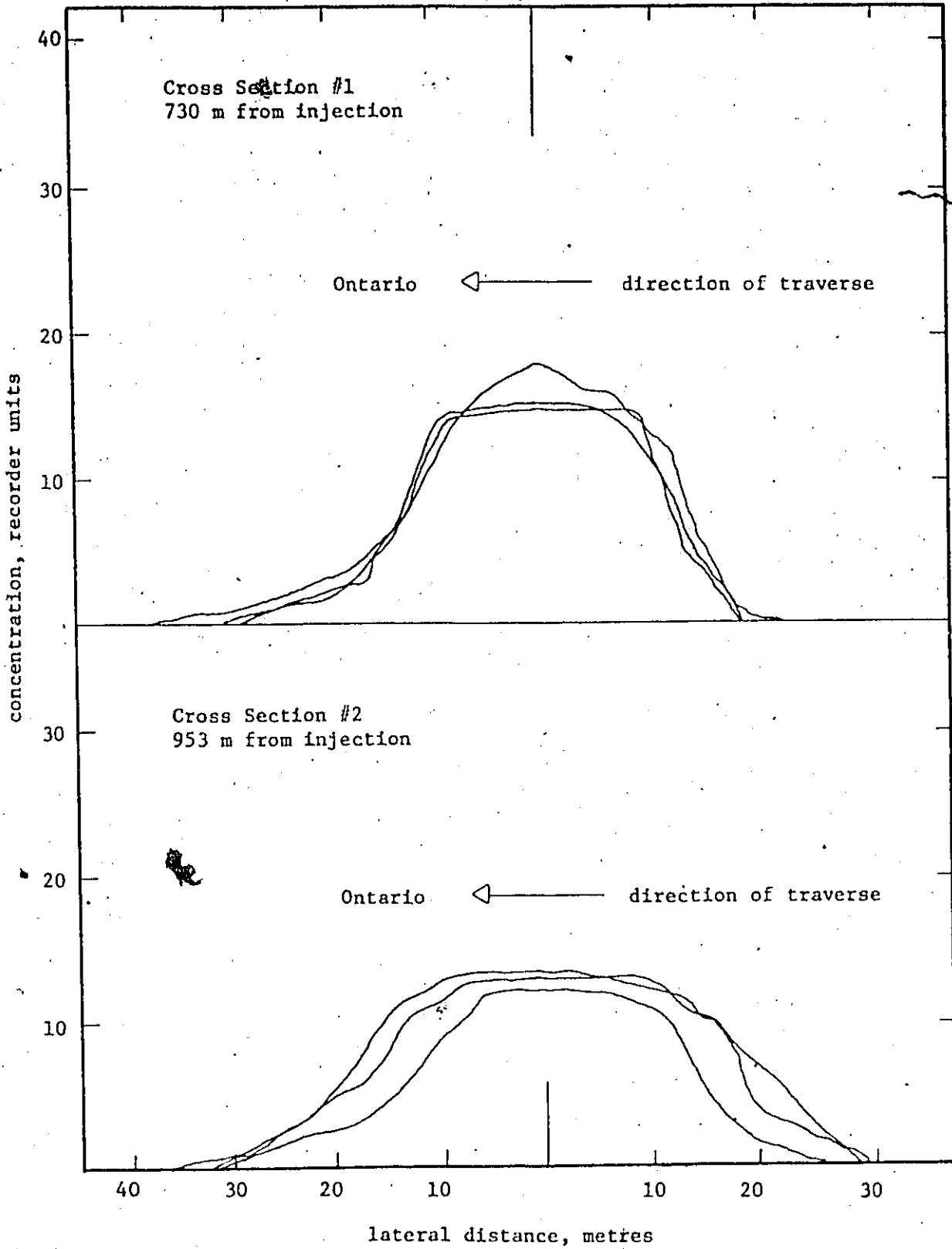


Fig. 6.1(B) Concentration Profiles - June 29

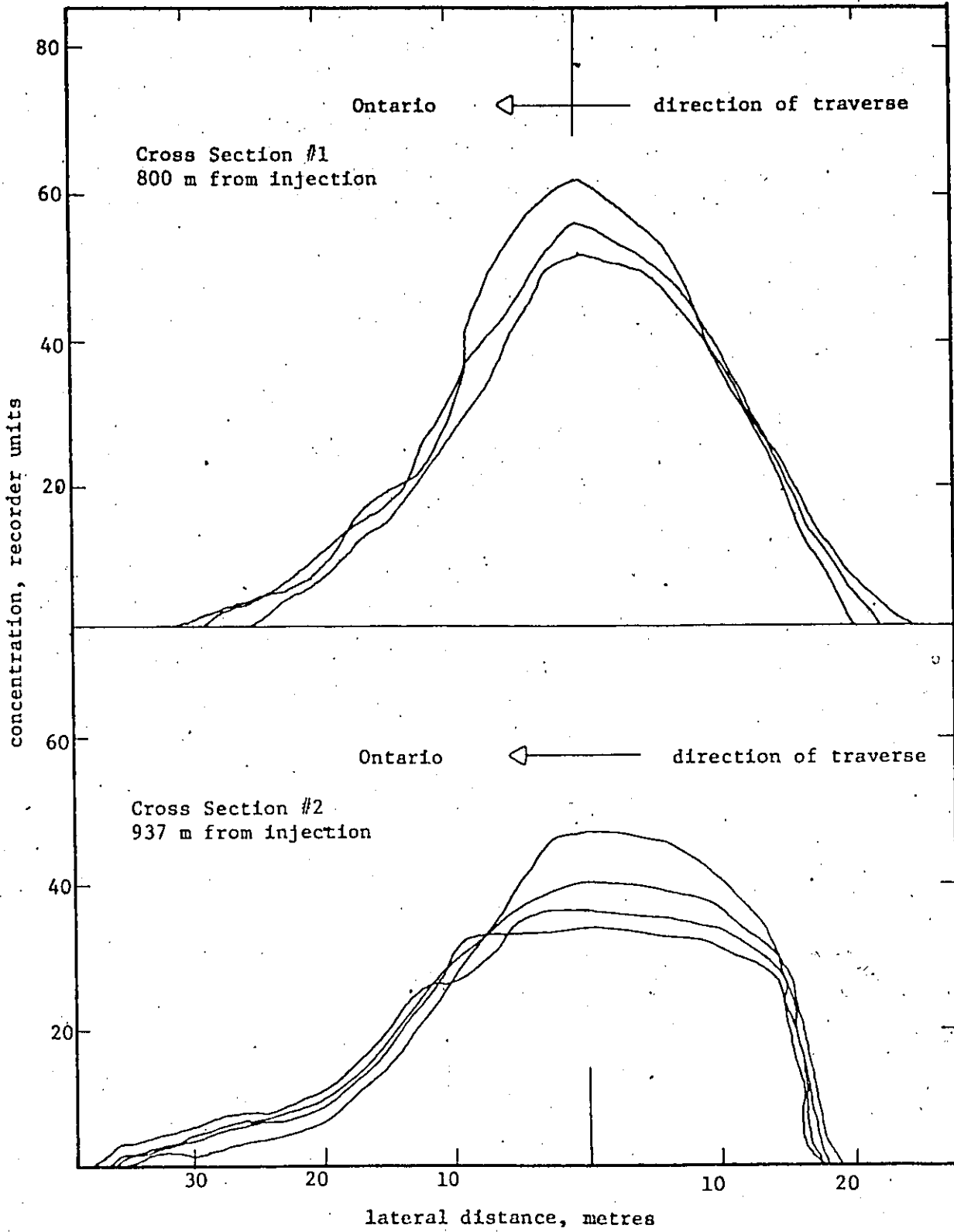


Fig. 6.1(C) Concentration Profiles - July 17

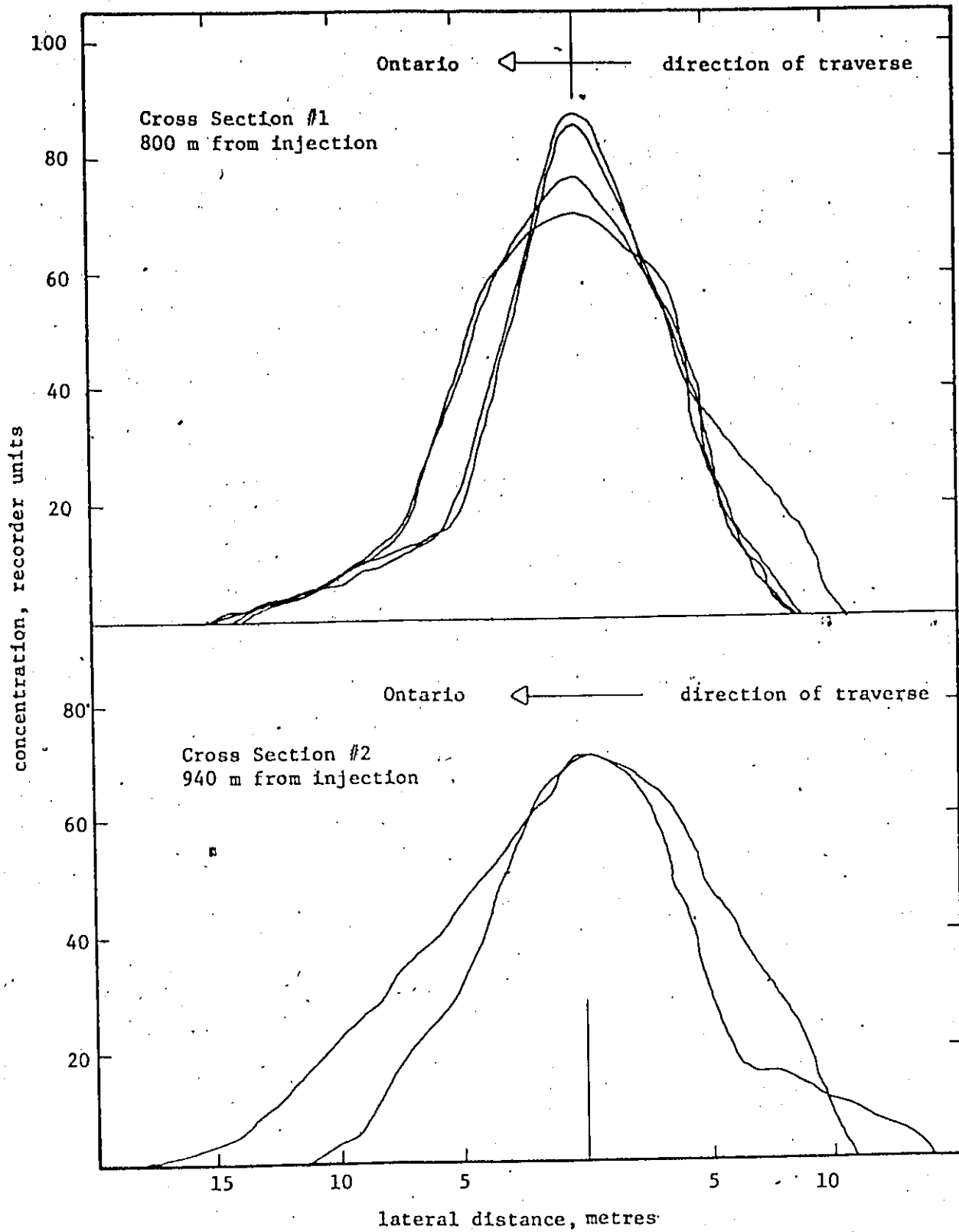


Fig. 6.1(D) Concentration Profiles - July 20

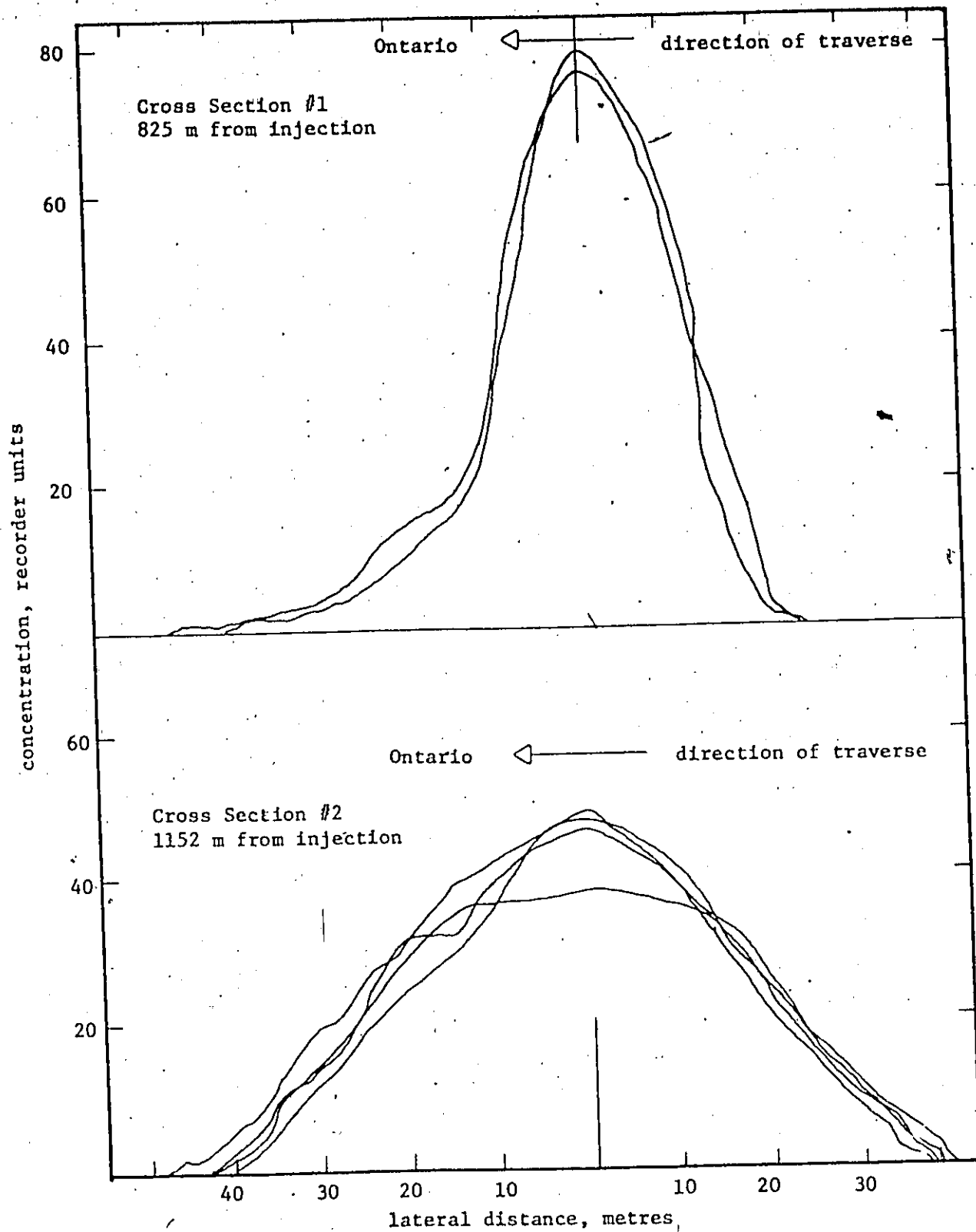


Fig. 6.1(E) Concentration Profiles - August 31

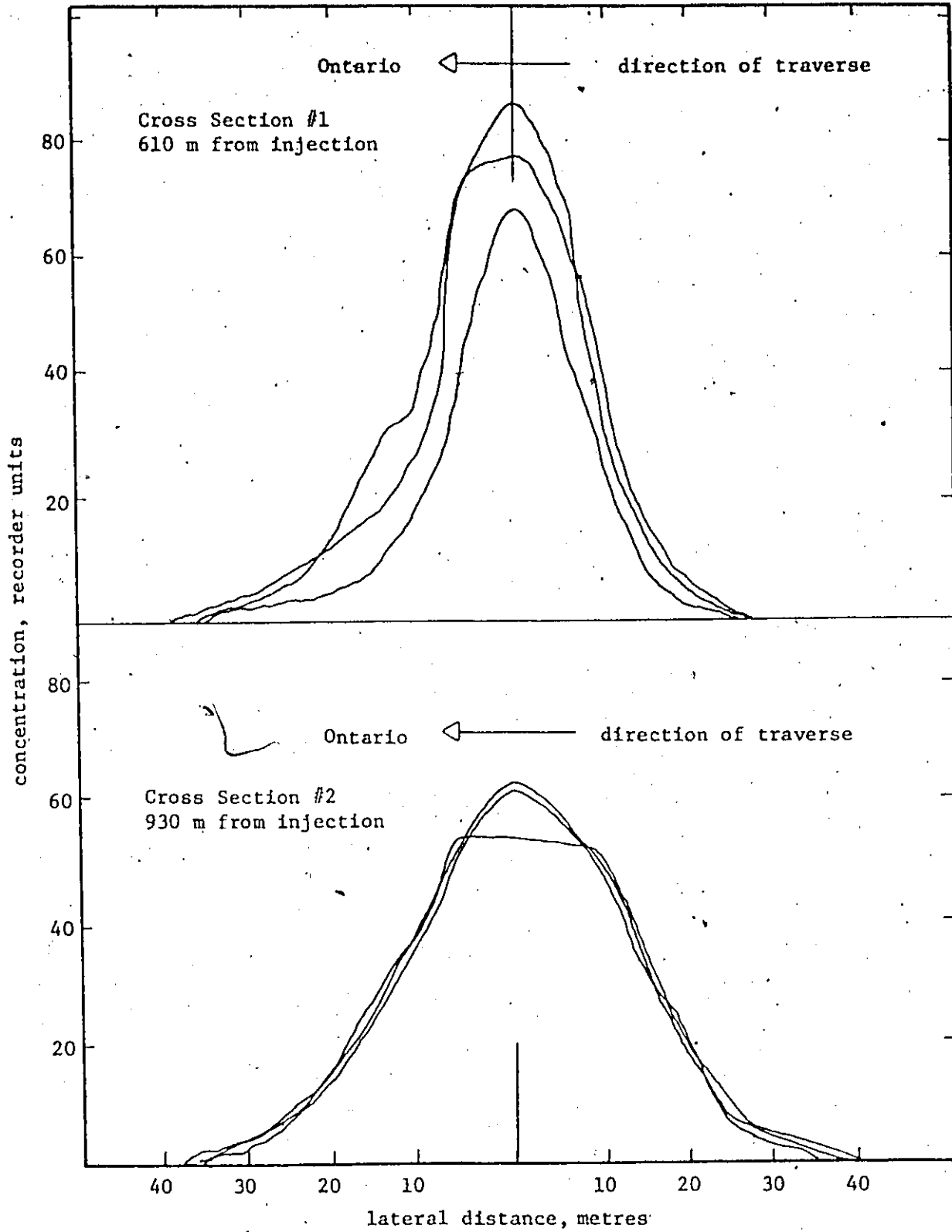


Fig. 6.1(F) Concentration Profiles - October 2

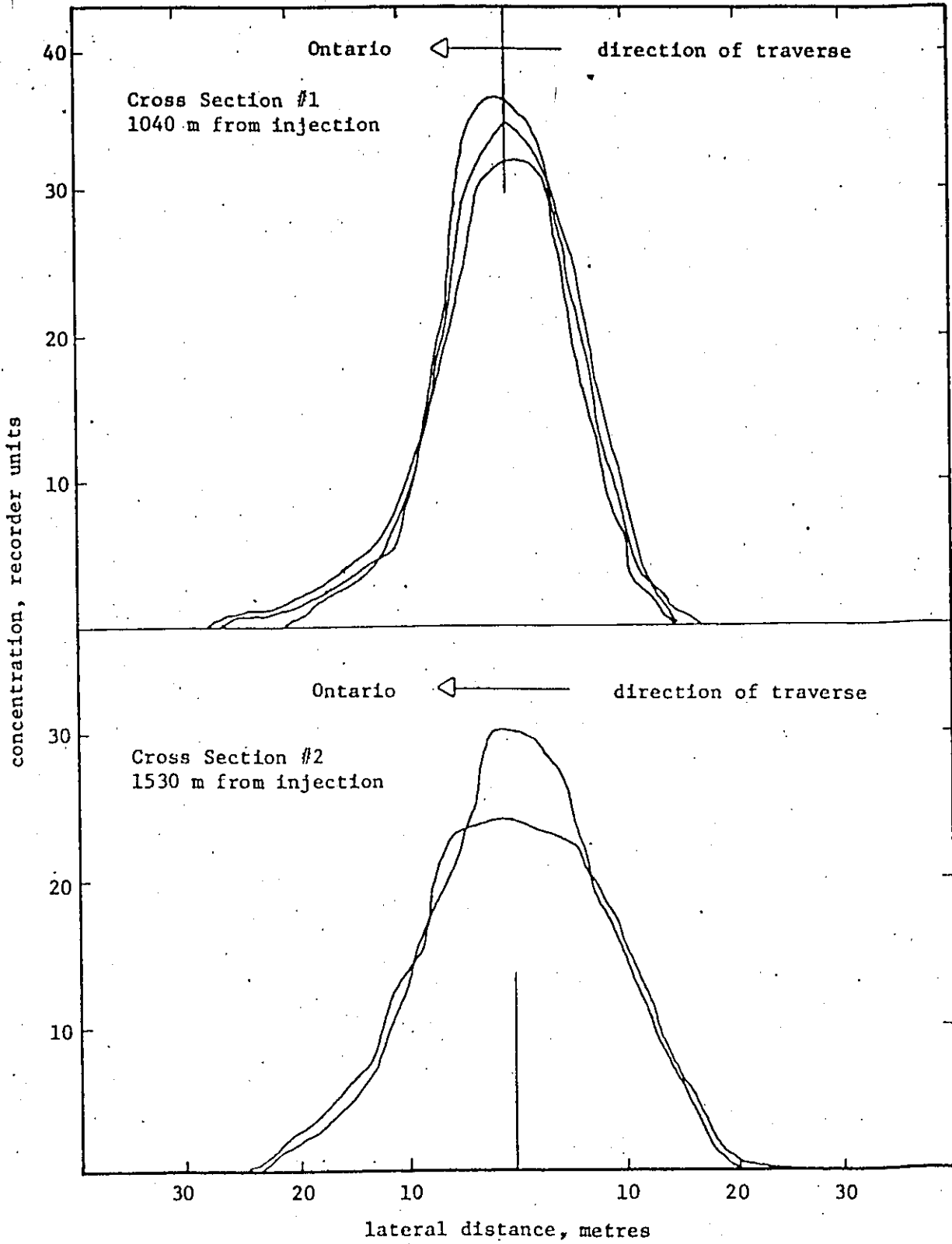


Fig. 6.1(a) Concentration Profiles - October 12



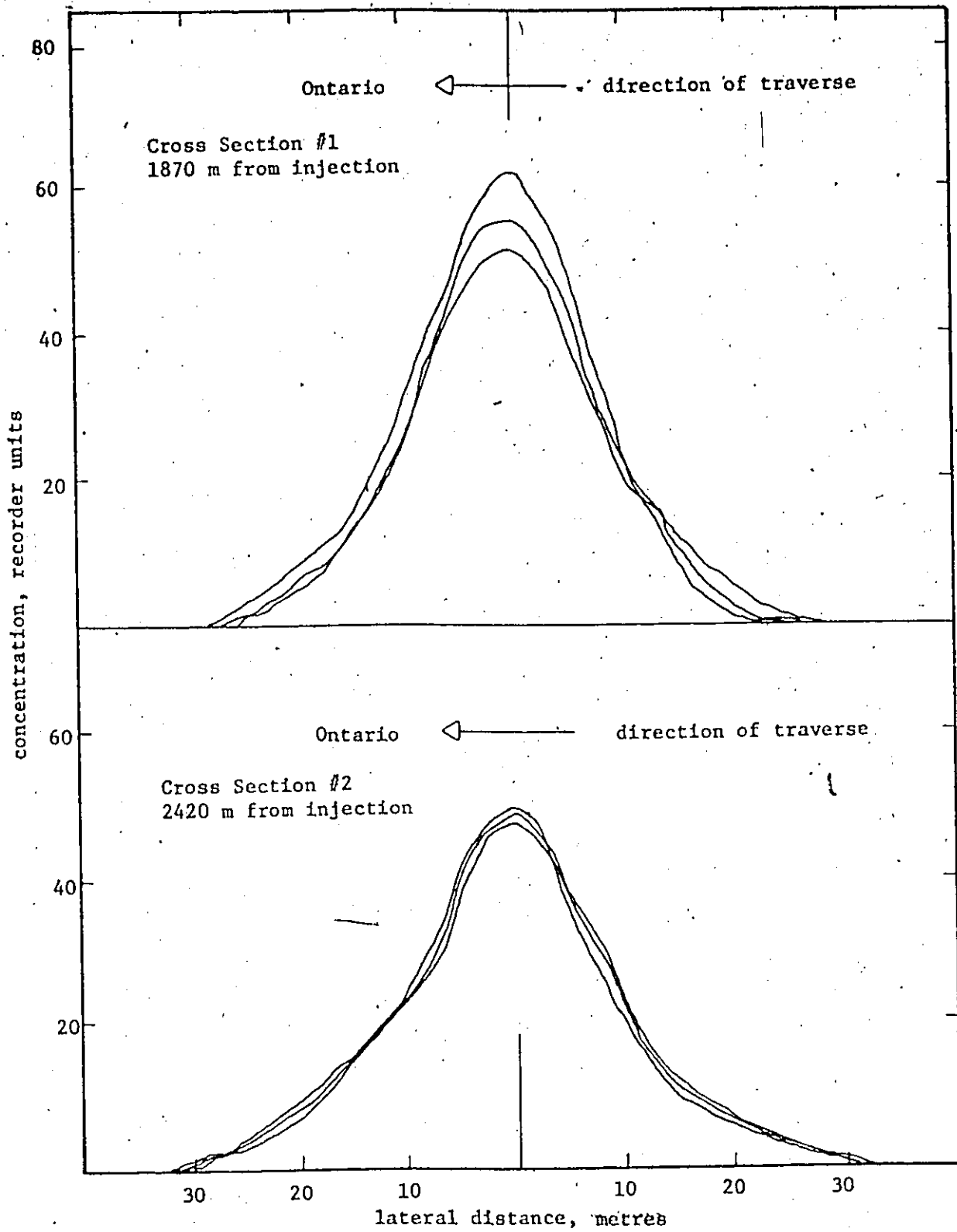


Fig. 6.1(H) Concentration Profiles - October 24

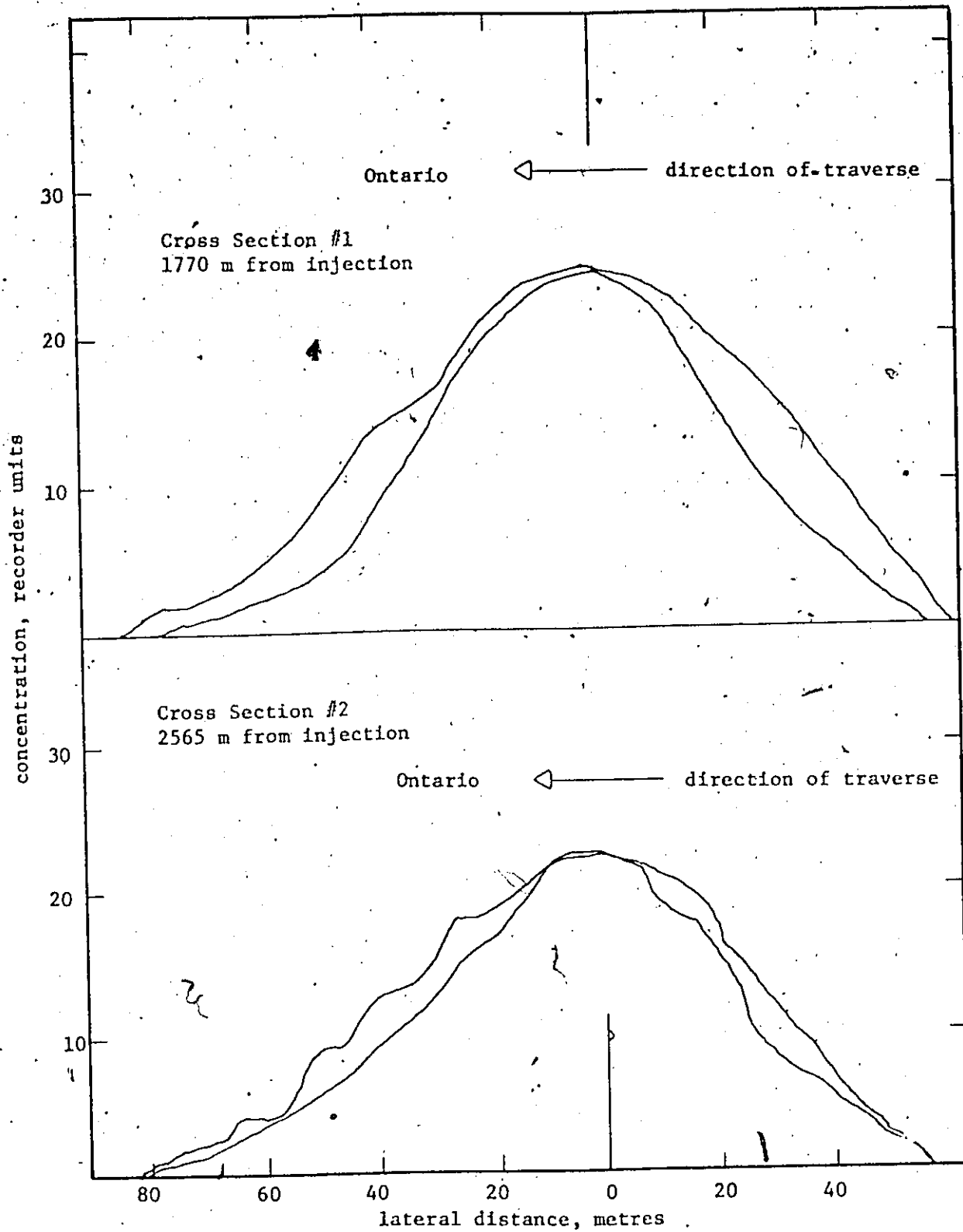


Fig. 6.1(J) Concentration Profiles - November 14

Non-coincidence of some other corresponding portions of the concentration profiles could have been caused by unsteadiness or by faulty boat handling.

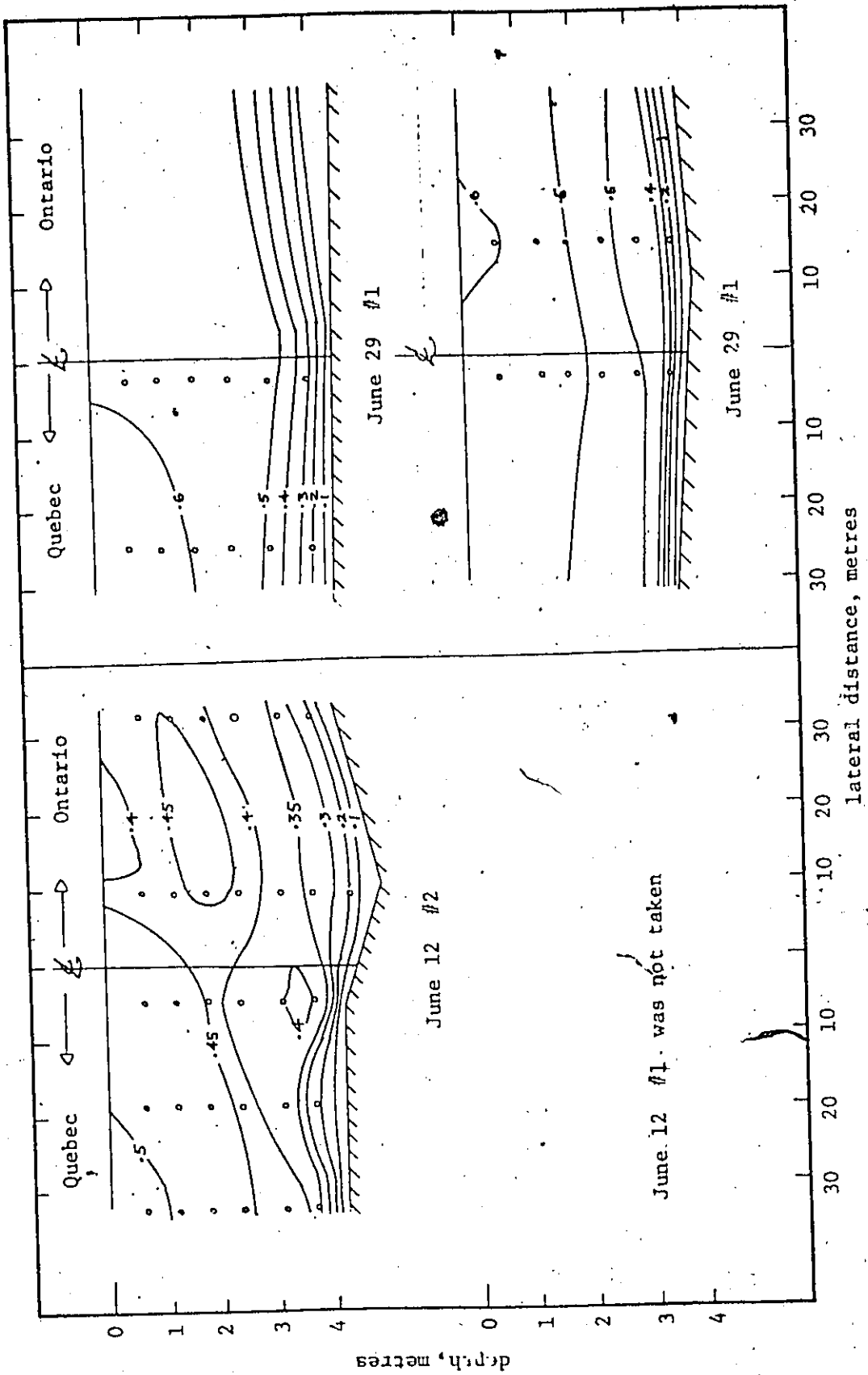
In the analysis which follows the mean of the concentration profiles is used.

6.2 Velocity Profiles

Isovels interpolated from the velocity measurements made at each experimental section are plotted on Figure 6.2. The plots are made looking downstream. The small circles denote the points of measurement. The velocity measurements in some cases could not be made on the same day as the dye study was conducted but they were made very soon afterwards.

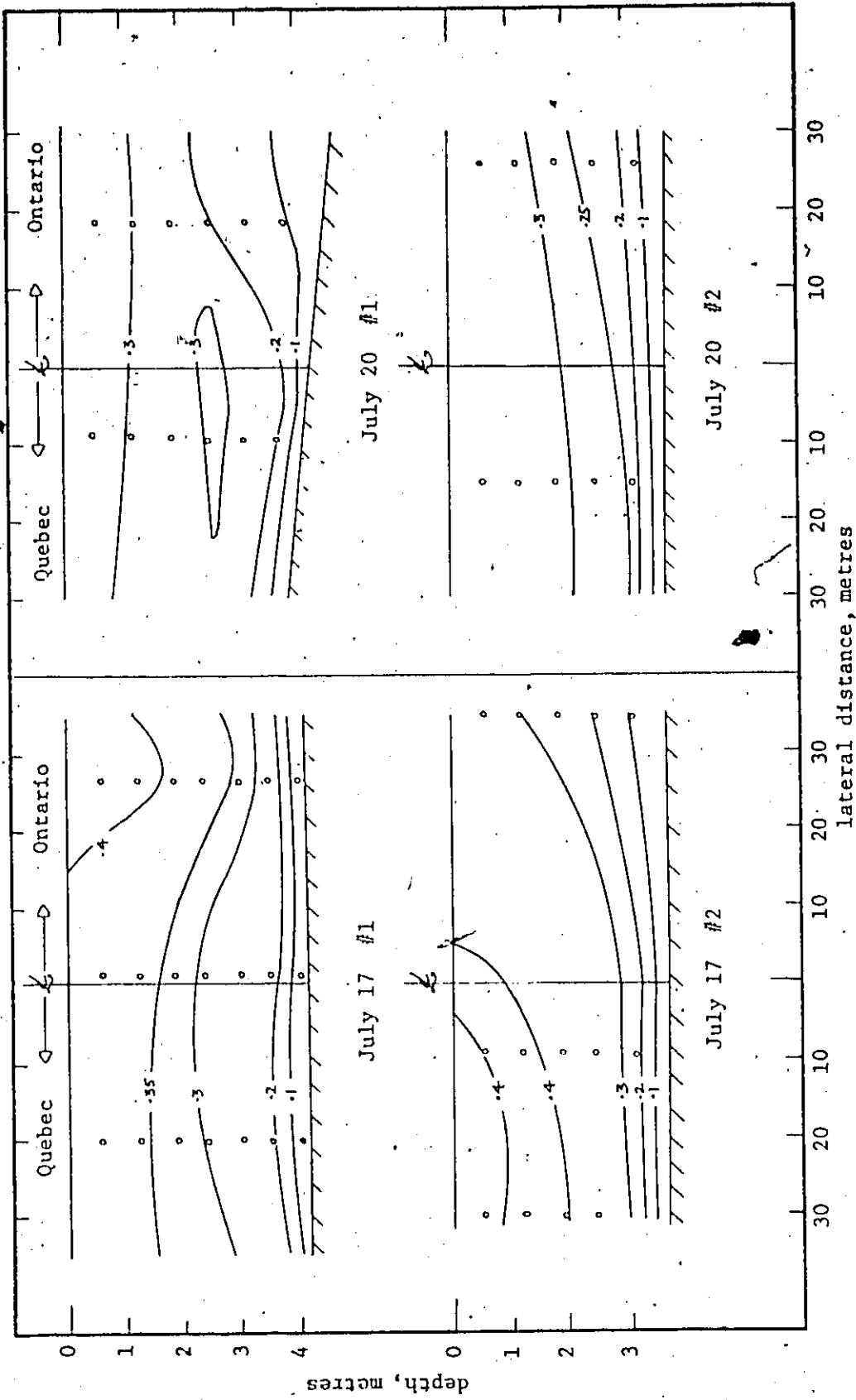
The pattern of the isovels is very similar to that of any natural open channel. On June 14 and on July 1 the isovels are close to one another in the region of flow close to the bed. As would be expected, very high hydraulic gradients were recorded on these two dates.

On November 14 the automatic revolution counter attached to the velocity meter did not work. The rate of revolution of the propeller at a point 1 m beneath the water surface at each section was visually counted. Knowing the approximate shape of the velocity profile the mean velocity was estimated from these counts. Thus, Figure 6.2 does not include an isovel plot for November 14.



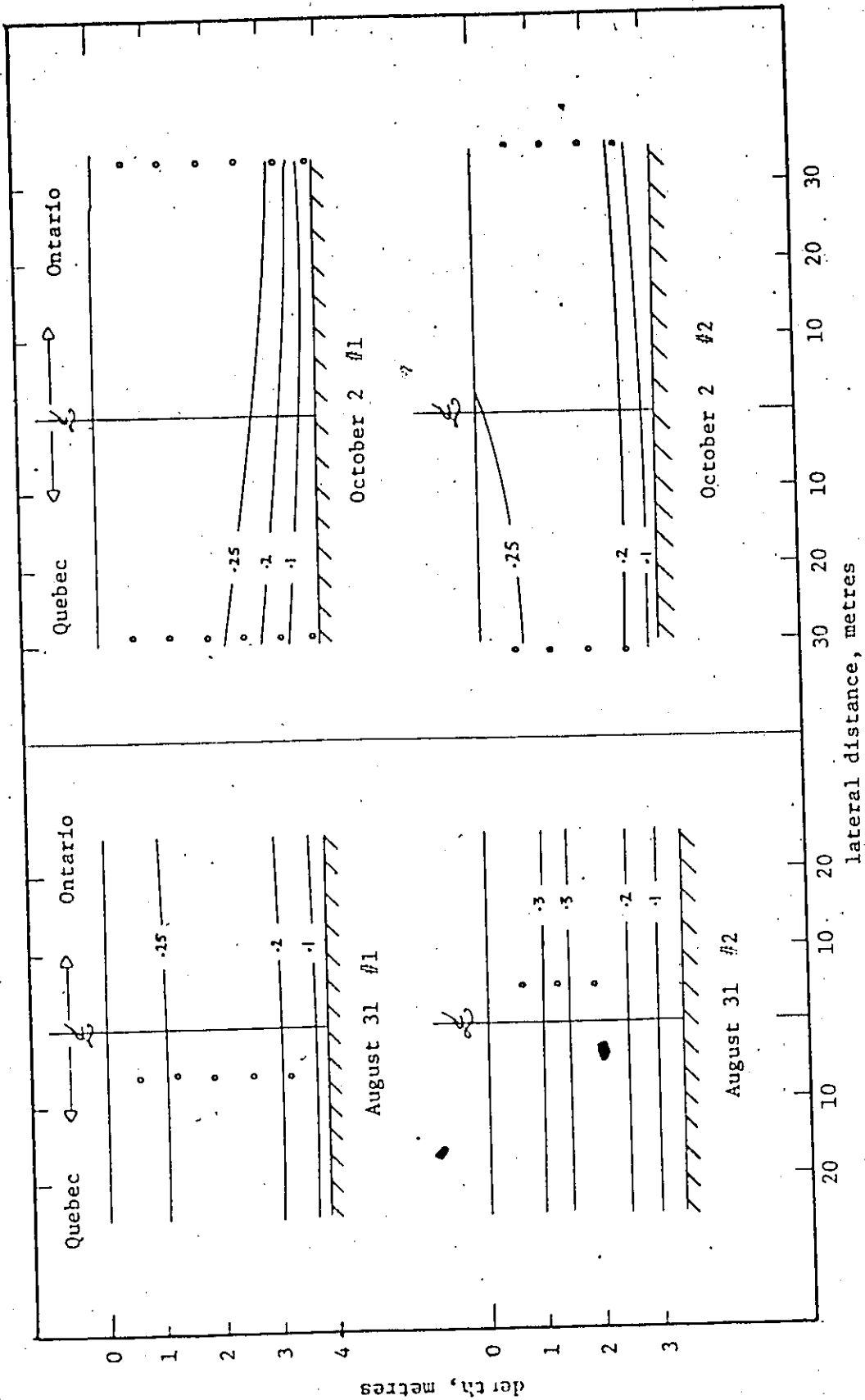
Velocities are in m/s
o denotes a point of velocity measurement

Fig. 6.2(A) Isovel Plots at the Experimental Sections



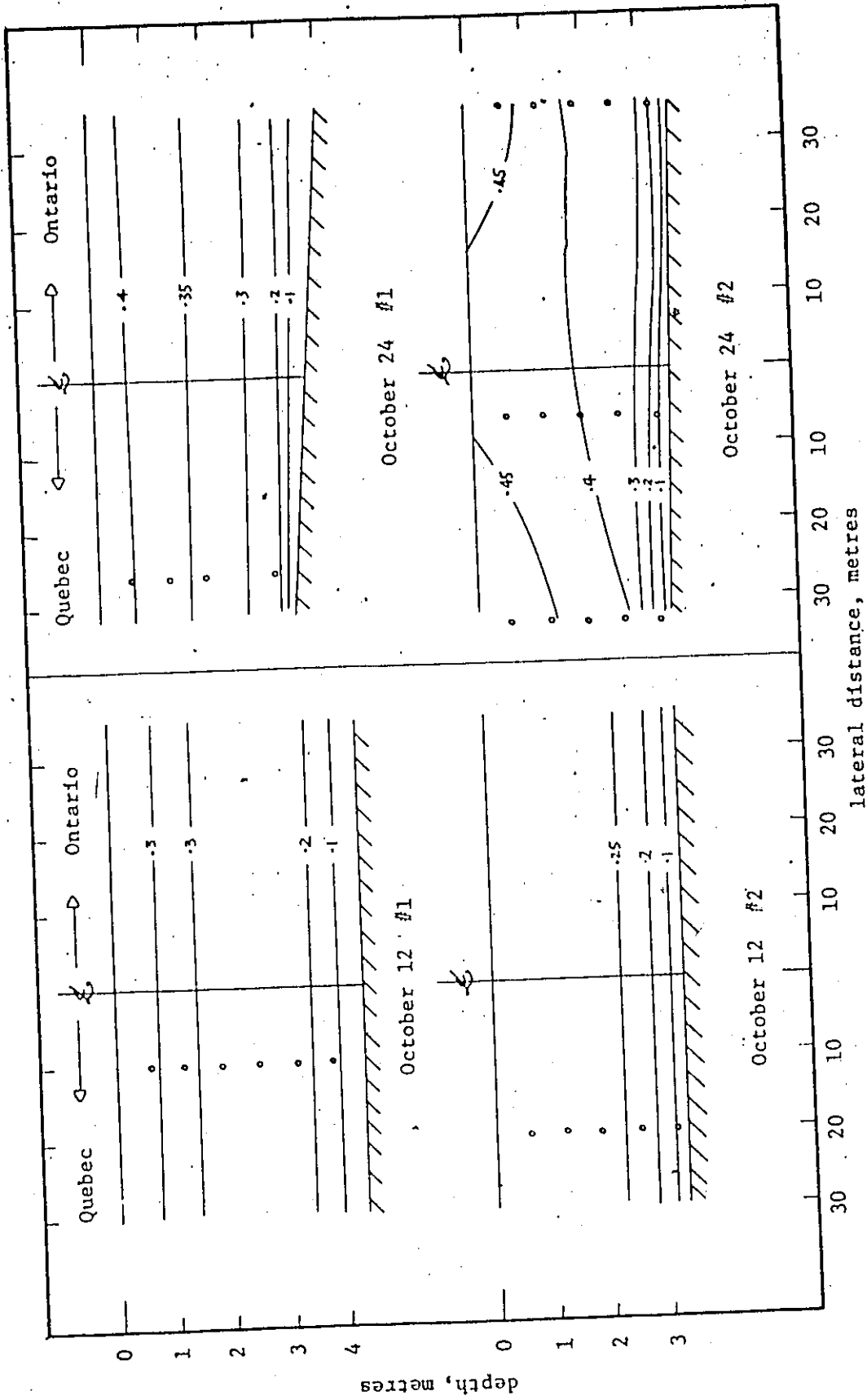
Velocities are in m/s
o denotes a point of velocity measurement

Fig. 6.2(B) Isovel Plots at the Experimental Sections



Velocities are in m/s
o denotes a point of velocity measurement

Fig. 6.2(C) Isovel Plots at the Experimental Sections



Velocities are in m/s
o denotes a point of velocity measurement

Fig. 6.2(D) Isovel Plots at the Experimental Sections

In the analysis which follows the depth averaged velocity is used.

6.3 Other Data

The hydraulic gradients along with the river temperature for each test date are given in Table 6.1. Table 6.1 also gives the distances to the upstream (#1) and downstream (#2) sections from the injection point.

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Table 6.1 Summary of Field Data

Date	June 12	June 29	July 17	July 20	Aug 31	Oct 2	Oct 12	Oct 24	Nov 14
Dist to #1 (m)	555	730	800	800	825	610	1040	1870	1770
Dist to #2 (m)	670	953	937	940	1152	930	1530	2420	2565
Hyd. Gradient (x 10 ⁵)	2.36	1.82	1.80	1.16	0.55	0.83	0.85	0.96	1.03
Temperature (°C)	19.0	20.5	22.0	22.5	22.0	15.5	14.0	13.5	7.0

CHAPTER 7

ANALYSIS OF RESULTS

7.1 Computations

The lateral turbulent diffusion coefficient is computed at different distances from the centreline of the dye plume using Eq. 15. These distances increment by 1 m in every case except for the November 14 experiment when the increment used was 2 m. The average of their values calculated over the fully mixed width as given by Eq. 17 is taken.

The computations were performed on an IBM 360/65. Printouts showing the input data, resultant K_z and other relevant data are given in Table 7.1. A summary of the results is given in Table 7.2.

7.2 Correlation of K_z with the Hydraulic Parameters

The experimental value of the dimensionless turbulent lateral diffusion coefficient K_z/du_x is 0.95 ± 0.41 . Due to the large deviation from the average value this parameter cannot be used to predict K_z . The dimensionless coefficient as expressed by $K_z/\overline{du_x}$ has an average value of 0.058 ± 0.016 . The deviation in this is smaller than in the former case.

	DIST FROM CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VEL #1 (M/S)	AV VEL #2	SLOPE #1 (FX UNITS)	SLOPE #2 (FX UNITS)	K ₂ (S ² M/S)
TOWARDS ONTARIO	0	46.1	17.6	4.30	4.30	0.41	0.41	0.00	0.00	0.000
	1	45.0	17.3	4.30	4.30	0.41	0.41	0.23	0.35	0.113
	2	45.5	16.8	4.30	4.30	0.41	0.41	0.45	0.48	0.139
	3	44.5	16.1	4.30	4.30	0.41	0.41	1.31	0.71	0.106
	4	42.7	15.1	4.30	4.30	0.41	0.41	1.97	0.93	0.059
	5	39.8	14.1	4.30	4.30	0.41	0.41	2.67	1.03	0.081
	6	37.1	13.6	4.30	4.30	0.41	0.41	2.79	1.21	0.095
	7	34.3	11.6	4.30	4.30	0.41	0.41	2.89	1.34	0.099
	8	31.1	22.8	4.30	4.30	0.41	0.41	3.09	1.66	0.099
	9	28.1	24.3	4.30	4.30	0.41	0.41	2.89	1.55	0.099
	10	25.4	27.0	4.40	4.40	0.40	0.40	2.56	1.43	0.098
	11	23.1	26.1	4.40	4.40	0.40	0.40	2.30	1.74	0.094
	12	21.1	23.5	4.40	4.40	0.40	0.40	2.08	1.55	0.101
	13	19.9	22.3	4.40	4.40	0.40	0.40	1.41	1.33	0.127
	14	18.6	20.8	4.40	4.40	0.40	0.40	1.29	1.40	0.123
	15	16.9	17.5	4.40	4.40	0.40	0.40	1.54	1.31	0.111
	16	15.7	18.5	4.40	4.40	0.40	0.40	1.29	1.01	0.139
	17	14.6	17.8	4.40	4.40	0.40	0.40	1.38	0.75	0.153
	18	13.6	17.1	4.40	4.40	0.40	0.40	1.08	0.74	0.181
	19	12.2	16.1	4.40	4.40	0.40	0.40	1.41	0.96	0.099
	20	10.5	14.9	4.40	4.40	0.39	0.39	1.60	1.22	0.071
	21	9.0	13.5	4.40	4.40	0.39	0.39	1.54	1.29	0.052
	22	7.6	12.4	4.40	4.40	0.39	0.39	1.37	1.11	0.058
	23	6.5	11.4	4.40	4.40	0.39	0.39	1.12	1.01	0.051
	24	5.6	10.5	4.40	4.40	0.39	0.39	0.94	1.05	0.080
	25	4.8	9.0	4.40	4.40	0.39	0.39	0.74	1.40	0.021

TOWARDS OUR REC

0	46.0	17.7	4.30	4.30	0.41	0.41	0.00	0.00	0.000
1	45.3	17.6	4.30	4.30	0.41	0.41	0.65	0.25	0.085
2	44.5	17.4	4.30	4.30	0.41	0.41	0.82	0.26	0.109
3	43.6	16.9	4.30	4.30	0.41	0.41	1.22	0.47	0.112
4	42.2	16.3	4.30	4.30	0.41	0.41	1.38	0.62	0.107
5	40.5	15.5	4.30	4.30	0.41	0.41	1.55	0.78	0.105
6	38.8	14.6	4.30	4.30	0.41	0.41	1.78	0.80	0.109
7	36.6	13.6	4.30	4.30	0.41	0.41	2.18	0.97	0.102
8	34.0	12.6	4.30	4.30	0.41	0.41	2.42	1.10	0.097
9	31.2	11.3	4.30	4.30	0.41	0.41	2.15	1.27	0.103
10	28.0	22.8	4.20	4.20	0.41	0.41	2.35	1.43	0.102
11	27.6	23.1	4.20	4.20	0.41	0.41	2.27	1.74	0.092
12	25.5	25.8	4.20	4.20	0.42	0.42	2.10	2.24	0.084
13	23.6	23.4	4.20	4.20	0.42	0.42	2.04	2.23	0.084
14	21.3	21.0	4.20	4.20	0.42	0.42	2.15	1.58	0.077
15	19.3	20.7	4.20	4.20	0.42	0.42	2.23	1.32	0.101
16	16.4	19.3	4.20	4.20	0.42	0.42	2.23	1.43	0.097
17	14.3	17.7	4.20	4.20	0.42	0.42	2.57	1.43	0.099
18	12.0	16.3	4.20	4.20	0.42	0.42	2.13	1.59	0.101
19	11.0	14.9	4.20	4.20	0.42	0.42	1.60	1.40	0.075
20	9.0	13.4	4.10	4.10	0.43	0.43	1.81	1.43	0.075
21	7.1	12.4	4.10	4.10	0.43	0.43	1.98	1.38	0.075
22	5.6	11.4	4.10	4.10	0.43	0.43	1.83	1.11	0.075
23	4.4	10.4	4.10	4.10	0.43	0.43	1.51	1.01	0.072
24	3.6	9.4	4.10	4.10	0.43	0.43	1.17	1.00	0.054
25	3.0	8.4	4.10	4.10	0.43	0.43	0.85	0.99	0.051

DISTANCE TO #1	555	(M)	DISTANCE TO #2	670	(M)
SHEAR VELOCITY	0.0316	(M/S)			
TEMPERATURE	19	(DEG CENT)			
FULLY MIXED WIDTH	15.7	(M)			
AVERAGE K ₂	0.100	(SQ M/S)	STAND DEV	0.014	(SQ M/S)

Table 7.1(A) Computation of K₂ for experiment on June 12

	DIST FRONT CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VEL #1 (M/S)	AV VEL #2	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	KZ (S) M/S)
TOWARDS ONTARIO	0	15.9	13.3	4.30	4.00	0.53	0.52	0.00	0.00	0.000
	1	15.8	13.3	4.30	4.00	0.53	0.52	0.05	0.05	0.185
	2	15.8	13.1	4.31	4.01	0.53	0.52	0.09	0.09	0.202
	3	15.6	13.0	4.31	4.01	0.53	0.52	0.11	0.10	0.266
	4	15.5	12.9	4.32	4.02	0.53	0.52	0.15	0.11	0.285
	5	15.3	12.8	4.32	4.02	0.53	0.52	0.20	0.16	0.256
	6	15.0	12.5	4.33	4.03	0.53	0.52	0.26	0.27	0.208
	7	14.7	12.1	4.34	4.04	0.53	0.52	0.34	0.43	0.164
	8	14.3	11.5	4.34	4.04	0.53	0.52	0.43	0.51	0.150
	9	13.6	11.0	4.35	4.05	0.53	0.52	0.67	0.57	0.131
	10	12.6	10.3	4.35	4.05	0.53	0.52	1.05	0.64	0.107
	11	11.1	9.6	4.36	4.05	0.53	0.52	1.43	0.72	0.091
	12	9.4	8.8	4.36	4.05	0.53	0.52	1.71	0.83	0.079
	13	7.6	7.9	4.37	4.05	0.53	0.52	1.92	0.83	0.079
	14	5.6	7.1	4.38	4.07	0.53	0.52	1.81	0.84	0.080
	15	3.8	6.3	4.38	4.08	0.53	0.52	1.32	0.84	0.093
	16	2.4	5.4	4.38	4.08	0.53	0.52	0.83	0.83	0.115
	17	1.6	4.6	4.39	4.08	0.53	0.52	0.51	0.74	0.141
	18	1.1	3.8	4.39	4.09	0.53	0.52	0.28	0.66	0.174
	19	0.9	3.2	4.40	4.09	0.53	0.52	0.20	0.60	0.193
	20	0.7	2.6	4.41	4.10	0.53	0.52	0.15	0.54	0.211
	21	0.5	2.1	4.42	4.08	0.53	0.52	0.11	0.46	0.245
	22	0.4	1.6	4.43	4.04	0.53	0.52	0.10	0.40	0.270
	23	0.3	1.2	4.43	4.04	0.53	0.52	0.09	0.35	0.297
	24	0.3	0.8	4.44	4.02	0.53	0.52	0.06	0.29	0.369
	25	0.2	0.5	4.45	4.00	0.53	0.52			
TOWARDS QUIBEC	0	15.9	13.3	4.30	4.00	0.54	0.54	0.00	0.00	0.000
	1	15.8	13.3	4.30	4.00	0.54	0.54	0.05	0.05	0.177
	2	15.8	13.2	4.30	4.00	0.54	0.54	0.10	0.05	0.236
	3	15.6	13.1	4.30	3.95	0.54	0.54	0.16	0.06	0.244
	4	15.3	13.0	4.30	3.95	0.54	0.54	0.23	0.09	0.218
	5	15.1	12.9	4.30	3.95	0.54	0.54	0.24	0.11	0.251
	6	14.9	12.8	4.30	3.95	0.54	0.54	0.21	0.17	0.278
	7	14.7	12.5	4.30	3.90	0.54	0.54	0.27	0.29	0.235
	8	14.3	12.1	4.30	3.90	0.54	0.54	0.39	0.41	0.173
	9	13.6	11.5	4.30	3.85	0.54	0.54	0.73	0.55	0.121
	10	12.6	10.8	4.30	3.85	0.54	0.54	1.01	0.67	0.103
	11	11.4	10.2	4.30	3.85	0.54	0.54	1.16	0.65	0.103
	12	9.9	9.6	4.30	3.80	0.54	0.54	1.47	0.62	0.096
	13	8.3	8.9	4.30	3.80	0.54	0.54	1.63	0.67	0.070
	14	6.8	8.1	4.30	3.80	0.54	0.54	1.49	0.80	0.091
	15	5.5	7.2	4.30	3.75	0.54	0.54	1.26	0.93	0.095
	16	4.4	6.3	4.30	3.75	0.54	0.54	1.09	0.94	0.100
	17	3.3	5.3	4.30	3.75	0.54	0.54	1.05	0.89	0.102
	18	2.5	4.5	4.30	3.70	0.54	0.54	0.85	0.79	0.117
	19	1.9	3.9	4.30	3.70	0.54	0.54	0.62	0.65	0.146
	20	1.4	3.4	4.30	3.70	0.54	0.54	0.45	0.52	0.182
	21	1.1	2.9	4.30	3.65	0.54	0.54	0.31	0.51	0.209
	22	0.9	2.4	4.30	3.65	0.54	0.54	0.20	0.52	0.226
	23	0.8	1.9	4.30	3.65	0.54	0.54	0.12	0.45	0.280
	24	0.8	1.5	4.30	3.60	0.54	0.54	0.10	0.35	0.344
	25	0.6	1.3	4.30	3.60	0.54	0.54	0.11	0.26	0.416
	DISTANCE TO #1	730	(M)					DISTANCE TO #2	953	(M)
	SHEAR VELOCITY	0.0275	(M/S)							
	TEMPERATURE	21	(DEG CENT)							
	FULLY MIXED WIDTH	23.0	(M)							
	AVERAGE KZ	0.181	(S) M/S)					STAND DEV	0.066	(S) M/S)

Table 7.1(B) Computation of K_z for experiment on June 29

	DIST FROM CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VFL #1 (M/S)	AV VFL #2	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	K ₂ (SO M/S)	
TOWARDS ONTARIO	0	55.3	70.3	4.25	3.75	0.33	0.34	0.00	0.00	0.000	
	1	54.4	70.1	4.25	3.75	0.30	0.34	0.85	0.15	0.073	
	2	51.8	70.8	4.25	3.75	0.30	0.34	1.06	0.32	0.104	
	3	51.0	70.3	4.25	3.74	0.30	0.34	1.72	0.53	0.093	
	4	49.6	70.5	4.25	3.74	0.30	0.34	3.07	0.75	0.071	
	5	48.0	70.4	4.25	3.74	0.31	0.34	3.51	1.14	0.068	
	6	41.4	70.0	4.25	3.74	0.31	0.34	3.68	1.50	0.070	
	7	37.5	70.2	4.25	3.73	0.31	0.34	4.15	1.70	0.070	
	8	32.5	71.1	4.25	3.73	0.31	0.34	4.52	2.03	0.065	
	9	28.5	70.5	4.25	3.72	0.31	0.34	4.04	2.65	0.065	
	10	25.0	70.3	4.25	3.72	0.32	0.34	3.67	3.25	0.065	
	11	21.0	71.4	4.25	3.72	0.32	0.34	3.75	3.50	0.062	
	12	18.0	70.4	4.25	3.72	0.32	0.34	2.95	2.90	0.078	
	13	16.1	70.7	4.25	3.71	0.32	0.34	1.97	1.95	0.119	
	14	14.4	70.0	4.25	3.71	0.32	0.34	1.97	1.73	0.125	
	15	11.8	70.3	4.25	3.71	0.32	0.34	2.52	1.62	0.114	
	16	9.1	70.0	4.25	3.70	0.33	0.34	1.97	1.38	0.119	
	17	7.2	70.7	4.25	3.70	0.33	0.34	1.43	1.27	0.144	
	18	5.9	70.4	4.25	3.69	0.33	0.34	1.53	1.22	0.159	
	19	4.1	70.4	4.25	3.69	0.33	0.34	1.59	1.08	0.163	
	20	2.5	70.3	4.25	3.69	0.33	0.34	0.95	1.03	0.158	
	21	1.6	70.3	4.25	3.68	0.34	0.34	0.62	0.94	0.200	
	22	1.0	70.3	4.25	3.68	0.34	0.34	0.49	0.81	0.241	
	23	0.5	70.5	4.25	3.68	0.34	0.34	0.34	0.70	0.277	
	24	0.2	70.8	4.25	3.67	0.35	0.34	0.17	0.58	0.328	
25	0.1	70.3	4.25	3.67	0.35	0.34	0.00	0.00	0.434		
TOWARDS QUEBEC	0	57.0	70.3	4.42	3.75	0.32	0.34	0.00	0.00	0.000	
	1	51.8	70.1	4.42	3.75	0.32	0.34	1.20	0.15	0.072	
	2	51.0	70.8	4.42	3.75	0.32	0.34	2.01	0.22	0.085	
	3	49.6	70.6	4.42	3.74	0.32	0.34	2.70	0.39	0.088	
	4	48.0	70.5	4.42	3.74	0.32	0.34	2.77	0.75	0.097	
	5	43.6	70.4	4.42	3.74	0.32	0.34	2.69	1.03	0.104	
	6	40.4	70.0	4.42	3.73	0.32	0.34	3.21	1.01	0.104	
	7	36.3	70.8	4.42	3.73	0.32	0.34	3.48	1.52	0.080	
	8	32.5	70.3	4.42	3.73	0.32	0.34	4.29	2.18	0.081	
	9	27.8	70.0	4.42	3.72	0.32	0.34	4.45	2.48	0.078	
	10	22.4	70.6	4.42	3.72	0.32	0.34	5.13	2.97	0.069	
	11	17.1	71.1	4.42	3.72	0.32	0.34	4.93	3.63	0.063	
	12	13.6	70.4	4.42	3.71	0.32	0.34	4.93	4.38	0.064	
	13	10.5	70.0	4.42	3.71	0.32	0.34	3.81	4.80	0.065	
	14	8.0	70.7	4.42	3.71	0.32	0.34	3.09	4.73	0.067	
	15	4.5	70.0	4.42	3.70	0.32	0.34	2.77	4.34	0.065	
	16	1.0	70.4	4.42	3.70	0.32	0.34	3.33	3.13	0.081	
	17	0.0	70.1	4.42	3.70	0.32	0.34	1.25	1.29	0.109	
	18	0.0	70.0	4.42	3.69	0.32	0.34	0.17	0.22	1.310	
	19	0.0	70.0	4.42	3.69	0.32	0.34	0.00	0.01	50.717	
	20	0.0	70.0	4.42	3.68	0.32	0.34	0.00	0.00	0.158	
	21	0.0	70.0	4.42	3.68	0.32	0.34	0.00	0.00	0.200	
	22	0.0	70.0	4.42	3.68	0.32	0.34	0.00	0.00	0.241	
	23	0.0	70.0	4.42	3.68	0.32	0.34	0.00	0.00	0.277	
	24	0.0	70.0	4.42	3.67	0.32	0.34	0.00	0.00	0.328	
25	0.0	70.0	4.42	3.67	0.32	0.34	0.00	0.00	0.434		
DISTANCE TO #1				000	(M)	DISTANCE TO #2				937	(M)
SHEAR VELOCITY				0.0274	(M/S)						
TEMPERATURE				22	(DEG CENT)						
FULLY MIXED WIDTH				24.0	(M)						
AVERAGE K ₂				0.075	(SO M/S)	STAND DEV				0.009	(SO M/S)

Table 7.1(C) Computation of K₂ for experiment on July 17

	DIST FROM CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VFL #1 (M/S)	AV VFL #2 (M/S)	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	<Z (50 M/S)
TOWARDS ONTARIO :	0	80.3	71.8	4.34	3.65	0.25	0.25	0.00	0.00	0.000
	1	79.6	71.3	4.35	3.65	0.26	0.25	0.70	0.55	0.073
	2	78.1	69.9	4.34	3.65	0.25	0.25	1.69	1.38	0.060
	3	75.0	67.4	4.37	3.65	0.26	0.25	3.01	2.50	0.050
	4	70.8	63.9	4.38	3.65	0.26	0.25	4.13	3.45	0.047
	5	66.0	59.8	4.39	3.65	0.26	0.25	4.79	4.14	0.049
	6	60.5	55.0	4.40	3.65	0.26	0.25	5.50	4.69	0.050
	7	54.3	50.0	4.42	3.65	0.26	0.25	6.38	4.02	0.052
	8	46.5	45.3	4.44	3.65	0.26	0.25	7.42	4.70	0.053
	9	39.3	41.1	4.45	3.65	0.26	0.25	7.04	4.17	0.061
	10	33.8	37.4	4.44	3.65	0.25	0.25	5.79	3.54	0.076
	11	29.3	34.5	4.47	3.65	0.26	0.25	5.38	3.06	0.086
	12	25.5	31.8	4.48	3.65	0.26	0.25	4.67	2.61	0.101
	13	20.0	29.0	4.40	3.65	0.25	0.25	3.63	2.09	0.127
	14	17.0	26.0	4.50	3.65	0.25	0.25	3.04	1.92	0.143
	15	14.3	25.0	4.50	3.65	0.25	0.25	2.67	2.14	0.142
	16	12.3	23.4	4.53	3.65	0.25	0.25	2.04	2.33	0.150
	17	10.8	21.2	4.54	3.65	0.25	0.25	1.54	2.14	0.170
	18	9.5	19.8	4.55	3.65	0.25	0.25	1.29	1.47	0.218
	19	8.3	19.0	4.56	3.65	0.25	0.25	1.25	1.00	0.256
	20	7.0	17.4	4.58	3.65	0.25	0.25	1.21	1.59	0.195
	21	6.0	14.8	4.59	3.65	0.25	0.25	1.04	2.42	0.149
	22	5.0	12.7	4.61	3.65	0.25	0.25	1.00	2.52	0.140
	23	4.0	10.1	4.63	3.65	0.25	0.25	1.00	2.04	0.155
	24	3.0	8.9	4.64	3.65	0.25	0.25	0.96	1.36	0.196
	25	2.3	7.8	4.65	3.65	0.25	0.25	0.75	1.06	0.242
TOWARDS QUEBEC	0	80.3	71.8	4.34	3.65	0.26	0.26	0.00	0.00	0.000
	1	79.5	71.4	4.33	3.65	0.26	0.26	0.75	0.40	0.071
	2	78.3	69.9	4.32	3.65	0.26	0.26	1.29	1.48	0.058
	3	76.3	67.4	4.30	3.65	0.26	0.26	2.17	2.42	0.052
	4	72.5	64.4	4.20	3.65	0.26	0.26	3.83	3.33	0.045
	5	67.5	58.2	4.20	3.65	0.26	0.26	5.79	5.56	0.035
	6	60.5	50.7	4.27	3.65	0.26	0.26	6.96	7.79	0.031
	7	51.8	42.8	4.25	3.65	0.26	0.26	7.58	7.33	0.035
	8	44.3	38.5	4.24	3.65	0.26	0.26	7.42	4.68	0.049
	9	37.5	35.3	4.23	3.65	0.26	0.26	6.95	3.42	0.061
	10	30.3	32.0	4.22	3.65	0.26	0.26	7.00	3.04	0.066
	11	24.0	30.0	4.20	3.65	0.26	0.26	6.04	2.21	0.082
	12	20.0	28.0	4.19	3.65	0.26	0.26	4.17	2.00	0.109
	13	17.3	26.0	4.18	3.65	0.25	0.26	2.92	2.02	0.132
	14	14.8	23.8	4.17	3.65	0.25	0.26	2.50	2.20	0.134
	15	12.5	21.3	4.15	3.65	0.25	0.26	2.09	2.65	0.122
	16	10.3	17.9	4.14	3.65	0.25	0.26	2.00	3.27	0.104
	17	7.8	14.3	4.13	3.65	0.25	0.26	2.34	3.52	0.094
	18	5.0	11.1	4.11	3.65	0.25	0.26	1.90	3.07	0.126
	19	4.5	8.9	4.09	3.65	0.25	0.26	1.38	2.22	0.144
	20	3.7	7.3	4.08	3.65	0.25	0.26	1.25	1.63	0.175
	21	2.9	6.1	4.05	3.65	0.25	0.26	1.17	1.31	0.199
	22	1.7	4.8	4.03	3.65	0.25	0.26	0.83	1.27	0.228
	23	0.5	3.5	4.01	3.65	0.25	0.26	0.71	1.27	0.236
	24	0.0	2.5	4.00	3.65	0.25	0.26	0.46	1.06	0.302
	25	0.0	1.5	4.00	3.65	0.25	0.26	0.08	0.94	0.438
	DISTANCE TO #1	800		(M)				DISTANCE TO #2	940	(M)
	SHEAR VELOCITY	2.0220		(M/S)						
	TEMPERATURE	23		(DEG CENT)						
	FULLY MIXED WIDTH	24.0		(M)						
	AVERAGE KZ	0.061		(50 M/S)				STAND DEV	0.019	(50 M/S)

Table 7.1(D) Computation of K_z for experiment on July 20

	DIST FROM CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VEL #1 (M/S)	AV VEL #2	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	KZ (SO M/S)
TOWARDS ONTARIO	0	79.9	46.5	3.90	3.40	0.27	0.30	0.00	0.00	0.000
	1	79.4	46.1	3.90	3.40	0.27	0.30	0.50	0.40	0.069
	2	78.0	45.6	3.90	3.40	0.27	0.30	1.52	0.49	0.261
	3	79.0	45.1	3.90	3.40	0.27	0.30	3.01	0.55	0.751
	4	70.3	44.4	3.90	3.40	0.27	0.30	4.57	0.62	0.046
	5	64.8	43.6	3.90	3.40	0.27	0.30	5.31	0.78	0.047
	6	59.4	42.8	3.90	3.40	0.27	0.30	5.30	0.49	0.053
	7	54.1	41.8	3.90	3.40	0.27	0.30	5.64	0.97	0.054
	8	40.4	40.6	3.90	3.40	0.27	0.30	6.53	1.13	0.059
	9	37.4	39.4	3.90	3.40	0.27	0.30	7.01	1.24	0.048
	10	27.8	36.8	3.90	3.40	0.27	0.30	6.79	1.29	0.050
	11	23.4	35.6	3.90	3.40	0.27	0.30	5.65	1.24	0.057
	12	23.4	34.5	3.90	3.40	0.27	0.30	4.38	1.20	0.068
	13	21.1	34.5	3.90	3.40	0.27	0.30	3.72	1.10	0.073
	14	18.1	33.5	3.90	3.40	0.27	0.30	2.13	1.05	0.106
	15	16.6	32.3	3.90	3.40	0.27	0.30	1.51	1.17	0.117
	16	15.6	31.1	3.90	3.40	0.27	0.30	1.05	1.18	0.128
	17	14.9	30.0	3.90	3.40	0.27	0.30	0.73	1.12	0.142
	18	14.1	28.9	3.90	3.40	0.27	0.30	0.72	1.18	0.125
	19	13.4	27.3	3.90	3.40	0.27	0.30	0.87	1.50	0.099
	20	12.3	25.6	3.90	3.40	0.27	0.30	1.08	1.54	0.072
	21	11.0	24.8	3.90	3.40	0.27	0.30	1.20	1.01	0.075
	22	9.0	24.0	3.90	3.40	0.27	0.30	1.14	0.85	0.072
	23	8.8	22.8	3.90	3.40	0.27	0.30	1.21	1.11	0.052
	24	7.4	21.7	3.90	3.40	0.27	0.30	1.29	1.11	0.040
	25	6.3	20.6	3.90	3.40	0.27	0.30	1.13	1.08	0.033

TOWARDS QUEBEC	0	79.6	46.7	3.90	3.40	0.27	0.30	0.00	0.00	0.000
	1	78.6	46.6	3.90	3.40	0.27	0.30	1.00	0.05	0.058
	2	77.1	46.6	3.90	3.40	0.27	0.30	1.47	0.09	0.077
	3	75.1	46.4	3.90	3.40	0.27	0.30	2.02	0.11	0.083
	4	72.5	46.3	3.90	3.40	0.27	0.30	2.66	0.18	0.081
	5	69.1	45.9	3.90	3.40	0.27	0.30	3.42	0.34	0.074
	6	64.0	45.4	3.90	3.40	0.27	0.30	4.42	0.49	0.066
	7	59.5	44.8	3.90	3.40	0.27	0.30	5.16	0.59	0.062
	8	57.6	44.7	3.90	3.40	0.27	0.30	5.84	0.67	0.059
	9	47.1	43.4	3.90	3.40	0.27	0.30	6.20	0.81	0.058
	10	41.8	42.4	3.90	3.40	0.27	0.30	5.52	1.04	0.063
	11	36.6	40.9	3.90	3.40	0.27	0.30	5.27	1.43	0.062
	12	31.3	39.1	3.90	3.40	0.27	0.30	5.12	1.71	0.060
	13	27.7	37.6	3.90	3.40	0.27	0.30	4.47	1.66	0.065
	14	22.5	37.6	3.90	3.40	0.27	0.30	4.46	1.75	0.062
	15	18.0	35.8	3.90	3.40	0.27	0.30	4.42	1.84	0.058
	16	14.0	33.9	3.90	3.40	0.27	0.30	4.05	1.74	0.058
	17	10.2	32.2	3.90	3.40	0.27	0.30	3.72	1.73	0.056
	18	7.1	31.4	3.90	3.40	0.27	0.30	3.07	1.72	0.056
	19	4.0	29.8	3.90	3.40	0.27	0.30	2.26	1.76	0.058
	20	3.3	27.0	3.90	3.40	0.27	0.30	2.26	1.82	0.056
	21	2.1	25.1	3.90	3.40	0.27	0.30	1.67	1.75	0.054
	22	1.7	21.4	3.90	3.40	0.27	0.30	1.20	1.65	0.050
	23	0.8	21.8	3.90	3.40	0.27	0.30	0.77	1.59	0.042
	24	0.5	20.2	3.90	3.40	0.27	0.30	0.48	1.67	0.027
	25	0.3	18.5	3.90	3.40	0.27	0.30	0.35	1.67	0.012

DISTANCE TO #1	425	(M)	DISTANCE TO #2	1152	(M)
SHEAR VELOCITY	0.0145	(M/S)			
TEMPERATURE	22	(DEG CENT)			
FULLY MIXED WIDTH	24.0	(M)			
AVERAGE KZ	0.041	(SO M/S)	STAND DEV	0.010	(SO M/S)

Table 7.1(E) Computation of K_z for experiment on August 31

	DIST FROM CENTRE (M)	AV CONC #1 (EX UNITS)	AV CONC #2 (EX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VFL #1 (M/S)	AV VFL #2	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	<Z (SO M/S)
TOWARDS ONTARIO	0	80.3	61.6	3.85	3.15	0.24	0.22	0.00	0.00	0.000
	1	79.8	61.3	3.85	3.15	0.24	0.22	0.50	0.35	0.065
	2	78.8	60.8	3.86	3.15	0.24	0.22	1.19	0.51	0.065
	3	77.5	59.9	3.86	3.15	0.24	0.22	2.35	0.82	0.053
	4	72.5	58.8	3.84	3.15	0.24	0.22	3.81	1.15	0.044
	5	67.9	57.4	3.84	3.15	0.24	0.22	4.50	1.40	0.045
	6	62.3	54.9	3.84	3.15	0.24	0.22	4.73	2.54	0.042
	7	57.9	51.0	3.84	3.15	0.24	0.22	5.37	3.67	0.038
	8	51.9	47.3	3.80	3.15	0.24	0.22	5.98	3.81	0.038
	9	45.4	41.3	3.80	3.15	0.24	0.22	6.48	3.85	0.039
	10	38.5	37.6	3.80	3.15	0.24	0.22	6.68	3.73	0.041
	11	32.5	34.1	3.80	3.15	0.24	0.22	5.82	3.46	0.047
	12	28.5	30.9	3.81	3.15	0.24	0.22	4.08	2.95	0.064
	13	26.0	27.9	3.82	3.15	0.24	0.21	2.67	2.47	0.089
	14	24.0	24.6	3.81	3.15	0.24	0.21	2.02	2.92	0.034
	15	22.4	22.0	3.84	3.15	0.25	0.21	1.67	3.13	0.097
	16	20.8	19.6	3.84	3.15	0.25	0.21	1.75	2.68	0.108
	17	18.4	17.3	3.85	3.15	0.25	0.21	2.17	2.42	0.107
	18	16.3	15.4	3.86	3.15	0.25	0.21	2.17	2.24	0.113
	19	14.2	11.8	3.86	3.15	0.25	0.21	2.17	1.89	0.124
	20	11.8	11.8	3.86	3.15	0.25	0.21	2.27	1.73	0.128
	21	10.0	9.9	3.87	3.15	0.25	0.21	1.72	1.89	0.142
	22	9.1	8.6	3.87	3.15	0.25	0.21	1.02	1.81	0.183
	23	8.3	7.8	3.88	3.15	0.25	0.21	0.84	1.37	0.242
	24	7.3	7.2	3.89	3.15	0.25	0.21	0.92	0.86	0.295
	25	6.4	7.2	3.89	3.15	0.25	0.21	0.92	0.69	0.328

TOWARDS QUEBEC	0	80.3	61.6	3.85	3.15	0.24	0.22	0.00	0.00	0.000
	1	79.7	61.3	3.85	3.15	0.24	0.22	0.60	0.30	0.063
	2	77.8	61.0	3.84	3.15	0.24	0.22	1.97	0.37	0.048
	3	74.2	60.3	3.84	3.15	0.24	0.22	3.32	0.72	0.041
	4	70.6	59.2	3.81	3.15	0.24	0.22	3.54	1.05	0.046
	5	67.5	57.8	3.83	3.15	0.24	0.22	3.45	1.42	0.052
	6	62.6	55.8	3.82	3.15	0.24	0.22	4.02	1.91	0.044
	7	56.1	51.4	3.82	3.15	0.24	0.22	6.42	1.92	0.039
	8	48.5	47.8	3.81	3.15	0.24	0.22	7.52	2.64	0.035
	9	40.5	44.8	3.81	3.15	0.24	0.22	7.61	3.33	0.034
	10	34.0	41.3	3.80	3.15	0.24	0.22	6.17	3.24	0.040
	11	29.5	37.0	3.79	3.15	0.24	0.22	5.33	3.56	0.043
	12	23.5	32.3	3.79	3.15	0.24	0.22	5.83	4.21	0.037
	13	17.8	27.8	3.78	3.15	0.24	0.22	5.67	4.61	0.034
	14	13.5	22.8	3.77	3.15	0.24	0.23	4.14	4.56	0.041
	15	10.6	19.6	3.77	3.15	0.23	0.23	2.94	4.77	0.044
	16	8.4	16.1	3.76	3.15	0.23	0.23	2.22	4.08	0.052
	17	6.9	13.5	3.76	3.15	0.23	0.23	1.52	2.81	0.074
	18	5.8	10.5	3.75	3.15	0.23	0.23	1.15	2.65	0.091
	19	4.8	9.0	3.75	3.15	0.23	0.23	1.07	2.85	0.077
	20	3.6	6.0	3.75	3.15	0.23	0.23	1.12	2.50	0.082
	21	2.6	4.2	3.74	3.15	0.22	0.23	1.01	2.05	0.095
	22	1.9	3.1	3.74	3.15	0.22	0.23	0.73	1.71	0.118
	23	1.4	2.4	3.73	3.15	0.22	0.23	0.53	1.12	0.172
	24	1.1	1.8	3.73	3.15	0.22	0.23	0.32	0.75	0.265
	25	0.9	1.8	3.73	3.15	0.22	0.24	0.18	0.62	0.355

DISTANCE TO #1	610	(M)	DISTANCE TO #2	930	(M)
SHEAR VELOCITY	2.0176	(M/S)			
TEMPERATURE	16	(DEG CENT)			
FULL MIXED WIDTH	10.0	(M)			
AVERAGE K _Z	0.046	(SO M/S)	STAND DEV	0.010	(SO M/S)

Table 7.1(F) Computation of K_Z for experiment on October 2

	DIST FROM CENTRE (M)	AV CONC #1 (FX UNITS)	AV CONC #2 (FX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VEL #1 (M/S)	AV VEL #2	SLOPE #1 (FX UNITS)	SLOPE #2 (FX UNITS)	K _Z (50 M/S)
TOWARDS ONTARIO	0	34.9	27.3	4.45	3.30	0.24	0.24	0.00	0.00	0.000
	1	34.8	27.3	4.45	3.30	0.24	0.24	0.15	0.10	0.066
	2	34.5	27.1	4.45	3.30	0.24	0.24	0.30	0.15	0.073
	3	33.1	26.9	4.45	3.30	0.24	0.24	0.62	0.22	0.058
	4	32.4	26.5	4.45	3.30	0.24	0.24	1.66	0.43	0.071
	5	29.5	25.8	4.45	3.30	0.24	0.24	2.68	0.60	0.024
	6	26.6	25.0	4.45	3.30	0.24	0.24	2.78	0.73	0.026
	7	24.3	24.3	4.45	3.30	0.24	0.24	2.41	0.66	0.033
	8	22.3	23.8	4.45	3.30	0.24	0.24	2.12	0.55	0.040
	9	19.0	23.3	4.45	3.30	0.24	0.24	2.24	0.83	0.049
	10	17.7	22.4	4.45	3.30	0.24	0.24	2.18	0.83	0.049
	11	15.9	21.3	4.45	3.30	0.24	0.24	1.83	1.08	0.040
	12	14.4	20.1	4.45	3.30	0.24	0.24	1.56	1.23	0.042
	13	12.8	19.8	4.45	3.30	0.24	0.24	1.57	1.27	0.041
	14	11.1	17.6	4.45	3.30	0.24	0.24	1.62	1.17	0.041
	15	9.8	16.5	4.45	3.30	0.24	0.24	1.39	1.10	0.045
	16	8.7	15.4	4.45	3.30	0.24	0.24	1.07	1.07	0.051
	17	7.8	14.3	4.45	3.30	0.24	0.24	0.85	1.09	0.055
	18	7.2	13.3	4.45	3.30	0.24	0.24	0.67	1.10	0.059
	19	6.6	12.1	4.45	3.30	0.24	0.24	0.57	1.09	0.061
	20	6.1	11.1	4.45	3.30	0.24	0.24	0.50	1.02	0.060
	21	5.4	10.3	4.45	3.30	0.24	0.24	0.44	0.91	0.062
	22	4.8	9.3	4.45	3.30	0.24	0.24	0.63	0.98	0.058
	23	4.3	8.3	4.45	3.30	0.24	0.24	0.54	0.97	0.060
	24	3.6	7.4	4.45	3.30	0.24	0.24	0.56	0.82	0.065
	25	3.2	6.8	4.45	3.30	0.24	0.24	0.43	0.79	0.077
TOWARDS QUEBEC	0	34.9	27.4	4.45	3.30	0.24	0.24	0.00	0.00	0.000
	1	34.9	27.3	4.45	3.30	0.24	0.24	0.15	0.05	0.082
	2	34.5	27.3	4.45	3.30	0.24	0.24	0.27	0.12	0.086
	3	34.1	27.0	4.45	3.30	0.24	0.24	0.47	0.27	0.067
	4	32.3	26.5	4.45	3.30	0.24	0.24	0.73	0.46	0.054
	5	29.4	26.0	4.45	3.30	0.24	0.24	0.98	0.52	0.053
	6	31.0	25.4	4.45	3.30	0.24	0.24	1.46	0.62	0.046
	7	28.6	24.6	4.45	3.30	0.24	0.24	2.24	0.75	0.036
	8	25.0	23.9	4.45	3.30	0.24	0.24	2.67	0.71	0.036
	9	23.4	23.3	4.45	3.30	0.24	0.24	2.41	0.68	0.042
	10	21.4	22.4	4.45	3.30	0.24	0.24	2.08	0.78	0.048
	11	19.5	21.6	4.45	3.30	0.24	0.24	1.96	0.77	0.052
	12	17.4	21.0	4.45	3.30	0.24	0.24	2.02	0.69	0.054
	13	15.5	20.3	4.45	3.30	0.24	0.24	1.94	0.81	0.053
	14	13.4	19.9	4.45	3.30	0.24	0.24	2.14	1.27	0.044
	15	11.0	17.4	4.45	3.30	0.24	0.24	2.34	1.37	0.040
	16	8.7	16.4	4.45	3.30	0.24	0.24	2.35	1.13	0.042
	17	6.2	15.3	4.45	3.30	0.24	0.24	2.33	1.16	0.041
	18	4.5	13.9	4.45	3.30	0.24	0.24	1.77	1.27	0.045
	19	3.5	12.6	4.45	3.30	0.24	0.24	1.12	1.30	0.051
	20	2.5	11.3	4.45	3.30	0.24	0.24	0.98	1.27	0.055
	21	1.6	10.3	4.45	3.30	0.24	0.24	0.87	1.14	0.058
	22	1.0	9.1	4.45	3.30	0.24	0.24	0.60	1.12	0.064
	23	0.7	8.1	4.45	3.30	0.24	0.24	0.33	0.97	0.070
	24	0.5	7.4	4.45	3.30	0.24	0.24	0.22	0.76	0.090
	25	0.3	6.6	4.45	3.30	0.24	0.24	0.19	0.76	0.096
		DISTANCE TO #1	1040	(M)		DISTANCE TO #2	1530	(M)		
		SHEAR VELOCITY	0.0190	(M/S)						
		TEMPERATURE	14	(DEG CENT)						
		FULLY MIXED WIDTH	30.0	(M)						
		AVERAGE K _Z	0.045	(50 M/S)		STAND DEV	0.016	(50 M/S)		

Table 7.1(G) Computation of K_Z for experiment on October 12

	DIST FROM CENTRE (M)	AV CONC #1 (FX UNITS)	AV CONC #2 (FX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VFL #1 (M/S)	AV VFL #2 (M/S)	SLOPE #1 (EX UNITS)	SLOPE #2 (FX UNITS)	KZ (SQ M/S)
TOWARDS ONTARIO	0	57.1	49.6	3.90	3.50	0.36	0.38	0.00	0.00	0.000
	1	56.0	49.4	3.90	3.50	0.36	0.38	0.10	0.15	0.056
	2	56.8	49.1	3.90	3.50	0.36	0.38	0.17	0.29	0.063
	3	56.5	48.6	3.90	3.50	0.36	0.38	0.10	0.44	0.054
	4	56.1	48.0	3.90	3.50	0.36	0.38	0.45	0.63	0.053
	5	55.4	47.7	3.90	3.50	0.36	0.38	0.61	0.68	0.055
	6	54.6	46.4	3.90	3.50	0.36	0.38	0.80	0.81	0.053
	7	53.6	45.6	3.90	3.50	0.36	0.38	1.01	1.03	0.049
	8	52.4	44.1	3.90	3.50	0.36	0.38	1.25	1.35	0.044
	9	50.0	42.6	3.90	3.50	0.36	0.38	1.58	1.51	0.042
	10	49.6	41.0	3.90	3.50	0.36	0.38	2.09	1.66	0.039
	11	48.6	37.1	3.90	3.50	0.36	0.38	2.01	1.72	0.042
	12	46.0	37.9	3.90	3.50	0.36	0.38	1.74	1.33	0.045
	13	41.0	36.8	3.90	3.50	0.36	0.38	1.93	1.25	0.057
	14	41.0	35.1	3.90	3.50	0.36	0.38	2.00	1.44	0.064
	15	39.0	34.0	3.90	3.50	0.36	0.38	2.21	1.21	0.065
	16	36.0	32.8	3.90	3.50	0.36	0.38	2.04	1.22	0.066
	17	34.0	31.7	3.90	3.50	0.36	0.38	2.05	1.32	0.066
	18	32.0	30.4	3.90	3.50	0.36	0.38	2.03	1.00	0.076
	19	30.0	29.5	3.90	3.50	0.36	0.38	1.87	0.95	0.083
	20	29.5	28.5	3.90	3.50	0.36	0.38	1.51	0.99	0.096
	21	28.0	27.5	3.90	3.50	0.36	0.38	1.57	1.00	0.094
	22	26.0	26.5	3.90	3.50	0.36	0.38	1.83	1.00	0.099
	23	24.5	25.5	3.90	3.50	0.36	0.38	1.50	1.00	0.114
	24	23.5	24.5	3.90	3.50	0.36	0.38	1.13	1.00	0.114
25	22.3	23.5	3.90	3.50	0.36	0.38	1.21	1.00	0.112	
TOWARDS QUEBEC	0	57.1	49.5	3.90	3.50	0.36	0.38	0.00	0.00	0.000
	1	56.0	49.3	3.90	3.50	0.36	0.38	0.10	0.25	0.040
	2	56.8	49.0	3.90	3.50	0.36	0.38	0.17	0.30	0.060
	3	56.5	48.6	3.90	3.50	0.36	0.38	0.28	0.35	0.067
	4	56.1	48.2	3.90	3.50	0.36	0.38	0.35	0.42	0.074
	5	55.4	47.6	3.90	3.50	0.36	0.38	0.48	0.57	0.068
	6	54.6	46.4	3.90	3.50	0.36	0.38	0.90	0.85	0.049
	7	53.6	45.6	3.90	3.50	0.36	0.38	1.16	1.12	0.044
	8	52.4	44.4	3.90	3.50	0.36	0.38	1.24	1.23	0.046
	9	50.0	43.1	3.90	3.50	0.36	0.38	1.39	1.23	0.049
	10	49.6	42.0	3.90	3.50	0.36	0.38	1.41	1.15	0.056
	11	48.0	40.9	3.90	3.50	0.36	0.38	1.61	1.08	0.054
	12	46.1	39.8	3.90	3.50	0.36	0.38	1.87	1.16	0.056
	13	44.1	38.5	3.90	3.50	0.36	0.38	1.96	1.29	0.056
	14	42.1	37.1	3.90	3.50	0.36	0.38	1.86	1.37	0.059
	15	40.5	35.8	3.90	3.50	0.36	0.38	1.77	1.28	0.066
	16	38.9	34.7	3.90	3.50	0.36	0.38	1.75	1.15	0.071
	17	37.0	33.5	3.90	3.50	0.36	0.38	1.87	1.21	0.071
	18	34.6	32.1	3.90	3.50	0.36	0.38	2.34	1.33	0.061
	19	32.1	30.8	3.90	3.50	0.36	0.38	2.40	1.38	0.061
	20	30.1	29.4	3.90	3.50	0.36	0.38	1.98	1.34	0.071
	21	28.5	28.1	3.90	3.50	0.36	0.38	1.64	1.29	0.081
	22	27.0	26.8	3.90	3.50	0.36	0.38	1.52	1.38	0.083
	23	25.5	25.3	3.90	3.50	0.36	0.38	1.46	1.34	0.096
	24	24.3	24.1	3.90	3.50	0.36	0.38	1.32	1.22	0.096
25	22.9	23.1	3.90	3.50	0.36	0.38	1.38	1.13	0.098	
DISTANCE TO #1				1470	(M)	DISTANCE TO #2				2420 (M)
SILAR VELOCITY				0.0200	(M/S)					
TEMPERATURE				14	(DEG CENT)					
FULLY MIXED WIDTH				32.0	(M)					
AVERAGE KZ				0.058	(SQ M/S)	STAND DEV		0.013	(SQ M/S)	

Table 7.1(H) Computation of K_z for experiment on October 24

	DIST FROM CENTRE (M)	AV CONC #1 (CX UNITS)	AV CONC #2 (FX UNITS)	DEPTH #1 (M)	DEPTH #2 (M)	AV VCL #1 (M/S)	AV VCL #2 (M/S)	SLOPE #1 (EX UNITS)	SLOPE #2 (EX UNITS)	K _Z (50 M/S)
TOWARDS ONTARIO	0	25.1	23.1	4.70	3.50	0.47	0.47	0.00	0.00	0.000
	2	24.9	22.9	4.70	3.50	0.47	0.47	0.10	0.05	0.143
	4	24.6	22.8	4.70	3.50	0.47	0.47	0.16	0.09	0.174
	6	24.1	22.4	4.70	3.50	0.47	0.47	0.25	0.17	0.152
	8	23.4	22.0	4.70	3.50	0.47	0.47	0.35	0.25	0.141
	10	22.6	21.2	4.70	3.50	0.47	0.47	0.41	0.39	0.128
	12	21.9	20.1	4.70	3.50	0.47	0.47	0.40	0.48	0.137
	14	21.0	19.3	4.70	3.50	0.47	0.47	0.39	0.42	0.172
	16	20.1	18.6	4.70	3.50	0.47	0.47	0.43	0.42	0.185
	18	19.1	17.6	4.70	3.50	0.47	0.47	0.53	0.40	0.172
	20	17.8	16.5	4.70	3.50	0.47	0.47	0.51	0.52	0.162
	22	16.6	15.5	4.70	3.50	0.47	0.47	0.62	0.50	0.181
	24	15.3	14.6	4.70	3.50	0.47	0.47	0.64	0.45	0.202
	26	13.9	13.8	4.70	3.50	0.47	0.47	0.69	0.38	0.219
	28	12.5	13.3	4.70	3.50	0.47	0.47	0.68	0.32	0.239
	30	11.3	12.5	4.70	3.50	0.47	0.47	0.60	0.30	0.254
	32	10.3	11.6	4.70	3.50	0.47	0.47	0.53	0.43	0.263
	34	9.3	10.8	4.70	3.50	0.47	0.47	0.50	0.43	0.276
	36	8.3	9.8	4.70	3.50	0.47	0.47	0.50	0.44	0.279
	38	7.3	9.0	4.70	3.50	0.47	0.47	0.50	0.40	0.295
	40	6.3	8.3	4.70	3.50	0.47	0.47	0.47	0.37	0.316
	42	5.5	7.4	4.70	3.50	0.47	0.47	0.41	0.45	0.312
	44	4.8	6.4	4.70	3.50	0.47	0.47	0.37	0.50	0.305
	46	4.1	5.4	4.70	3.50	0.47	0.47	0.32	0.47	0.335
	48	3.6	4.6	4.70	3.50	0.47	0.47	0.29	0.40	0.388
	50	2.9	4.1	4.70	3.50	0.47	0.47	0.32	0.32	0.416
TOWARDS QUEBEC	0	25.1	23.1	4.70	3.50	0.47	0.47	0.00	0.00	0.000
	2	25.0	22.9	4.70	3.50	0.47	0.47	0.08	0.05	0.173
	4	24.6	22.8	4.70	3.50	0.47	0.47	0.18	0.09	0.162
	6	24.0	22.4	4.70	3.50	0.47	0.47	0.29	0.18	0.136
	8	23.3	21.8	4.70	3.50	0.47	0.47	0.37	0.28	0.129
	10	22.4	21.2	4.70	3.50	0.47	0.47	0.42	0.33	0.137
	12	21.5	20.5	4.70	3.50	0.47	0.47	0.47	0.35	0.147
	14	20.5	19.7	4.70	3.50	0.47	0.47	0.50	0.40	0.154
	16	19.4	18.8	4.70	3.50	0.47	0.47	0.54	0.44	0.157
	18	18.2	17.8	4.70	3.50	0.47	0.47	0.63	0.57	0.141
	20	16.9	16.2	4.70	3.50	0.47	0.47	0.72	0.72	0.126
	22	15.1	14.8	4.70	3.50	0.47	0.47	0.78	0.66	0.135
	24	13.6	13.8	4.70	3.50	0.47	0.47	0.74	0.54	0.161
	26	12.4	12.7	4.70	3.50	0.47	0.47	0.63	0.57	0.178
	28	11.3	11.4	4.70	3.50	0.47	0.47	0.55	0.65	0.185
	30	10.3	10.0	4.70	3.50	0.47	0.47	0.57	0.67	0.193
	32	9.2	9.8	4.70	3.50	0.47	0.47	0.54	0.58	0.212
	34	8.1	8.0	4.70	3.50	0.47	0.47	0.52	0.47	0.260
	36	7.2	7.3	4.70	3.50	0.47	0.47	0.47	0.34	0.311
	38	6.4	6.7	4.70	3.50	0.47	0.47	0.41	0.34	0.343
	40	5.6	5.9	4.70	3.50	0.47	0.47	0.38	0.41	0.328
	42	4.8	4.8	4.70	3.50	0.47	0.47	0.38	0.48	0.305
	44	4.3	4.1	4.70	3.50	0.47	0.47	0.33	0.40	0.363
	46	3.5	3.4	4.70	3.50	0.47	0.47	0.39	0.39	0.399
	48	2.4	3.0	4.70	3.50	0.47	0.47	0.49	0.21	0.387
	50	1.5	2.8	4.70	3.50	0.47	0.47	0.47	0.10	0.471

DISTANCE TO #1 1770 (M) DISTANCE TO #2 2565 (M)

SHEAR VELOCITY 0.0214 (M/S)

TEMPERATURE 7 (DEG CENT)

FULLY MIXED WIDTH 52.0 (M)

AVERAGE K_Z 0.164 (50 M/S) STAND DEV 0.026 (50 M/S)

Table 7.1(K) Computation of K_Z for experiment on November 14

The absolute value of K_z is plotted against the Reynolds and the Froude numbers in Figures 7.1 and 7.2 respectively. K_z increases with increases in both of these dimensionless numbers. As the variation in depth throughout the series of experiments was small these trends result almost exclusively from changes in the mean convective velocity and the kinematic viscosity.

To relate K_z to the depth and the mean velocity omits the effects of shear. The flow must have a velocity gradient in order to have turbulence. In flows with high Reynolds numbers these effects are well-described by the boundary roughness (3). The relative roughness (\bar{u}_x/u_*), has been evaluated for each experiment. By assuming a functional form for the dimensionless turbulent lateral diffusion coefficient of

$$\frac{K_z}{\bar{u}_x} = k \left(\frac{\bar{u}_x}{u_*} \right)^n$$

it was found that the best correlation was got when n was equal to 0.7 and k equal to 0.008. Figure 7.3 gives a plot of K_z/\bar{u}_x against \bar{u}_x/u_* . Figure 7.3 also shows that there is little benefit to be got by considering the relative roughness on account of the large scatter of experimental values.

Table 7.2 Summary of Results

Date	June 12	June 29	July 17	July 20	Aug 31	Oct 2	Oct 12	Oct 24	Nov 14
K_z (m ² /s)	.100	.181	.075	.061	.061	.046	.045	.058	.164
$\pm gK_z$ (m ² /s)	.014	.066	.009	.019	.010	.010	.016	.013	.026
K_z/du_*	.74	1.50	.65	.64	1.40	.68	.55	.69	1.17
$K_z/d\bar{u}_x$.056	.080	.048	.054	.056	.052	.043	.040	.091
$Fr \times 10^2$	6.3	8.5	5.5	4.1	4.8	3.9	3.9	6.3	7.4
$Re \times 10^{-6}$	1.70	2.20	1.64	1.17	1.11	0.77	0.85	1.17	1.24
(\bar{u}_x/u_*)	13.0	19.4	13.5	11.8	19.3	13.0	12.7	17.5	18.7

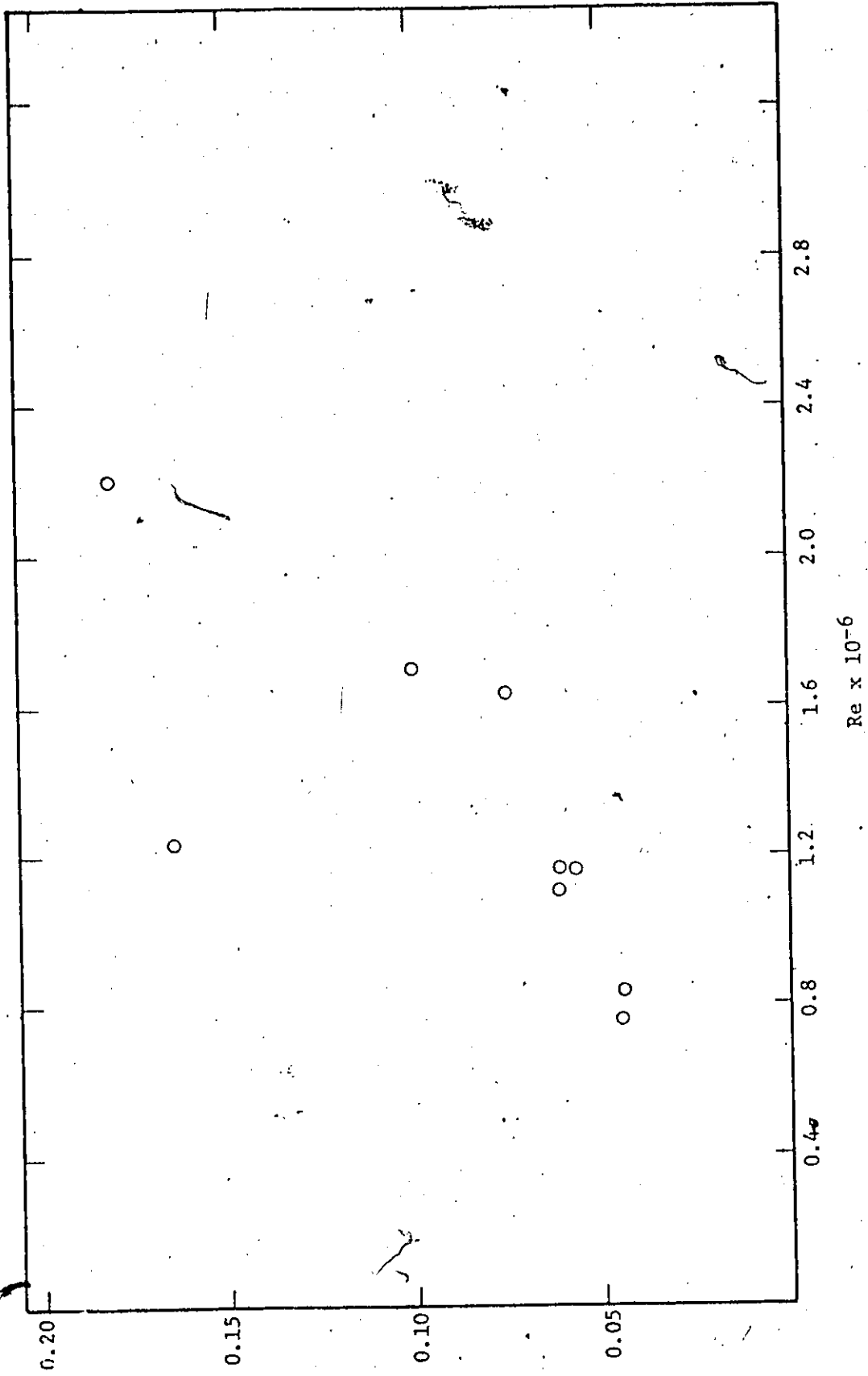


Fig. 7.1 K_z against Reynolds Number

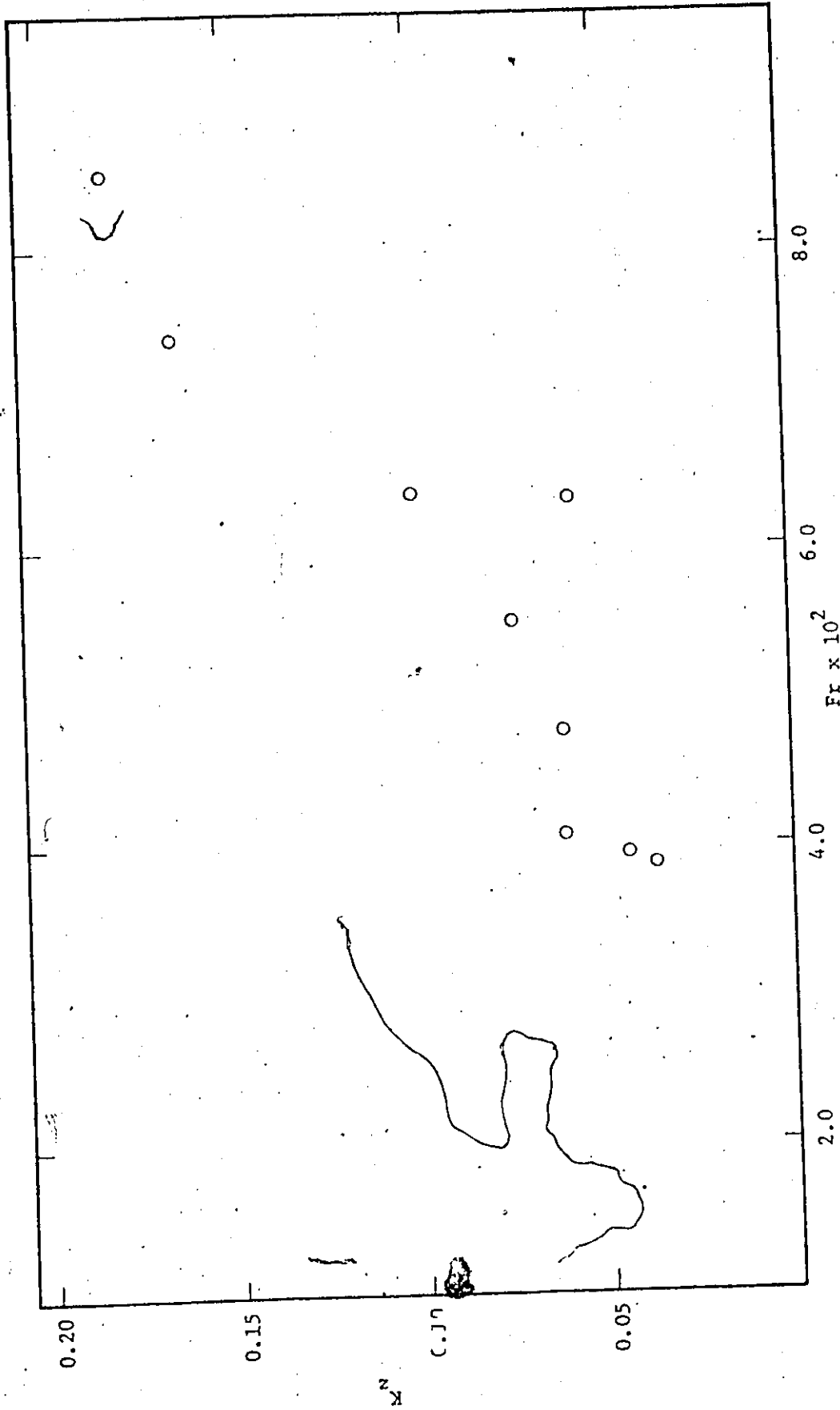


Fig. 7 K_z against Froude Number

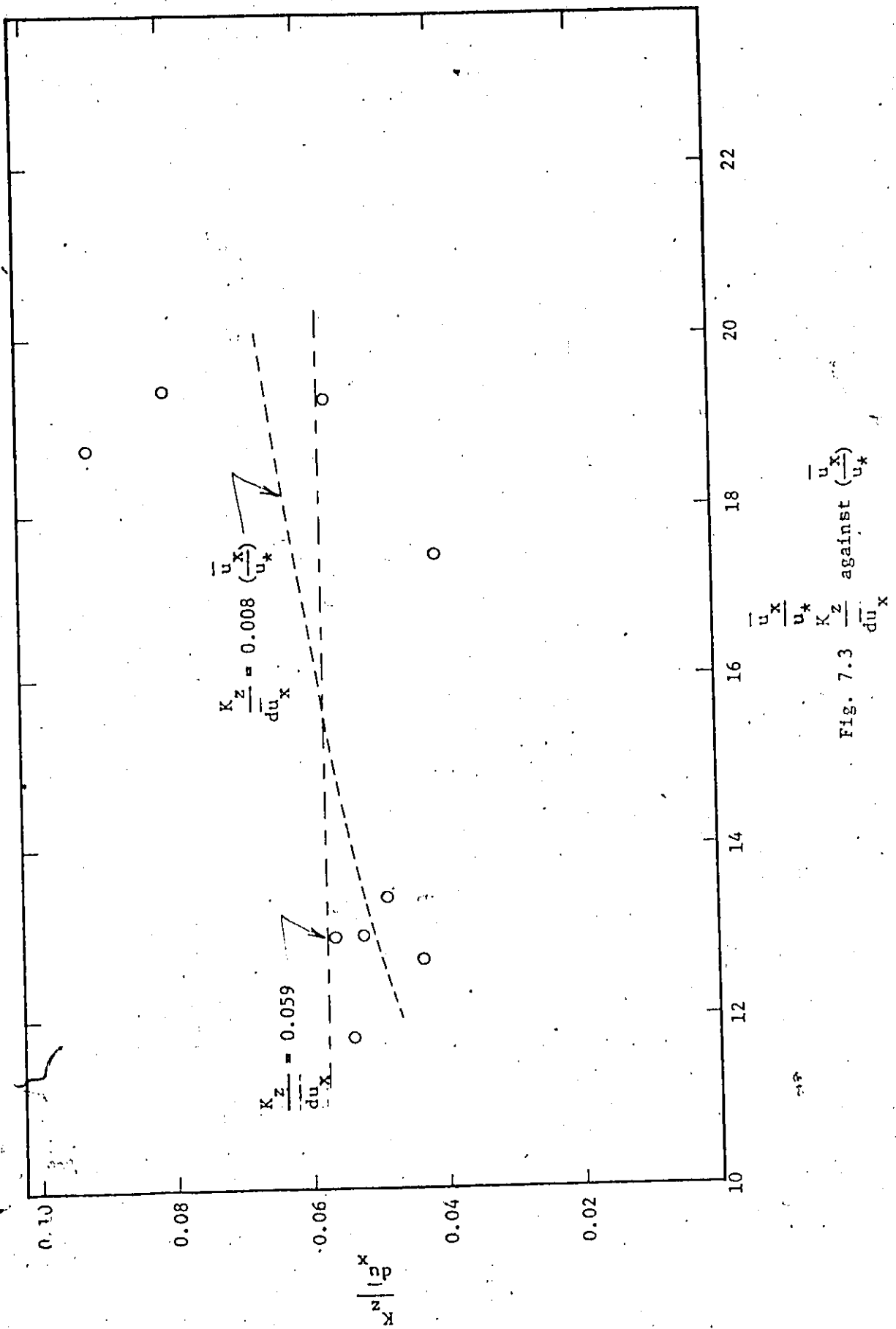


Fig. 7.3 $\frac{u_x}{u_*}$ against $\frac{du_x}{dx}$

CHAPTER 8

DISCUSSION OF RESULTS

8.1 Correlation of K_z with the Hydraulic Parameters

The Reynolds numbers encountered throughout the study are in the order of 10^6 . As was the case with other studies dealing with flows in this range the dimensionless parameter $\frac{K_z}{d\bar{u}_x}$ described lateral turbulent diffusion better than did $\frac{K_z}{d u_*}$. Throughout the study there was little variation in the mean depth, d . However from dimensional considerations whether K_z is considered as $f(\bar{u}_x)$ or as $f(\bar{u}_x, \frac{\bar{u}_x}{u_*})$ the value of K_z must be proportional to d . The average value for $\frac{K_z}{d\bar{u}_x}$ of 0.059 is roughly twice that from the literature study. This justifies an investigation into the method of analysis which follows in the next section, 8.2.

8.2 The Validity of the Idealized Gradient Diffusion Model

Detailed field data of a study conducted by Yotsukura et al which was on a scale similar to the author's study are given in (33). The essential details of this study are given in Appendix E. The Idealized Gradient Diffusion Model was used to calculate an average K_z from these data. A value of $0.110 \pm 0.125 \text{ m}^2/\text{s}$ was got. Yotsukura et al using "the rate of change of the variance" method got K_z equal to $0.127 \text{ m}^2/\text{s}$. The average values obtained by the

two methods are close to being equal. This shows that the Idealized Gradient Diffusion Model as described by the author is valid for analyzing the results of Yotsukura et al (33).

The "rate of change of the variance" method is applied to the author's data in Appendix F. The correlation between the values got and those using the Idealized Gradient Diffusion Model is very bad. The reason for this most likely is that the plume was not well-mixed vertically. This resulted in an apparent breakdown in dye continuity between the upstream and downstream sections. It is necessary to allow the dye to go much further downstream before there is near equality of the values of K_z got from the two methods. This was done by Yotsukura et al.

8.2.1 Fischer's Constraint

Fischer (13) states that unless the concentration gradient is a constant over a width greater than the scale of the largest eddies that Fickian type equations, e.g., Eq. 15, do not ~~adequately~~ describe mixing due to turbulence. This statement is not mathematically proven but does seem physically reasonable. Experimental evidence (20) shows the scale of these eddies to be roughly equal to the depth of the flow.

All the data necessary to find the values of K_z considering this constraint are in Table 7.1. Table 8.1 summarizes the observations.

Both of the values for the dimensionless coefficient on November 14 are much in excess of the other values. Consequently it is deemed justified to omit the values for November 14 when averaging. The best relationship which could be found to describe lateral turbulent diffusion from Table 8.1 is

$$\frac{K_z}{\overline{du}_x} = 0.043$$

The standard deviation of this parameter is 10% of its mean value. This expression gives a value of K_z/\overline{du}_x roughly 33% larger than the average value for the same expression resulting from the literature.

It has to be noted regarding Table 8.1 that the lateral positions at which the values for K_z are calculated lie in the region of the boundary between vertically-mixed and not vertically-mixed dye as given in Table 7.1.

The dimensionless coefficient of K_z/\overline{du}_x equal to $0.043 \pm (10\%)$ is closer to already reported values than 0.059. By excluding the value on November 14 the dimensionless coefficient from averaging over the complete mixed width goes from 0.059 to $0.053 \pm (21\%)$. Thus, applying Fischer's constraint gives a considerably improved result.

8.3 Significance of Roughness

From the results it can be said that for flows with Pe in the order of 10^6 the coefficient of lateral

turbulent diffusion is relatively unaffected by the bed roughness. The slight trend that is shown on Figure 7.3 for this study is the reverse of that shown on Figure 2.3 for the literature study. No explanation can be offered for this. The variation of $K_z/d\bar{u}_x$ after applying Fischers constraint with \bar{u}_x/u_* is completely random.

On the subject of bed roughness it is interesting to note from the results that there is a definite trend towards increasing the value of (\bar{u}_x/u_*) with a decrease in the Froude number. This is not caused by dune formations as no such formations were found in this region by sonar profiles. The wood chip covering is apparently getting less rough with an increase in the Froude number.

8.4 Effect of Experimental Method

Subsequent to the study an examination of the mixing effect in the tube carrying the sample from the river to the fluorometer was carried out. This is described in Appendix G. The flow was not ideal plug flow thus causing the sample to be distorted. It was estimated that the standard deviation of each plume was altered by an amount in the order of 20% due to dispersion in the tube. The standard deviation here was calculated for the complete plume which is not totally justified due to the lack of complete vertical mixing. This gives an idea of the extent to which the plumes were distorted. It does not tell us how to rectify the results to allow for it.

8.5 Spatial Variation of K_z

There are no data from this study to indicate how one should estimate the lateral turbulent diffusion coefficient in the littoral regions as against that for the mid-stream regions. It is necessary to use a great amount of dye and allow it to go well downstream so that it is vertically mixed towards the shore. None of the experiments reported had dye approaching the shores. Due to the size of the river and the presence of a channel between Upper and Lower Duck Island (see Figure 4.1) it was difficult to control the positioning of the dye plume at the study sections.

On the basis of this study the best estimation would be gotten by applying a dimensionless coefficient $K_z / \overline{u_x}$ equal to 0.043 locally.

Table 8.1 Summary of Results after Applying Fischer's Constraint
 W_D is the distance from the centre line where $\partial \bar{c} / \partial z$ is
 closest to being constant at both #1 and #2

Date	June 12	June 29	July 17	July 20	Aug 31	Oct 2	Oct 12	Oct 24	Nov 24
W_D (m)	8.5 13.0	15.0 18.0	11.0 13.5	8.0 7.0	11.5 15.0	9.5 13.0	13.0 17.5	14.5 21.5	28.0 24.0
K_z (m ² /s)	.082 .084	.079 .097	.065 .065	.052 .033	.050 .063	.039 .037	.041 .042	.057 .071	.135 .230
\bar{K}_z (m ² /s)	.083	.088	.065	.043	.056	.038	.042	.064	.182
\bar{K}_z / du_x	.047	.039	.041	.038	.051	.043	.041	.043	.182
\bar{K}_z / du_x^*	.61	.76	.56	.45	.78	.56	.51	.76	1.9

CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Conclusions

1. The Idealized Gradient Diffusion Model for depth averaged lateral turbulent diffusion gives a good description of the diffusion process. By applying Fischers constraint, i.e., the concentration gradient must be almost constant over a width at least equal to the depth, the model gives meaningful numerical results which compare favourably with results already reported in the literature.

2. The depth-averaged lateral turbulent diffusion coefficient for flows in the Ottawa River can be well estimated by using the following expression

$$K_z = 0.043 \frac{d\bar{u}}{dx}$$

3. The mean velocity is a better parameter for describing the lateral turbulent diffusion coefficient in the Ottawa River than is the shear velocity.

9.2 Recommendations for Future Investigators

1. For deep flows it is particularly desirable to distribute the dye evenly throughout the depth at injection. A method for doing this in fluvial studies is

not reported but its development would be most advantageous to workers in the field.

2. It is better to sample directly rather than to pump the sample through a tube. This eliminates any distortion of the sample which may occur in the tube and it also requires less sophisticated equipment to be taken to the field. It does however entail more station surveying and this requires more manpower. A good description of a method employing this is given in the Missouri study (33). For a river of the dimensions of the Ottawa River it is necessary therefore to have wide plumes to permit meaningful surveying. To do this it would be necessary to sample at least six Eulerian length scales downstream of the injection.

An alternative to surveying a rope or chain could be extended between two fixed buoys. By marking this rope or chain at fixed intervals the location of the sampling stations could be easily defined.

3. The method described earlier by Cleary (2) could be employed. Nowhere in the literature is the use of this method for large scale dye studies reported. It has the advantages that only one study section is needed and also that the dye injection is instantaneous. The problem would be to ensure that the time taken to sample across the plume is not significant. The further downstream the test is taken the easier it would be to achieve this. Instantaneous vertical and source injection may pose a problem but point source injection may also be used. The

major advantage of this method appears to be that it employs a relatively small amount of dye.

4. The author experienced some unusual convection patterns in the river. These patterns resulted most probably from the channel configuration and from lingering secondary currents caused by winds. Careful selection of the injection point is sometimes necessary to get the dye plume to flow to the required downstream sampling area. It is particularly important not to attempt dye diffusion studies when cross winds are blowing.

9.3 Recommended Further Studies

1. The experiment reported in this study deals solely with depth-averaged diffusion. It would be interesting to make a field study of the depth variation in the diffusion coefficient. This has been done on a laboratory scale using hot wire anemometry to measure turbulent velocities directly.

2. It is necessary to find-out if any expression used to estimate the lateral diffusion coefficient in the mid-stream region can be used to estimate the same parameter in the shore region using the local depth and velocity. The mechanisms of diffusion may be totally different in these regions.

3. Further experimental evidence is needed to prove that Fischer's assumption which says that Fickian type diffusion equations are accurate only in regions where the concentration gradient is constant for a width greater than the depth.

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APPENDIX A

ESTIMATION OF THE EULERIAN LENGTH SCALE

From dimensional analysis (8) the Eulerian Time Scale for vertical mixing is expressed as

$$E_T \propto d^2 / K_y$$

E_T and E_L are connected by the mean velocity \bar{u}_x . Elder (5) showed that in a shear flow

$$K_y \propto du_*$$

Therefore

$$E_L = r d \bar{u}_x / u_*$$

The constant of proportionality r is measured from field data collected on May 31, June 19 and November 30. Fig. A.1 shows details of the experiments and Table A1 summarizes the results. Fig. A.2 shows a plot of the variance coefficient of the vertical dye concentration profile at the plume centre against the distance of the section from the injection. The variance coefficient v , is defined as

$$v = \frac{\text{standard deviation}}{\text{mean}} \times 100$$

In the analysis dye was taken as vertically mixed if v was less than 7.5%. This figure was chosen as it suited the data in Appendix B.

The average value of r in Table A.1 is used to give the following estimate for the Eulerian length scale:

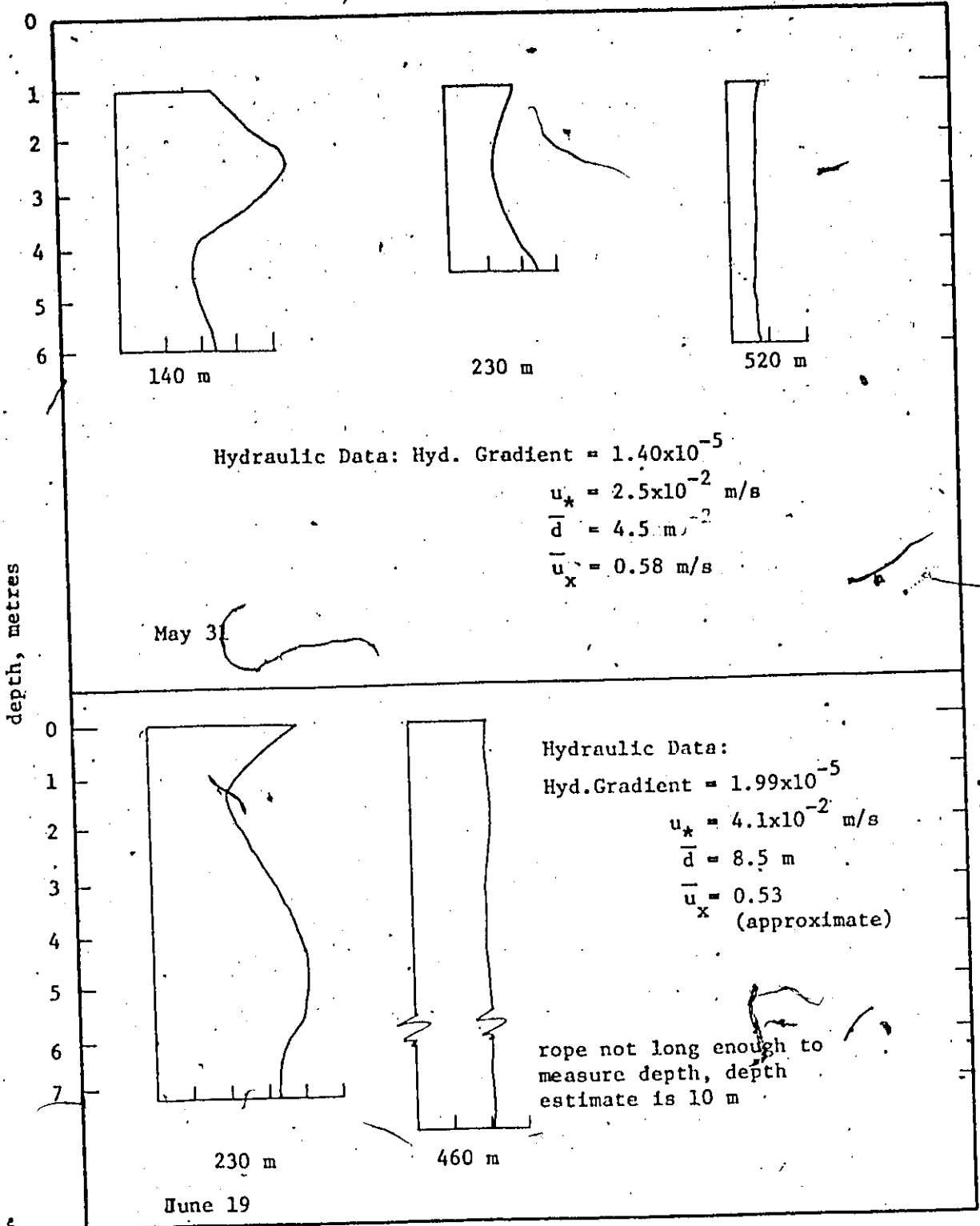
Thus,

$$E_L = 4.26 \cdot d \frac{\bar{u}_x}{u_*}$$

Table A.1 Results of Mixing Length Experiments

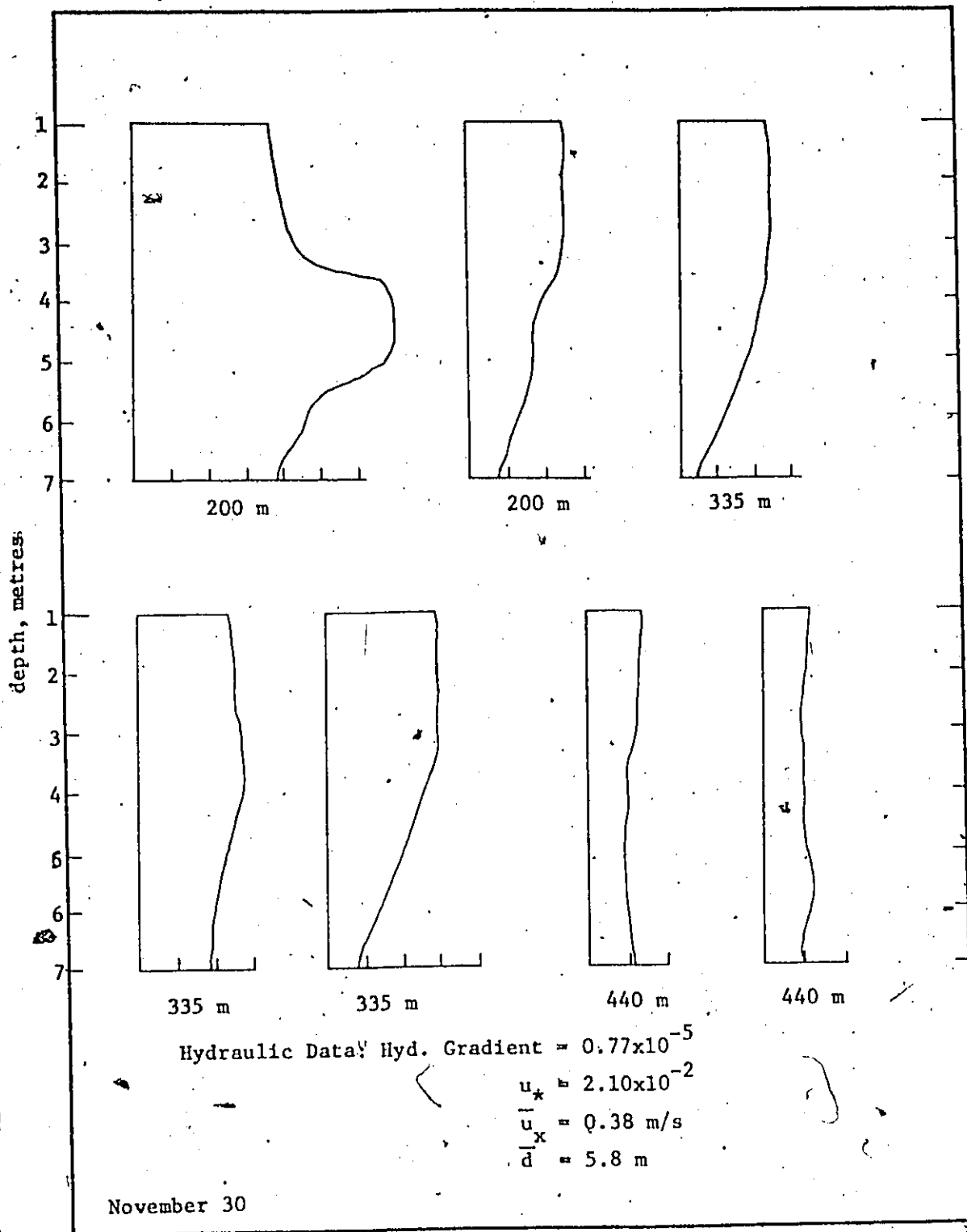
Date	d (m)	u_x (m/s)	u_* (m/s)	$\frac{\bar{u}_x}{u_*}$	E_L (from Fig.6)	r (from Eq.3)
May 31	4.5	0.58 ¹	2.5×10^{-5}	106	430	4.1
June 19	8.5	0.53 ¹	4.1×10^{-2}	110	410	3.8
Nov 30	5.8	0.38	2.1×10^{-2}	95	480	4.9

¹ Estimated from other field data (30,31)



- Notes: 1. Concentrations are in arbitrary units
 2. Stations were located as closely as possible to the centre of the plume
 3. Injection was roughly at mid depth for each experiment

Fig. A.1(A) Vertical Concentration Profiles at Distances Downstream of the Injection



- Notes: 1. Concentrations are in arbitrary units
 2. Stations were located as closely as possible to the centre of the plume
 3. Injection was roughly at mid point for the experiment

Fig. A.1(B) Vertical Concentration Profiles at Distances Downstream of the Injection

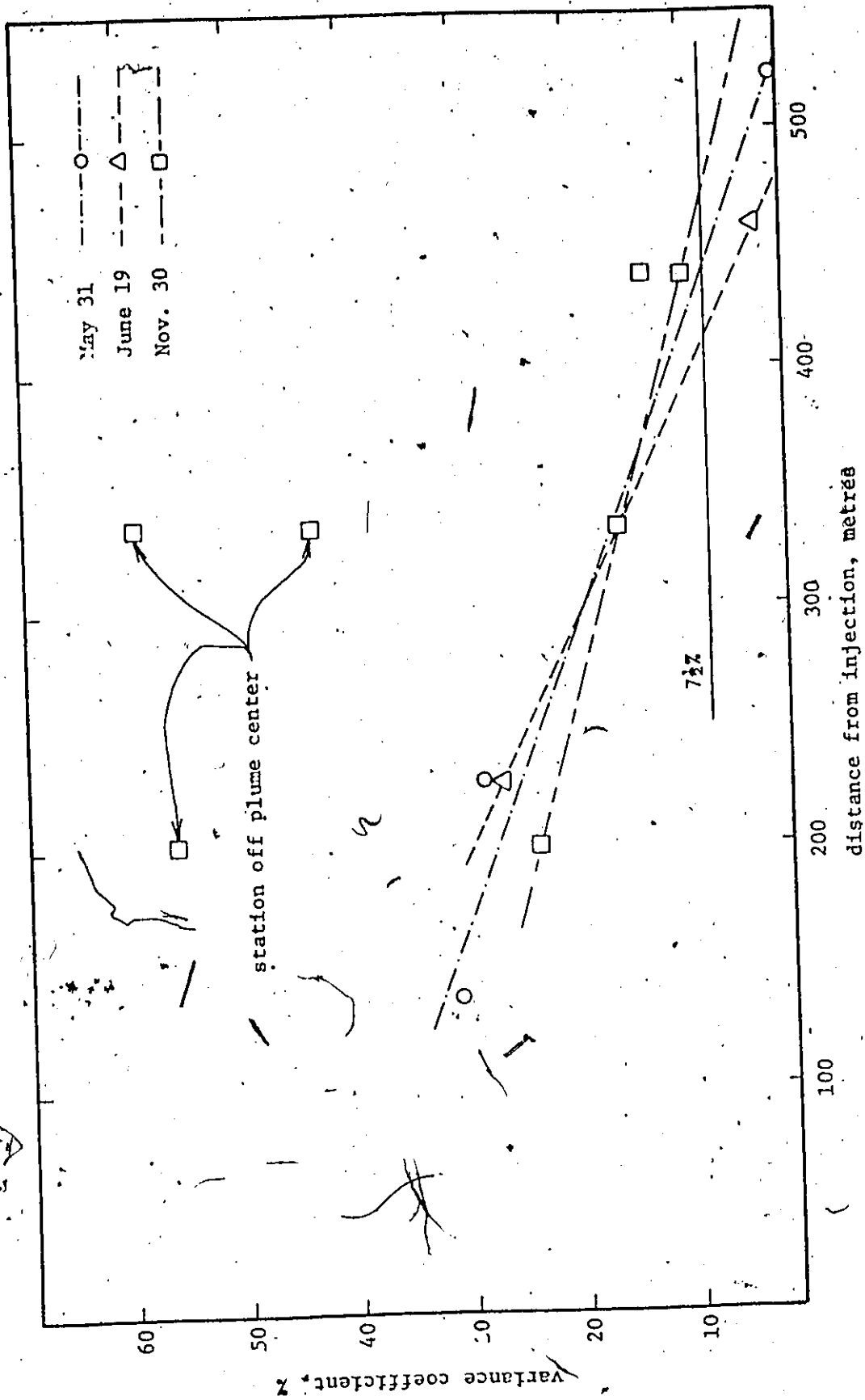


Fig. A.2 The Variance Coefficient of the Vertical Concentration Profile versus the Distance from the Injection

APPENDIX B

ESTIMATION OF WIDTH OF THE DYE PLUME OVER WHICH THE DYE
CONCENTRATION IS CONSTANT WITH DEPTH

Let $w = \frac{\text{width of totally mixed portion of plume}}{\text{Eulerian Length Scale}}$

and $\ell = \frac{\text{distance from injection}}{\text{Eulerian Length Scale}}$

As turbulence is homogenous and stationary and w is equal to zero if $\ell < 1$ the following functional form is assumed for w :

$$w = k(\ell - 1)^n$$

where k and n are constants.

Experiments were conducted to measure the variation in the degree of mixing at lateral stations at downstream sections on October 12, October 24 and November 30. Fig. B.1 shows details of the experiment and Table B.1 gives a summary of the results. Results from November 30 are omitted from Table B.1 as it was considered that the spurious results were due to bad weather conditions. Again the criterion for vertical mixing was a variance coefficient of less than 7.5%.

Differentiating the above equation gives

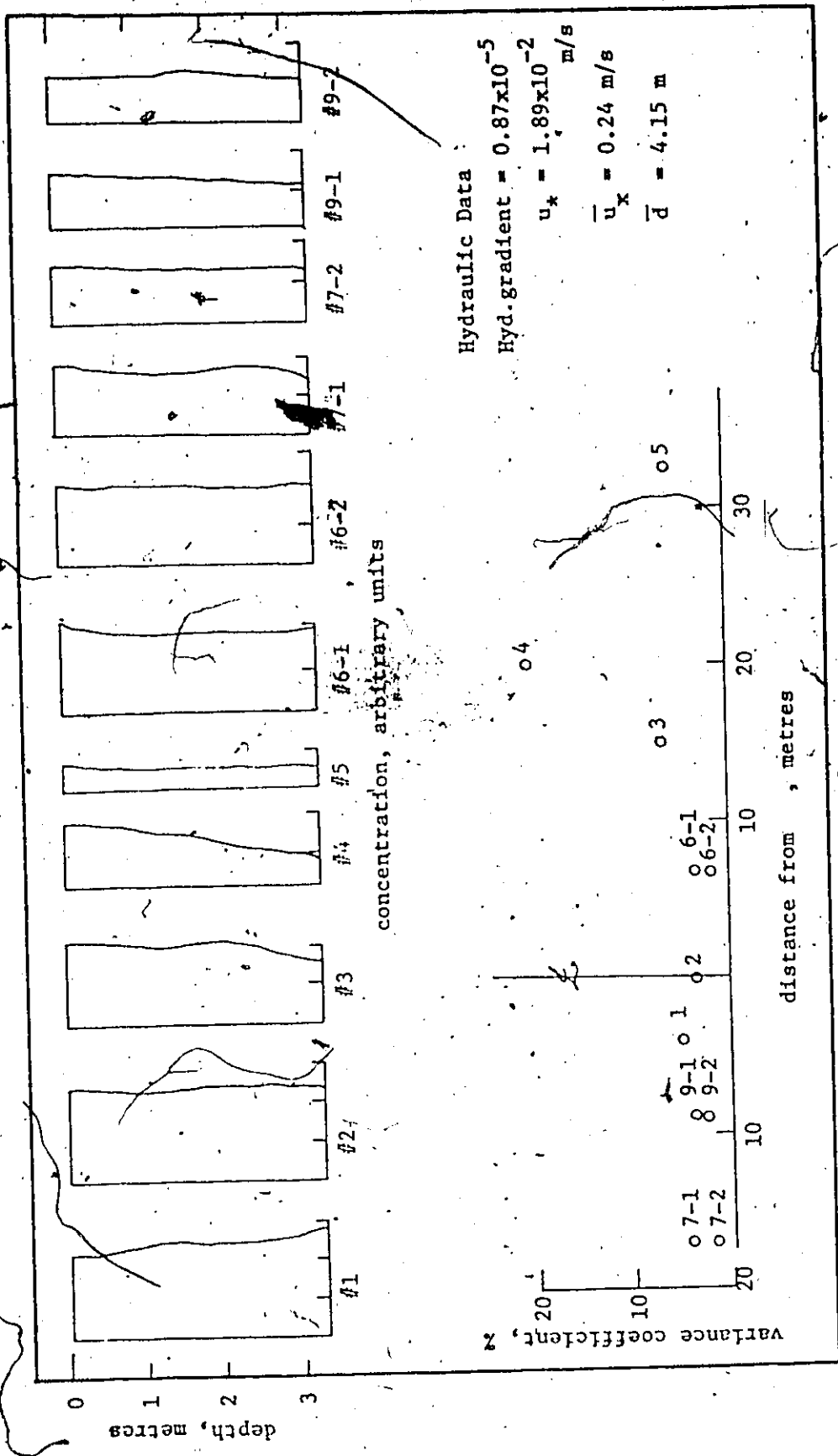
$$\frac{\partial w}{\partial (\ell - 1)} = kn(\ell - 1)^{n-1}$$

Table B.1 Results of Experiments to Measure the Width of the Fully Mixed Portion of the Dye Plume

Date	d (m)	\bar{u}_x (m/s)	u^* (m/s)	E_L	Distance from injection	Fully mixed width	w	2-1
Oct 12	4.30	0.24	1.90×10^{-2}	230	1530	40	0.0308	5.65
Oct 24	4.20	0.35	2.00×10^{-2}	315	1870	50	0.0318	5.25

Using the two sets of values given in Table B.1 this equation was solved to give values for k and n. The resulting expression is

$$w = 0.055 (\ell-1)^{0.70}$$



- Notes: 1. Section was located 1530 m from release
- 2. Station number indicates sequence of sampling

Fig. B.1(A) Lateral Variation of the Depth Concentration Profiles on October 12

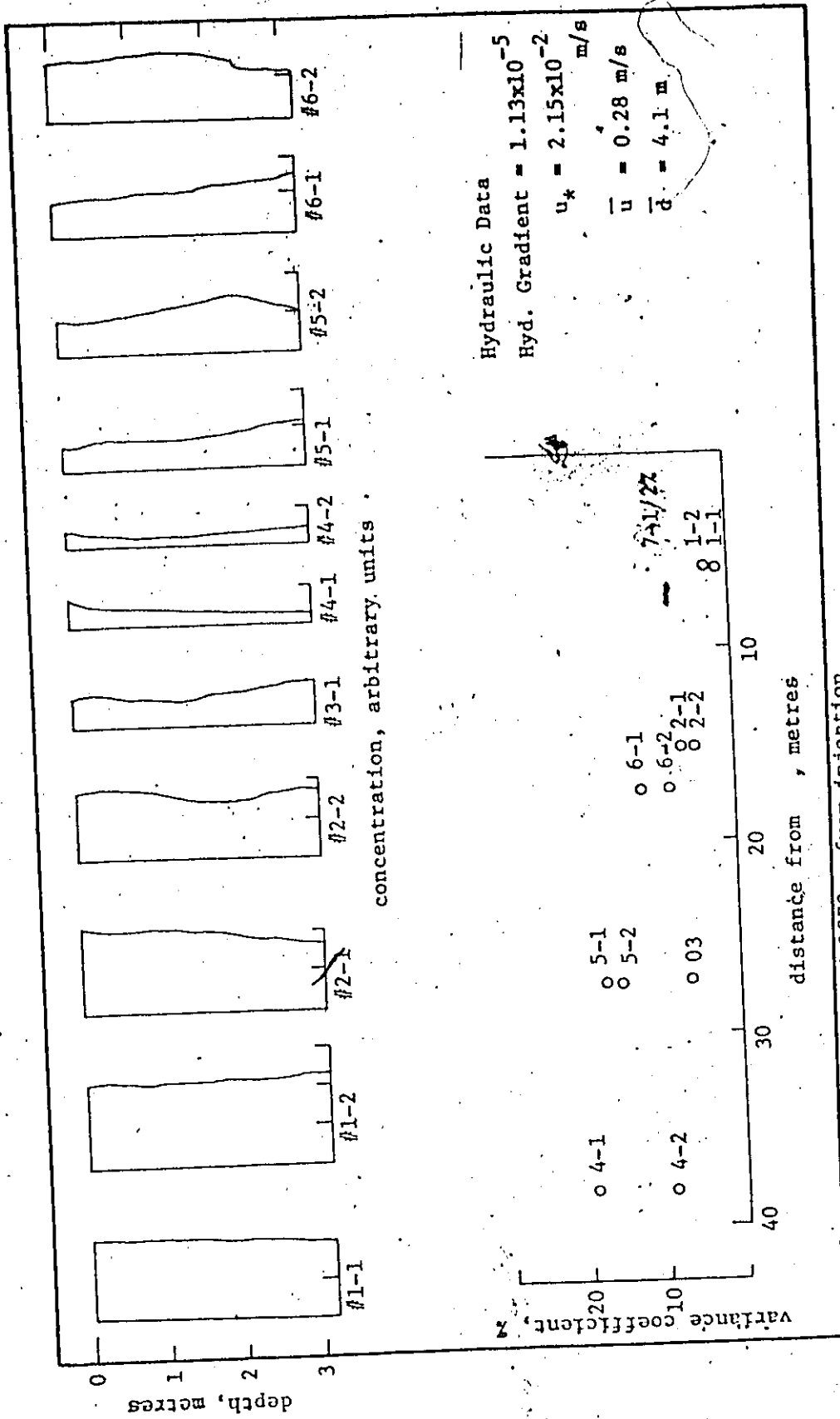
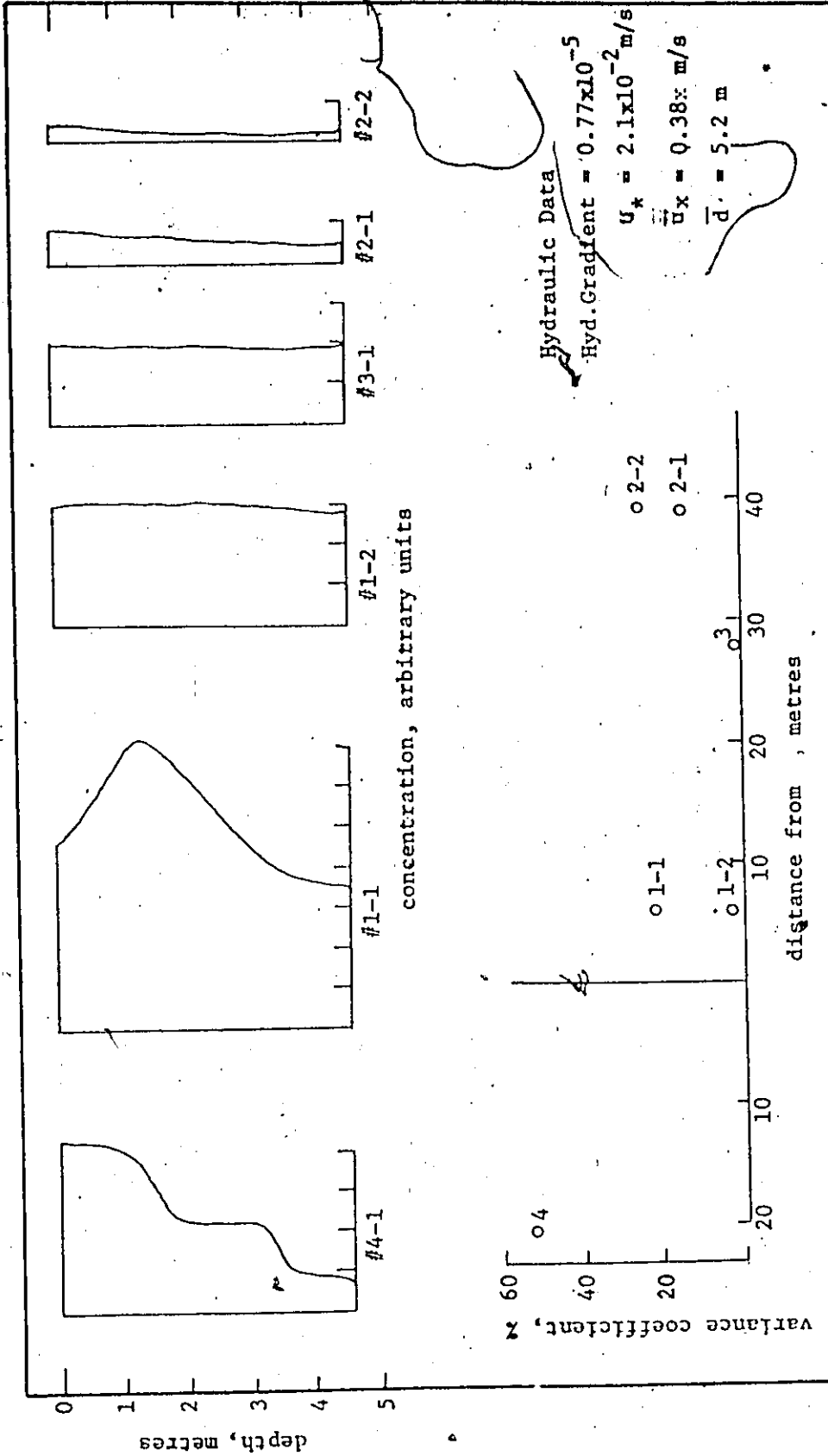


Fig. B.1(B) Lateral Variation of the Depth Concentration Profiles on October 24



Notes: 1. Section was located 1950 m from injection
 2. Station number indicates sequence of sampling

Fig. B.1(C) Lateral Variation of the Depth Concentration Profiles on November 30

APPENDIX C

CALIBRATION OF FLUOROMETER

Tests were conducted under laboratory conditions to check the linearity between the fluorometer dial reading and the sample concentration. Standard Rhodamine B solutions were made up to cover the range of concentration expected in the field study. Each standard was placed in a 5 ml cuvette and the fluorometer dial reading was recorded. The results of this test are plotted on Fig. C.1. The correlation was linear throughout for the 30x intensity and linear, except at very low concentrations, for the 10x intensity.

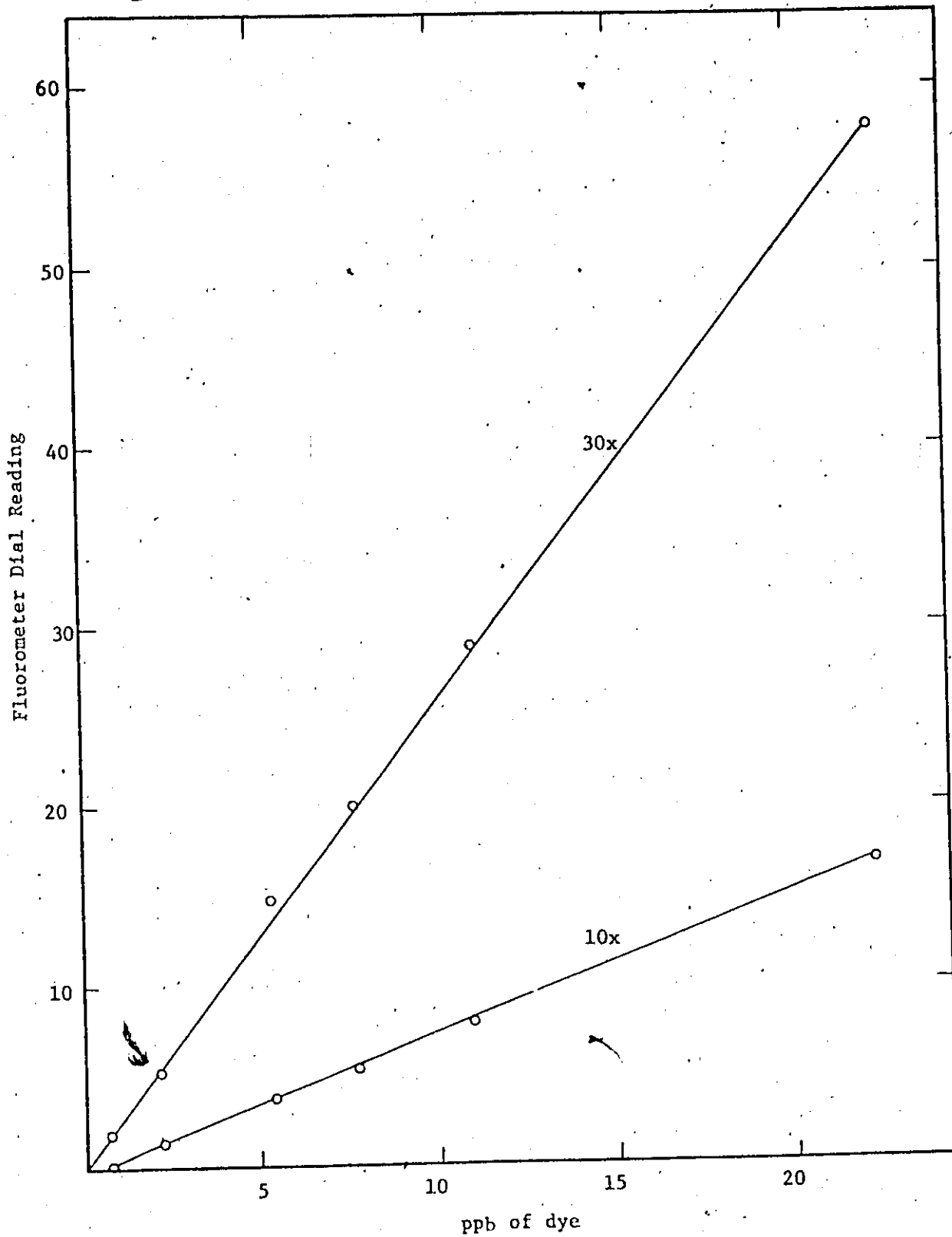


Fig. C.1 Calibration of the Fluorometer

APPENDIX D

RELATION BETWEEN TRAVERSE SPEEDS AND PEAK CONCENTRATIONS

It was thought that the variation in crossing speed might be causing a variation in the peak concentration. Fig. D.1 shows the peak concentration plotted against the crossing time at each section for each experiment. No clear pattern is discernible. It is concluded therefore that it is not necessary to make any correction in the peak concentration on account of the crossing speed.

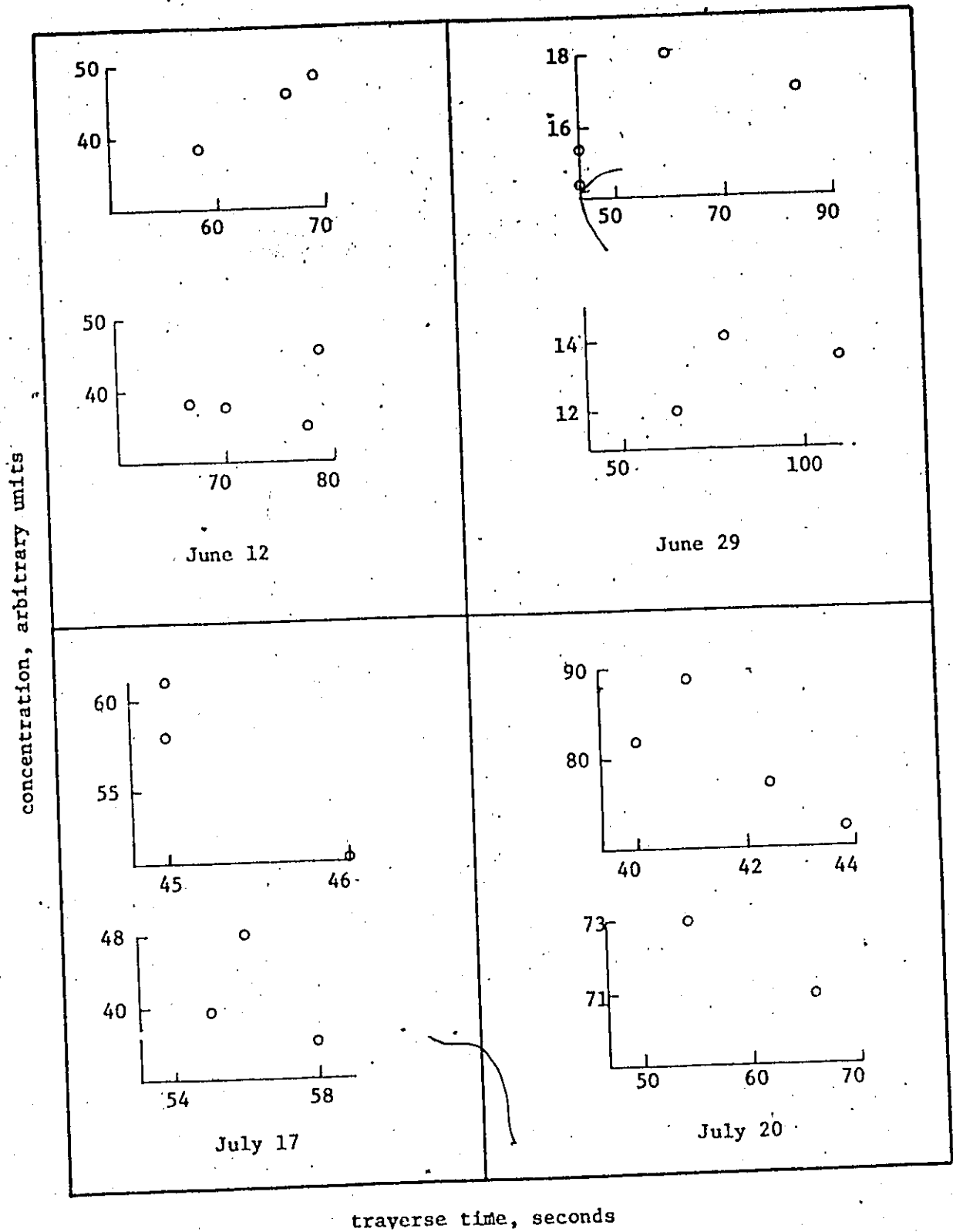


Fig. D.1(A) Peak Concentrations versus Traverse Times

concentration, arbitrary units

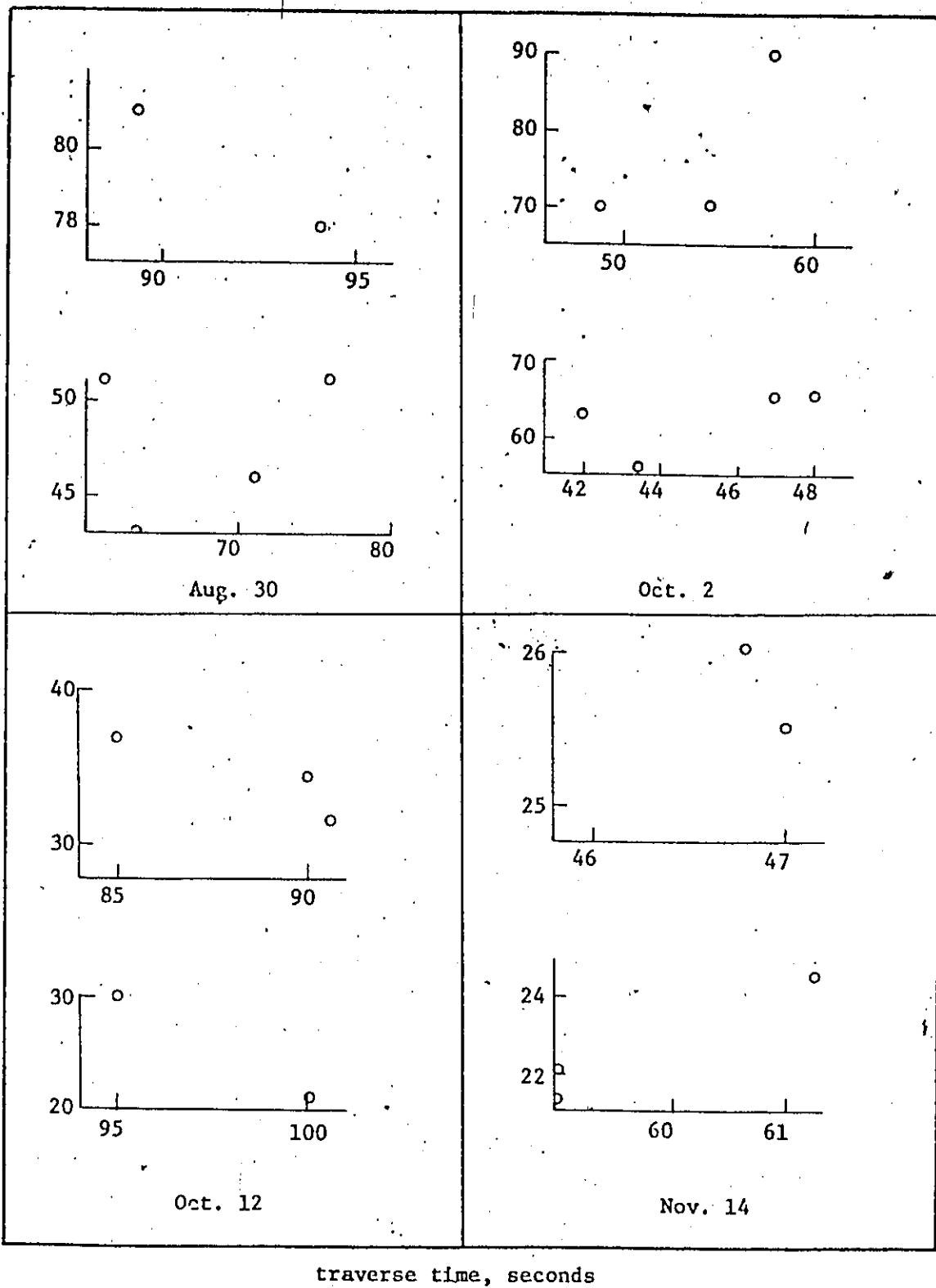


Fig. D.1(B) Peak Concentrations versus Traverse Times

APPENDIX E

THE IDEALIZED GRADIENT DIFFUSION METHOD APPLIED TO THE MISSOURI RIVER STUDY (33)

The average hydraulic parameters for the overall study reach of this river are given in Table 2.1. Three reaches within the study reach were chosen for analysis. These three reaches lay between 1750 m and 4750 m downstream of the injection. The Eulerian mixing length from Eq. 16 was roughly 300 m. The width of the lateral dye profile which was fully mixed throughout the depth was calculated from Eq. 17 for each section. An average of 97% of the dye profile was contained in the fully mixed portion at each section. This percentage was estimated by comparing $\sum c_i \bar{u}_{xi} d_i \Delta z_i$ for the fully mixed portion and for the total plume. Δz_i is the width of a lateral segment. The average K_z resulting from an analysis similar to the author's analysis of his results was $0.110 \pm 0.123 \text{ m}^2/\text{s}$. Roughly 10% of the results used to reach this figure were incorrect negative results. This happened because the reported convective outflow of dye from one control volume contained in the reach was greater than the convective inflow. There was also a marked increase in values calculated for K_z for the outer portions of the plume as against those calculated for portions close to the plume centre.

APPENDIX F

THE RATE OF CHANGE OF VARIANCE METHOD APPLIED TO THE
AUTHORS RESULTS

The following form of Eq. 7 is used to calculate

K_z :

$$K_z = \frac{1}{2} \bar{u}_x \frac{d}{dx} \sigma_z^2$$

where

$$\sigma_z^2 = \frac{\sum c_i \bar{u}_{xi} d_i z_i^2 \Delta z_i}{\sum c_i \bar{u}_{xi} d_i \Delta z_i} - \left[\frac{\sum c_i \bar{u}_{xi} d_i z_i \Delta z_i}{\sum c_i \bar{u}_{xi} d_i \Delta z_i} \right]^2$$

where z_i is the transverse distance from an arbitrary reference point (9).

The values got using this method are given in Table F.1.

Most of the values for K_z are not numerically reasonable. The reason for this is that an insufficient percentage of the dye plume is vertically mixed and this results in the inadequacy of a two-dimensional analysis. It can be clearly seen also from Table F.1 that to assume that $\sum c_i \bar{u}_{xi} d_i \Delta z_i$ is a constant is not justified.

Table F.1 Rate of Change of Variance Method Applied to the Authors Results

	June 12	June 29	July 17	July 20	Aug 31	Oct 2	Oct 12	Oct 24	Nov 14
K_z (from analysis of variance) (m^2/s)	.050	.016	.007	.016	.042	.001	.013	.015	.025
% dye accounted for in the mixed portion of #1	50	80	82	85	80	67	86	79	74
$\sum c_i \bar{u}_i d_i \Delta z_i$ at #1 (exp. units)	2265	1004	1495	1865	1931	1711	955	3487	3272
$\sum c_i \bar{u}_i d_i \Delta z_i$ at #2 (exp. units)	2234	886	1280	1656	2204	1244	834	3509	2482

APPENDIX G

EFFECT OF MIXING IN THE SAMPLING TUBE

The following were typical hydraulic conditions for flow in the sampling tube:

$$\bar{u}_x = 0.15 \text{ m/s}$$

$$D \text{ (diameter)} = 0.006 \text{ m}$$

$$\gamma = 1.41 \times 10^{-6} \text{ m}^2/\text{s}$$

The flow was laminar with a Reynolds number of 640. This gives a friction factor, f , equal to 0.1 which gives a shear velocity, u_* , equal to 0.017 m/s.

Taylor (28), using the Reynolds Analogy, shows that the longitudinal dispersion coefficient for turbulent flow in a tube is

$$K_x = 5.05 D u_*$$

This gives a value of K_x equal to $5.2 \times 10^{-4} \text{ m}^2/\text{s}$. This figure underestimates the dispersion as the flow is actually laminar. The resulting change of variance applying the formula

$$\frac{\partial \sigma_x^2}{\partial t} = 2K_x$$

with a travel time of 20 secs is equal to 0.15 m. This figure accounts for roughly 20% of the upstream variances in the lateral concentration profiles as calculated over the vertically mixed and unmixed portions.

The extent to which this distortion of the plume affects the calculations in the Idealized Gradient Diffusion method is not known.

Subsequent to the field study, dye was pumped through the 3.5 m sampling tube in the laboratory under the same hydraulic conditions. It was found that dispersion in the tube caused dye to reach the fluorometer at 1.4 times the discharge velocity.



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