THE UNIVERSITY OF ALBERTA

DISPERSION OF DYES AND POLLUTANTS IN NORTH SASKATCHEWAN RIVER

by

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A THESIS

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ABSTRACT

DISPERSION OF DYES AND POLLUTANTS IN NORTH SASKATCHEWAN RIVER

The object of this thesis was to study the capacity of North Saskatchewan river to assimilate wastes, particularly the problem of dispersion of pollutants. The study area involved the reach of river below Edmonton to the Vinca bridge.

Field measurements and sampling were carried out during the winter months from September 1971 to March, 1972, because this is the period of low flows in the river and of ice cover. The examination of the river water took place regularly at two locations - Fort Saskatchewan bridge and Vinca bridge sampling stations. At both locations several samples were taken across the river cross-section to determine the distribution of pollutants. The results of chemical laboratory tests confirmed the suspected incomplete mixing below the Town of Fort Saskatchewan, whereas the Fort Saskatchewan bridge cross-section showed quite uniform distribution of pollutants.

In January 1972 an extensive survey of the river cross-section at Vinca was carried out in order to obtain

the necessary data for a dispersion coefficient determination. This, together with a dye tracer study, provided data for mathematical solution of the dispersion equation, applicable to this reach of river.

A twenty percent solution of Rhodamine W. T. was used in the dye tracer study. Two runs were made, the first, from Dow Chemical at Fort Saskatchewan to Vinca, showed incomplete mixing at Vinca and provided the basis for the development of the three-dimensional model of dispersion, the second, from Edmonton to Fort Saskatchewan, showed quite uniform mixing at Fort Saskatchewan Bridge.

The results of the three-dimensional model of dispersion as well as the first dye test was the basis for determination of coefficients relating the mean concentration in the river to the values obtained at the Government of Alberta, Department of Environment sampling point. These coefficients, shown in the last chapter, indicate the dispersion in the stretch of river between Fort Saskatchewan and Vinca.

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GLOSSARY OF TERMS

ASSIMILATIVE CAPACITY	- The capacity of a river to assimilate waste loads.
DISPERSION	- The mixing and spreading of concentrated mass of pollutant or dye tracer in a natural stream.
LEFT BANK (RIGHT BANK)	- Looking downstream the right and left bank is considered to be the one on the right and left side subsequently.
WATER POLLUTION	- Impairment of water quality and the resulting adverse effect on water use.

CHAPTER I

INTRODUCTION

1. Pollution of Natural Streams.

Not the least of the important uses of water is its use for the disposal of liquid wastes from cities and industries. There is nothing on the horizon to suggest the discovery of waste handling systems superior in efficiency and economy to our present water carriage systems. We will continue to discharge wastewater into our streams. We have no choice in this matter. Our only choice lies in the extent to which we allow the discharge of wastewater of all kinds to impair and interfere with other beneficial water uses. To the extent that we can eliminate or reduce water quality damage and consequent interference with water use, we have accomplished water pollution control.

2. Assimilative Capacity of Natural Streams.

With ever increasing demands being placed on surface waters for disposal of man's waste products, it is essential that the capacity of these waters for assimilating wastes be known for the protection of their many beneficial uses. The determination of this assimilative capacity is dependent on three important factors:

1. The dispersion of the wastes and the dilution effected;
2. The net advection of the waste receiving water system;
3. The decomposition of the wastes.

To permit the prediction of the concentrations of waste constituents in receiving waters, all three factors either must be known or estimated realistically. The natural ability of rivers to assimilate waste is limited and varies from stream to stream. This variation is largely dependent on character of wastes, local climatic conditions, amount of waste and character of the stream.

3. Past Problems and Research on North Saskatchewan River.

The examination of the river water in the early 1950's showed very low levels of dissolved oxygen downstream of Edmonton. In 1955-1956 it was found that the oxygen in the river at Duvernay, Lindbergh and Lloydminster was depleted and septic conditions which developed in absence of oxygen produced strong odors. This situation resulted in an attempt by the Alberta Department of Public Health to artificially aerate the river. The reaeration was, unfortunately, not successful. In the following years more stringent controls of all waste discharges were introduced and oxygen levels in the river during the winter months were significantly higher. The situation was further improved by the new sewage treatment plant at Edmonton, completed in 1956 for primary treatment and 1957 for secondary. Newly constructed sewage lagoons for packing house wastes in 1965 also reduced the load of wastes in the winter months.

In the summer of 1971 the Interdisciplinary Committee for Environmental Quality (ICEQ) and the Fish and Game Association, together with the Edmonton Anti-Pollution Group, conducted a survey and published jointly the study "Effluent Flow Patterns in the North Saskatchewan River" (3). This study attempted to determine the extent of mixing of effluents discharged into the North Saskatchewan River in the Edmonton-Fort Saskatchewan area. It also pointed out the fact, that sampling on the river is usually done by taking 'grab' samples at midstream, whereas almost all effluents in the Edmonton area enter the river on the south bank. The Government of Alberta, Department of Environment monitor, installed every year at Vinca Bridge, has a pipe intake extending about 150 feet from the north bank and is, according to the Edmonton Anti-Pollution Group study, providing samples which do not reflect the true river water quality.

4. Study Objectives.

Most studies of the natural purification in streams have been carried out on rivers of more southerly latitudes, flowing under warm conditions. The Department of Civil Engineering, at the University of Alberta has been involved for several years in studying and investigating pollution problems, biooxidation and oxygen utilization in the North Saskatchewan River under ice cover at temperatures close to 0 degrees C. This study is a further step in this continuing program and its object is to study dispersion in the North Saskatchewan River under ice cover so as to aid in the selection of representative sampling points.

The goal of this study is:

1) To determine a dispersion coefficient for the dispersion equation, which may be applied to pollutants entering the river at or above Fort Saskatchewan and measured at the Vinca Bridge Government sampling station.
2) To determine the concentration distribution of wastes at Fort Saskatchewan Bridge.
3) To determine the concentration distribution of

effluents from Fort Saskatchewan in the river cross-section at Vinca.

4) To determine the relation between the mean concentration in Vinca cross-section and the values obtained at the point of government sampling.

5) To verify the distribution by means of dye tracer test.

CHAPTER II

STUDY AREA

1. General Discription.

The North Saskatchewan River, part of the Hudson Bay drainage system, rises in the Rocky Mountains near the continental divide. The high summer flow is derived from the melting snow and glaciers in the mountains, whereas the low winter flow is mainly from lakes and groundwater storage.

The river flows in an easterly direction through Alberta to Saskatchewan, where it is joined by the South Saskatchewan River. From this junction it flows again in an easterly direction to Manitoba and into Lake Winnipeg. The upper part (upstream of Drayton Valley) drops from an elevation about 5000 feet to 2400 feet in about 200 miles. Below Drayton Valley the slope diminishes so that at Edmonton the Water elevation is 2010 feet above the geodetic datum and 210 miles downstream at the Alberta-Saskatchewan border it drops to an elevation of 1639 feet. In our study area the actual drop is 72.6 feet between Edmonton and Vinca ferry, a distance of 39.8 miles.

There are only small tributaries in this stretch of river and they are almost completely frozen during the winter months; therefore, the rate of flow is uniform between Edmonton and Vinca ferry. The river is covered with ice for 5 to 6 months each year.

Ice formation usually appears by the end of October or beginning of November and remains until April. Duration of ice cover in the period 1915-1965 and its frequency distribution was studied by R. D. Cameron (1) and Figure 1 is taken from his study.

2. River Discharge.

The mountain and foothill portion of the North Saskatchewan River basin provides a greater part of the streamflow than do the plains of the prairie provincies. The average yield of the higher back range areas is over 40 inches per year, while the drier plains yield less than one inch. In relatively dry years, such as 1948-1949, the plains portion of the basin with 87% of the area contributed less than 16% of the flow (see Table I).

There are large variations in the annual maximum and minimum daily discharge. There is a tendency toward two peaks a year, but not necessarily in every year. The first maximum occurs as a result of snowmelt and rainfall in April and May, the second, in June or July, is due to

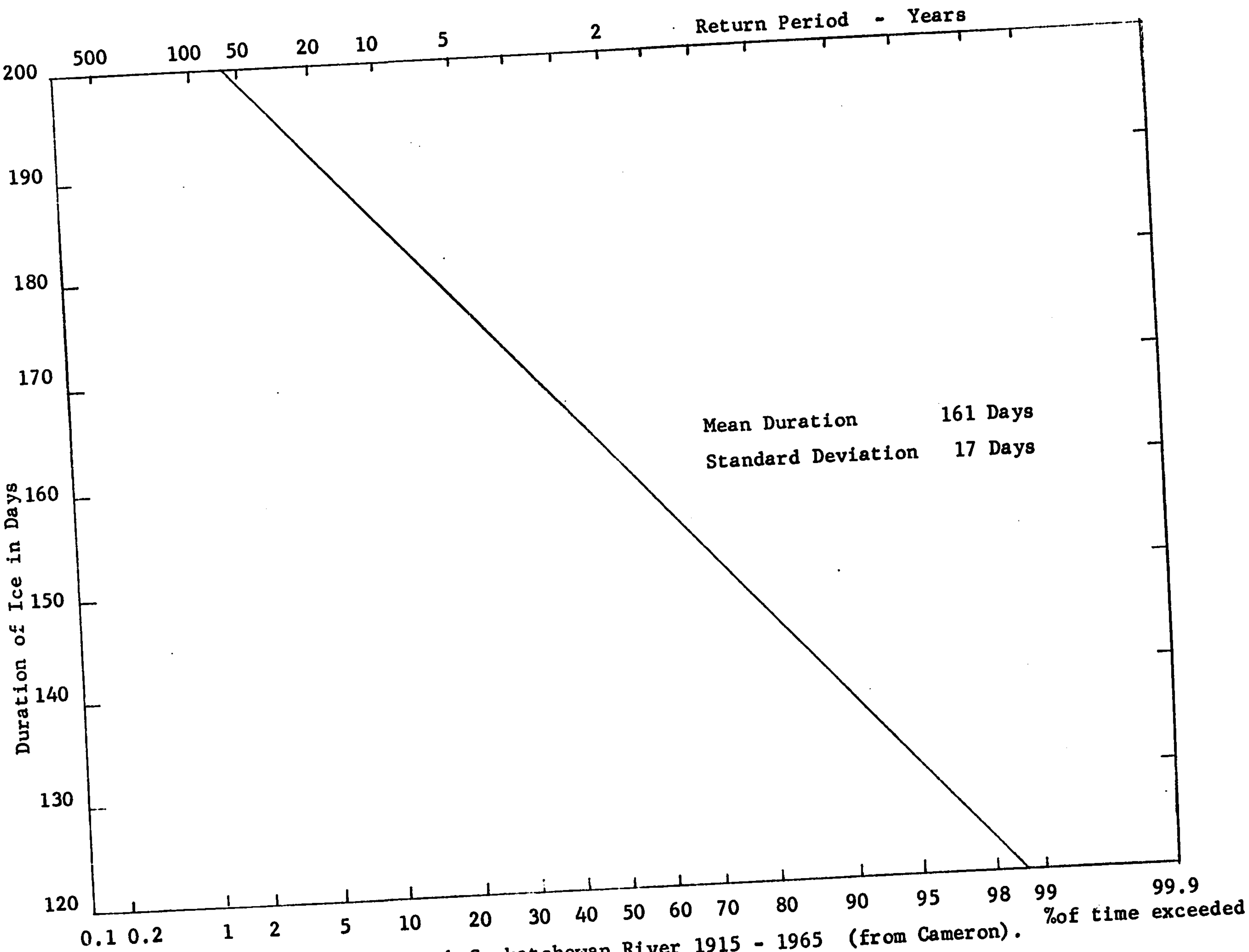

FIGURE 1 : Duration of Ice - North Saskatchewan River 1915 - 1965 (from Cameron).

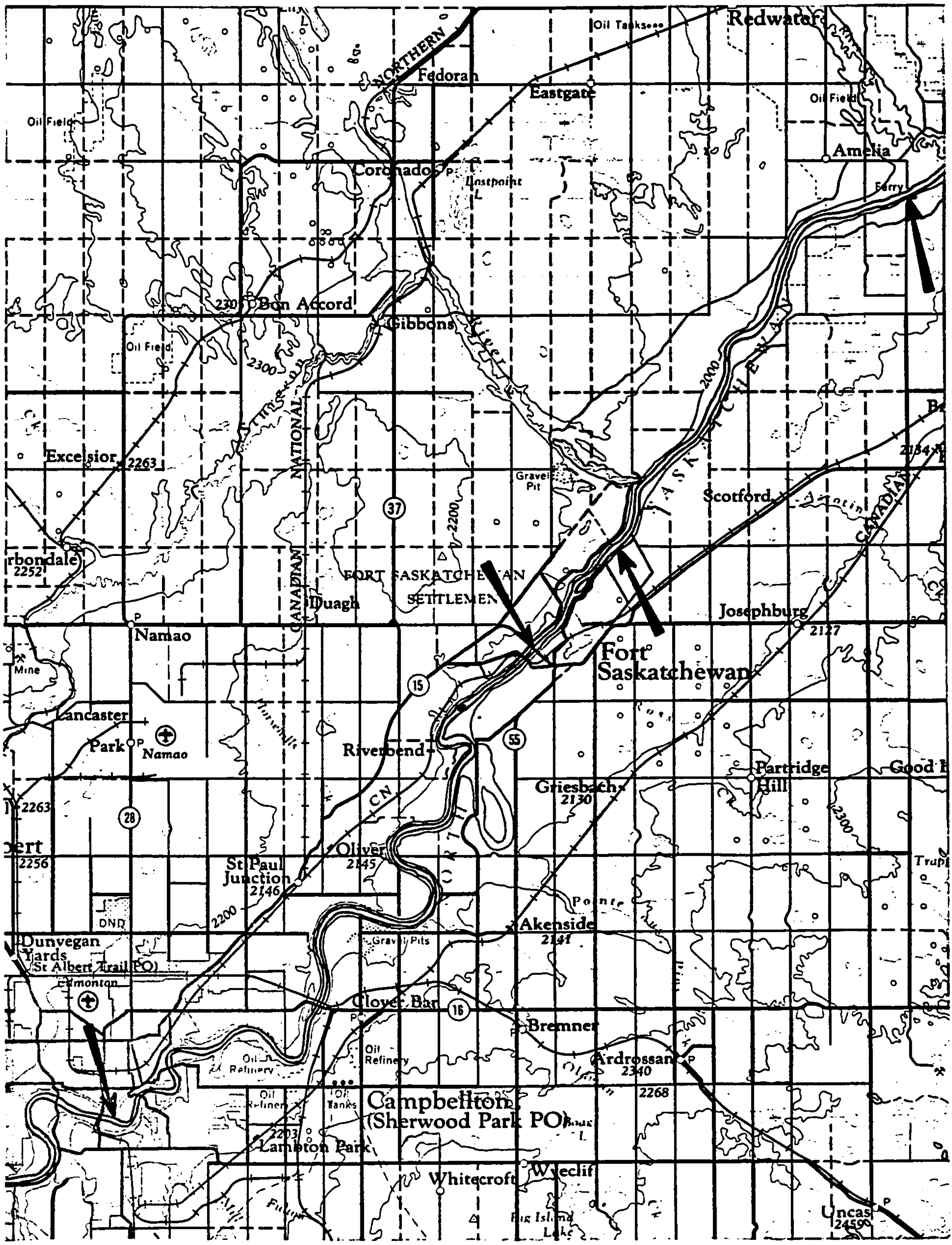

FIGURE 2 : Map Showing the Study Area.

(Arrows indicate sampling points and points of releasa of dye)

TABLE I

STREAMFLOW OF THE NORTH SASKATCHEWAN RIVER - 1948-1949

Source Area	Area Sq. Mi.	% of Basin Area	Streamflow Acre Feet	% of Total Streamflow	Water Yield Inches
A. National Parks	1,336	2.8	1,300,000	32.6	18.2
Jasper	445	0.9	350,000	8.8	14.7
Banff	891	1.9	950,000	23.8	20.0
B. Forest Reserve Clearwater Forest	4,468	9.4	1,944,000	48.7	8.1
C. Other Foothills	223	0.5	40,000	1.0	3.4
D. Plains	41,473	87.3	626,000	15.7	0.3
TOTAL	47,500	100.0	3,910,000	100.0	1.5

heavy rainfall and snowmelt in the mountains. The minimum discharge usually occurs during the months of January and February, when the flow is supplied from lakes and groundwater storage only. The minimum mean daily discharge in 1971 was about 1450 cubic feet a second, but prior to 1963 winter flows were as low as 220 cubic feet a second (January 1st, 1940). Since 1963 the winter flow conditions have been improving by releases from Brazeau Dam storage. This dam, built on the Brazeau River, one of the major tributaries of the North Saskatchewan River above Edmonton, was designed primarily as a source of electrical energy but it also serves to reduce the peaks of summer floods and increase winter flows in the North Saskatchewan River.

3. River Use.

The North Saskatchewan River serves, to a limited extent, for sport fishing and some boating, but the main purpose it serves is to supply water for cities and industry. Unfortunately, since there is no other choice, it must serve also as a carrier of wastes. The main water users on the North Saskatchewan River are listed in Table III. To mention just a few more closely related to our study area, we can start with the City of Edmonton, which

TABLE II

MAIN EFFLUENT DISCHARGERS INTO NORTH SASKATCHEWAN RIVER IN ALBERTA

Source	Character of Waste	Type of Treatment
Town of Rocky Mountain House	Domestic	none
Town of Drayton Valley	Domestic	lagoon
Town of Devon	Domestic	ST
Imperial Oil - Devon	Industrial	lagoon
City of Edmonton	Domestic	ST in winter
Canadian Industries Ltd.	Industrial	well
Building Products Ltd.	Industrial	AL
Imperial Oil Ltd.	Industrial	A.P.I., well
Texaco	Industrial	A.P.I., well
Union Carbide	Industrial	lagoon
S & L Oil	Industrial	lagoon
Gulf Oil Canada Ltd.	Industrial	A.P.I., lagoon
Chemcell	Industrial	well, lagoon
Uniroyal	Industrial	lagoon
Alberta Hospital - Oliver	Waste stored in lagoons during winter months and discharged in summer	
City of Edmonton Packing Plants		
Sherwood Park		

TABLE II. (cont'd)

Source	Character of Waste	Type of Treatment
Town of Fort Saskatchewan	Domestic	lagoon
Sherritt Gordon Mines Ltd.	Industrial	lagoon
Dow Chemicals Ltd.	Industrial	lagoon, disposal well
Redwater Imperial Fertilizer	Industrial	lagoon
Town of Redwater	Domestic	lagoon
Redwater Imperial Oil Gas Plant	Industrial	lagoon
Waskatenau	Domestic	lagoon
Chemcell - Duvernay	Industrial	no treatment
Elk Point	Domestic	lagoon
Canadian Salt Co. Ltd.	Industrial	no treatment

ST - secondary treatment

AL - aerated lagoons

A.P.I. - API separator (American Petroleum Institute)

TABLE III

EFFLUENT CHARACTERISTICS OF EDMONTON #5 SEWAGE TREATMENT PLANT

1970 mon.	Flow M.G.D.	SS lbs/day	B.O.D. lbs/day	Oil & Grease mg/1	Phenols mg/1	Coliforms MPN/100	Phos-phates mg/1
1	28.96	16,503	14,256	6	18	8.1	-
2	30.25	21,152	16,851	15	24	1.3	31.0
3	31.99	26,145	11,583	4	16	3.3	26.0
4	34.36	29,066	14,470	5	11	1.7	34.2
5	30.74	61,509	51,688	3	19	0.1	-
6	32.06	63,895	72,606	-	96	7.9	40.7
7	41.47	86,261	79,192	-	-	-	-
8	34.38	56,181	55,610	38	85	-	44.4
9	32.99	54,768	50,924	59	64	-	25.9
10	32.38	48,209	43,981	6	24	-	25.1
11	30.40	23,528	23,364	9	15	-	24.8
12	29.87	21,725	14,618	14	17	-	26.3

EFFLUENT CHARACTERISTICS OF EDMONTON #3 SEWAGE TREATMENT PLANT

1	3.71	3,518	4,040	22	42	-	-
2	3.85	3,224	3,830	47	58	-	18.0
3	4.47	6,469	3,623	26	43	-	19.0
4	4.52	4,826	3,797	17	27	-	13.7
5	4.72	4,006	4,617	20	30	-	-
6	4.36	2,954	3,880	30	25	-	21.3
7	4.98	3,820	3,963	-	16	-	-
8	4.59	3,044	2,906	18	30	-	22.4
9	3.89	3,204	3,522	25	29	-	16.9
10	3.50	2,829	3,638	14	24	-	20.9
11	3.08	2,629	3,696	26	26	-	23.8
12	3.25	2,514	4,046	37	34	-	26.1

is the major source affecting the river for a considerable distance downstream. Treated domestic waste is discharged into the river from the number 5 and number 3 (until December 1971) sewage treatment plants. Waste characteristics are summarized in Table II.

During the summer high flows the sewage from sewage lagoons located approximately 16 miles downstream from the Low Level Bridge is discharged into the river. These lagoons store wastes from three packing houses, and households in the northeastern section of the city as well as from the Town of Sherwood Park.

The Edmonton industrial complex has at times been responsible for odor problems found downstream from Edmonton, because of its phenol containing wastes.

Farther downstream there are waste flows from the Town of Fort Saskatchewan (discharging domestic wastes) and Sherritt Gordon Mines Ltd. and Dow Chemicals Ltd., which discharge industrial wastes. The wastes from Dow Chemicals is of special importance to our study, because of its high chloride content, which could be traced a long way downstream and was used in this study to verify our calculations of variations in concentration over the river cross-section.

CHAPTER III

THEORY OF DISPERSION IN NATURAL STREAMS

1. Introduction.

With the growth of industry and development of new technological processes the number of potentional pollution sources increases as does the total concentration of pollutants in natural streams. There are limits, however, on how much waste streams can assimilate, and those limits are determined not only by the amount of flow, but also by the individual dispersion characteristic of every particular stream. The dispersion characteristics of natural streams vary greatly from stream to stream.

A pollutant introduced into the river tends to spread out and become more diluted because of mixing processes fundamental to fluid mechanics and the dispersion characteristics of the river.

In this study, an attempt has been made to study the mixing process with the use of dye and to predict cross-sectional variations of pollutants in the North Saskatchewan River below the Town of Fort Saskatchewan.

2. Basic Theory of Mixing.

The use of dyes in stream diffusion studies has been recognized for some time. Some detailed techniques concerning the use of dyes in measuring some of the physical parameters, that are involved in the stream dispersion,have been developed. There are variations in the techniques presented by different authors, but all of the derivations have their fundamental assumption based on a finite element approach using an elemental cube, as shown in Figure 3.

The concentration of any dissolved substance in a given liquid in an equilibrium state is constant throughout the whole body of the liquid. If the concentration is higher in one part of the liquid as compared with another,then, over a period of time, there is an increase in concentration in that part of the liquid that has a lower concentration and a simultaneous decrease in concentration in the part of the liquid with the higher concentration. This phenomena can be explained by an equal and random transport of liquid particles with their contained dissolved materials from one part of the body of the liquid to another. An assumption can then be made, that the rate of transfer of anymaterial in any direction is proportional to the variation of concentration in that direction.

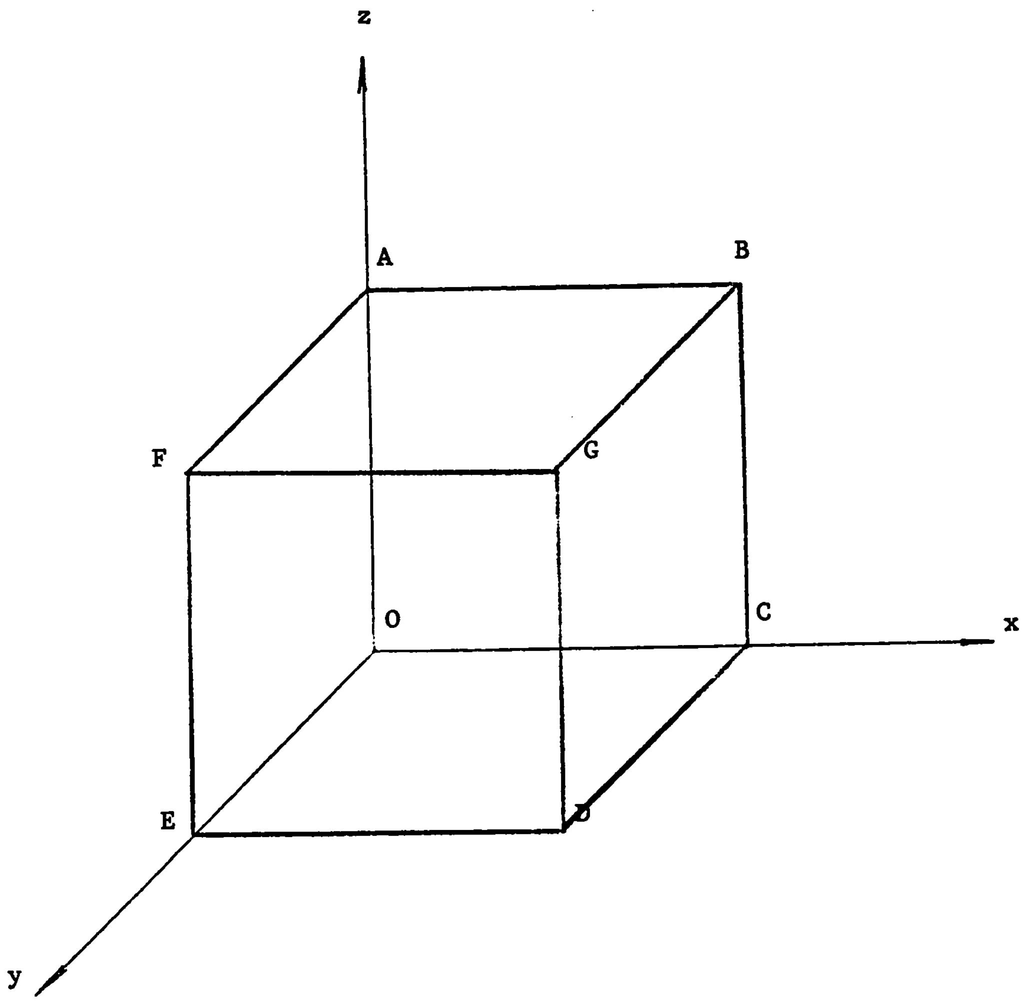

FIGURE 3 : Elemental Cube.

justification of such an assumption can be given on the basis of the kinetic theory of gases and liquids for molecular diffusion (17).

The infinitesimal cube as shown in Figure 3, has sides dx, dy, dz. Let us consider, that through the side AOEF, with the area dy dz, a quantity of substance equal to

$$-D_x \left[\frac{\partial c}{\partial x}\right]_{x=0} dy\ dz\ dt$$

enters the cube during the interval of time dt. Through the side CBGD a quantity equal to

$$-D_x \left[\frac{\partial c}{\partial x}\right]_{x=dx} dy\ dz\ dt$$

is leaving. The minus sign is used to indicate that the movement occurs in the direction of decreasing concentration. The constant of proportionality, D_x, is called the coefficient of diffusion for molecular diffusion and similarly is termed for turbulent dispersion phenomena. Because

$$\frac{\partial c}{\partial x}\Big|_{x=dx} = \frac{\partial c}{\partial x}\Big|_{x=0} + \frac{\partial}{\partial x}\left[\frac{\partial c}{\partial x}\right]dx = \frac{\partial c}{\partial x}\Big|_{x=0} + \frac{\partial^2 c}{\partial x^2}\,dx \qquad (1)$$

the difference between the quantity entering and leaving is equal to

$$D_x \frac{\partial^2 c}{\partial x^2} \, dx \, dy \, dz \, dt$$

in which D_x is the coefficient of diffusion. The total excess of material entering the cube equals the change in concentration within the cube per unit time

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} \qquad (2)$$

3. Mixing in Natural Stream.

The mixing in natural streams is a very complicated process. It is known that it is a three-dimensional process, in which vertical, lateral, and longitudinal mixing is determined by the geometry of the stream. Probably the most important part of this process is longitudinal mixing, which occurs as the consequence of the lateral velocity gradients. The surface velocity across the stream varies in direct relation to the depth, so that the deepest part of the channel has the greatest surface velocity and the effluent or tracer dye in this portion of the channel moves faster than in other parts of the cross-section.

In most natural streams the flow is turbulent and diffusion takes place in a vertical direction between subsequent longitudinal layers of water which have different velocities. Because of the relatively small depth of streams this vertical mixing takes place much faster than longitudinal and transverse mixing. Vertical mixing can be taken into consideration only in cases in which the effluent is soluble or forms a fine dispersion. Oily substances with a specific weight less than that of water will not mix in the vertical direction but will stay and spread on the water surface.

The third constituent of the mixing process, the transverse mixing, is primarily due to secondary currents existing in every stream. The three patterns of secondary currents are dependent on directional changes in the channel. Looking downstream, when the channel turns to the right the mass of water tends to follow a counterclockwise spiral, which often persists behind the curve into the straight part of the channel. A similar pattern in the opposite direction is known to be formed in left turn curves of the channel. In both cases strong, spiral-like patterns of flow cause lateral mixing by bringing the water from one side to the other.

In straight stretches of the river two spirals are usually formed with opposite directions of motion joining in the middle like a gear (15).

The spiral-like flow in curves is much stronger than that in straight channels and therefore complete mixing could be expected to be achieved much sooner in curved channels.

4. Basic Equation for Dispersion in Natural Stream.

Using the same concept as applied for molecular diffusion, we can place the infinitesimal cube, as shown in Figure 3 and described in part 2. of this chapter, into the moving body of water, in our case into a natural stream. Similarly, it can be shown that the change in concentration is equal to

$$\frac{\partial c}{\partial t} = D_x \frac{\partial^2 c}{\partial x^2} + D_y \frac{\partial^2 c}{\partial y^2} + D_z \frac{\partial^2 c}{\partial z^2} - u \frac{\partial c}{\partial x} - v \frac{\partial c}{\partial y} - w \frac{\partial c}{\partial z} \qquad (3a)$$

This equation governs the dispersion of a slug of dye or any readily dispersable substance dumped into any turbulent stream.

If there are no tributaries nor loss of water, the governing equation is more commonly used in the following form:

$$\frac{\partial c}{\partial t} + u\frac{\partial c}{\partial x} + v\frac{\partial c}{\partial y} + w\frac{\partial c}{\partial z} = \frac{\partial}{\partial x}\left[D_x\frac{\partial c}{\partial x}\right] + \frac{\partial}{\partial y}\left[D_y\frac{\partial c}{\partial y}\right] + \frac{\partial}{\partial z}\left[D_z\frac{\partial c}{\partial z}\right] \qquad (3)$$

where

c = instantaneous local concentration of the dye, in ppb by volume.

x, y, z = spatial coordinates in longitudinal, lateral and vertical direction respectively.

u, v, w = instantaneous velocity components in x, y, z directions respectively.

D_x, D_y, D_z = turbulent dispersion coefficients in ft^2/sec, in x, y, z directions respectively.

t = time since the injection of the dye, in seconds.

The first term on the left hand side of equation (3) is the local change in concentration with time; the next three terms are the change in concentration due to convection by the instantaneous velocity components. The right hand side represents change due to turbulent dispersion. Molecular diffusion in natural streams is relatively small and is therefore neglected.

The solution of this equation is very difficult because of its variable coefficients. In natural conditions variations in u have the greatest effect on the amount of mixing. The parameters v and w are small or often zero. At the present time no complete solution of equation (3) exists. Various workers have devised some approximate solutions, mostly based on a one-dimensional dispersion model, by considering variations in the mean flow velocity in the cross-section as the primary cause of dispersion.

The following equation was originally developed by Taylor (5) for this one-dimensional model:

$$\frac{\partial \bar{c}}{\partial t} + \bar{u} \frac{\partial \bar{c}}{\partial x} = D_L \frac{\partial^2 \bar{c}}{\partial x^2} \qquad (4)$$

where

$\bar{u}$ = average velocity of flow

D_L = constant longitudinal dispersion coefficient ($D_x = D_L$).

Several assumptions have been made in deriving this equation:

1. Water is incompressible and its velocity $\bar{u}$ is time independent.

2. The density of the solute is equal to that of water.
3. The dispersion coefficient D_L is constant.
4. The mixing is uniform and the mean concentration $\bar{c}$ depends only on x and t.

The solution of equation (4) is then:

$$c(x,t) = \frac{M}{A(4\pi D_L t)^{1/2}} \exp\left[- \frac{(x - \bar{u}t)^2}{4D_L t}\right] \qquad (5)$$

where $c(x,0) = 0$, for $x>0$.

The boundary conditions which must be satisfied are:

$\int_{-\infty}^{\infty} A(x)\ c(x,t)\ dx = M$ for all values of t

$c(\infty,t) = 0$ $t \geq 0$

$\frac{\partial c}{\partial x} \to 0$ as $t \to \infty$

where M = total volume of dye injected,

A = effective cross-sectional area of flow.

Equation (5) gives only a theoretical distribution of pollutant or dye concentration. Its applicability to natural streams has often been questioned.

In the practical measurements of dye dispersion, an unknown amount of dye is lost due to photochemical decay and benthic adsorption by vegetation and suspended solids present in the stream. Variable amounts of dye may be temporarily detained in and later released from dead zones, which are usually present both in lateral and vertical directions along a natural stream.

Equation (5) does not take account of these two important factors and therefore its applicability for practical purposes remains restricted. Factors K and K_0 in the following equation better express the above described effects.

$$c(x,t) = \frac{1}{K} \frac{M}{A(4\pi D_L t)^{1/2}} \exp\left[- \frac{(x-ut)^2}{4D_L t}\right] \left(1-K_0 \frac{x}{Vt}\right) \qquad (6)$$

where

K = regional dispersion factor

K_0 = coefficient for the loss of the dye in the reach

V = the average velocity of flow

The value of the regional dispersion factor K is expected to vary from stream to stream. Values of K must be found by the trial and error process of comparing the computed values with those observed.

The value of K_0 is expected to depend upon the following parameters:

D_L = the longitudinal dispersion coefficient,

B = the top width of flow,

t_p = the time to peak arrival of dye concentration,

x = the reach length,

L = the characteristic length to which the lateral and vertical mixing is complete,

K_1 = the coefficient for the loss of dye due to the decay and absorption.

A dimensional analysis shows that:

$$K_0 = f\left(\frac{xB}{D_L t}, \frac{x}{Vt}, \frac{H}{L}, \frac{D_L t_p}{L^2}, \frac{D_L}{VB}, K_1\right) \tag{7}$$

The empirical formula for the distance L is:

$$L = \frac{16\ D_L}{0.05V} \tag{8}$$

and for coefficient K_0

$$K_0 = \frac{1}{4}\left[\frac{V\ B}{4D_L} + \frac{\log(2\frac{H}{L})}{\log(D_L\ \frac{t_p}{L^2})} + K_1\right] \tag{9}$$

In the equation (9)

$$\frac{V\,B}{4D_L}$$

is a factor accounting for the detention of dye in lateral dead zones,

$$\frac{\log(2\frac{H}{L})}{\log(D_L\,\frac{t_p}{L^2})}$$

is a factor accounting for the detention of dye in vertical dead zones, and K_1 is a coefficient defined for a given reach for the loss of dye due to decay and absorption (in our study $K_1 = 0.5$). This coefficient is taken as a constant, but it is rather time and concentration dependent.

The resulting final solution of equation (4) is then:

$$c(x,t) = \frac{1}{K}\,\frac{M}{A(4\pi D_L t)^{1/2}}\,\exp\left[-\,\frac{(x-Vt)^2}{4D_L t}\right]$$

$$\left[1-\frac{x\,B}{16D_L t} - \frac{x}{4Vt}\,\frac{\log(2\,\frac{H}{L})}{\log(D_L\,\frac{t_p}{L^2})} - K_1\,\frac{x}{4Vt}\right] \qquad (10)$$

This solution of the dispersion equation satisfies all the necessary initial and boundary conditions required in the case of a natural stream. It may be used to calculate the dispersion coefficient for different reaches of the stream where time concentration curves are available, and for a given dispersion coefficient it can be used to determine time-concentration curves.

5. Previous Studies.

The first study of dispersion phenomena was carried out by Taylor (5) using the concept of longitudinal dispersion as a one-dimensional process. He limited his study to a flow in a long straight pipe for which be obtained dispersion coefficients.

$$D = 10.1 \text{ a } U^* \tag{11}$$

where,

D - dispersion coefficient

a - the pipe radius

U* - the shear velocity

Applying the same concept as Taylor, Elder developed a formula for an infinitely wide two-dimensional channel and obtained

$$D = 5.93\ d\ U^* \tag{12}$$

where d = depth of flow.

Taylor's concept, derived only for the flow in pipes, has become widely accepted and it took further studies to prove that dispersion coefficients for natural streams are in fact of much higher values. Engineering practice since then has been to assert that a coefficient exists, but because of specific stream characteristics it must be obtained only by experiment.

Various investigators have derived empirical diffusion formulas applying to the flow in pipes, in open channels under laboratory conditions, and in natural streams. For our study, only formulas for natural streams are of concern (9). They are:

$$\text{Glover} \qquad D_L = 500\ U^*\ H \tag{13}$$

$$\text{Thackston} \qquad D_L = 7.25\ U^*\ H \left(\frac{\bar{u}}{U^*}\right)^{1/4} \tag{14}$$

$$\text{Fischer} \qquad D = -\frac{1}{A} \int_0^b q'(z)dz \int_0^z \frac{1}{E_z d(z)}\, dz \int_0^z q'(z)dz \tag{15}$$

where

U^* = overall bed shear velocity

H = hydraulic depth of flow

$\bar{u}$ = mean velocity of flow in direction of flow

A = area of flow cross-section

q' = depth integrated velocity

E_z = transverse turbulent mixing coefficient

z = transverse cartesian coordinate

B - width of channel

d = depth of flow

6. Three-Dimensional Mathematical Model of Dispersion.

The one-dimensional model is expected to be valid only for cross-sections at a considerable distance downstream from the point of injection, where the mixing is expected to be uniform. Near the point of injection the mixing is incomplete especially in y and z directions. The last two terms on the right hand side of eq. (3) cannot be neglected, but the convective terms due to mean velocity components in y and z direction can, as they are usually small compared with u term. The equation can thus be rewritten as follows:

$$\frac{\partial c}{\partial t} + u\,\frac{\partial c}{\partial x} = D_x\,\frac{\partial^2 c}{\partial x^2} + D_y\,\frac{\partial^2 c}{\partial y^2} + D_z\,\frac{\partial^2 c}{\partial z^2} \qquad (16)$$

The initial conditions are:

$$c(x,y,z) = 0 \qquad \text{for } x>0,\ y>0,\ z>0 \qquad (17)$$

The boundary conditions are:

$$\int_{\infty}^{\infty}\int_{-B/2}^{B/2}\int_{0}^{H} c(x,y,z,t)\;dx\;dy\;dz = M \qquad (18)$$

for all values of t

$$c(\infty,y,z,t) = 0 \qquad \text{for all values of } t \qquad (19)$$

$$\frac{\partial c}{\partial x} \to 0 \qquad \text{as } x \to \infty$$

$$\frac{\partial c}{\partial y} \to 0 \qquad \text{as } y \to \infty \text{ (physically } y = \tfrac{B}{2}) \qquad (20)$$

$$\frac{\partial c}{\partial z} \to 0 \qquad \text{as } z \to \infty \text{ (physically } z = H$$

Assuming $D_x = D_L$ and the mean velocity u = average velocity V for the reach, the solution of eq. (16) is

$$c(x,y,z,t) = \frac{M}{(4\pi D_L t)^{1/2}} \exp \left[-\frac{(x - Vt)^2}{(4\ D_y t)^{1/2}}\right]$$

$$\frac{2}{(4\ D_y t)^{1/2}} \exp \left[-\frac{y^2}{4D_y t}\right] \frac{2}{(4\ D_z t)^{1/2}} \exp$$

$$\left[-\frac{z^2}{4D_z}\right] \tag{21}$$

This equation satisfies the initial and boundary conditions given by eq. (17), (19), (20), but it does not satisfy the boundary condition given by eq. (18). However, eq. (21) does satisfy the similar boundary condition:

$$\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{0}^{\infty} c(x,y,z,t)\ dx\ dy\ dz = M \tag{22}$$

for all values of t

Incorporating the preceeding, eq. (18) can be hypothetically approximated as:

$$\int_{\infty}^{\infty} \int_{-B/2}^{B/2} \int_{0}^{H} c(x,y,z,t)\ dx\ dy\ dz = M$$

$$\int_{-\infty}^{\infty}\int_{-\infty}^{B/2}\int_{0}^{H} c(x,y,z,t)\,dx\,dy\,dz$$

$$\int_{-\infty}^{\infty}\int_{B/2}^{\infty}\int_{0}^{H} c(x,y,z,t)\,dx\,dy\,dz$$

$$\int_{-\infty}^{\infty}\int_{-B/2}^{B/2}\int_{H}^{\infty} c(x,y,z,t)\,dx\,dy\,dz \qquad (23)$$

Eq. (20) indicates that for natural flow conditions in a stream with finite values of B and H, the amount of dye recovered would be less than the total amount of dye injected. The amount of dye lost or detained in dead zones laterally and vertically is assumed to be given by the three quantities on the right hand side of eq. (21).

Eq. (21) still does not take into the account the amount of dye which may be lost due to adsorption or decay, and therefore could only be valid for a short time after injection of dye, when dye losses are relatively small. For distances further downstream some modification of eq. (21) may be necessary to account for such losses.

Eq. (21), known as the three-dimensional mathematical model of dispersion, has been used in this study to determine dispersion of dye in the reach of river from Dow Chemical's outfall at Fort Saskatchewan to the government sampling station at Vinca, where measured time concentration curves were available.

To use this equation for three-dimensional mathematical determination of dispersion it is necessary to know the coefficients D_x, D_y, D_z. The value of D_x is assumed to be equal to D_L - the longitudinal dispersion coefficient determined from one-dimensional model of dispersion. However, D_x may not necessarily be equal to D_L, but for larger values of either x or t, it would approximate it.

The lateral dispersion coefficient, D_y, is a function of the vertical dispersion coefficient, D_z, the top width, B; the depth of flow, H; the average velocity of flow in the reach, V; and the mean velocity of flow at the sampling station, V_s. A dimensional analysis shows that:

$$D_y = f\left(\frac{V_s}{V}, \frac{B}{H}, D_z\right) \qquad (24)$$

where $V_s = \frac{Q}{A}$; $V = \frac{x}{t_p}$; and Q = discharge, in cubic feet per sec.

The following is the empirical equation for D_y used in this study:

$$D_y = \left(\frac{V_s}{V}\right)^2 \left(\frac{B}{H}\right)^2 D_z \qquad (25)$$

The value of D_z which gives the best fit between the computed and the measured time concentration curves is accepted as an appropriate value of D_z at that location of the stream. For practical calculations the value of D_z is usually assumed. In our case the value of D_z was assumed to be 1.52×10^{-5} ft.^{2}/sec.

CHAPTER IV

DISPERSION COEFFICIENT DETERMINATION

1. Mathematical Analysis.

The eq. (10), as stated in Chapter III, is the solution of the basic equation for the one-dimensional mathematical model of dispersion. It is necessary to measure several physical parameters of the particular stream to complete the solution. The most important factor is the longitudinal dispersion coefficient D_L. As explained in Chapter III, part 5, this dispersion coefficient must be obtained by experiment. There are several methods for determining the dispersion coefficient, but in this case eq. (15) and calculations based on physical data of the river seemed to be most convenient.

To use eq. (15) for the dispersion coefficient calculation, the integrals must be replaced by the summation, resulting in the following expression:

$$D = -\frac{1}{A} \sum_{k=2}^{n} q'_k \Delta_z \left[\sum_{j=2}^{k} \frac{\Delta z}{E_{z_j} d_j} \left(\sum_{i=1}^{j-1} q'_i \Delta_z \right) \right] \qquad (26)$$

in which $q'_i = \frac{1}{2} (d_i + d_{i+1}) \ u'_i$

u_k = mean velocity in i-th vertical slice $u'_i = u_k - \bar{u}$, where

$\bar{u}$ = mean velocity of flow within entire cross-section,

d_i = depth at the beginning of the i-th vertical slice,

$_z = 0.23\ d_i\ U^*$ = transfer coefficient between i-th and i-1 th vertical slice,

n = number of vertical slices (not less than 20),

A = area of flow cross-section,

U^* = the overall shear velocity.

The shear velocity may be calculated

$U^* = (g\ r\ S_e)^{1/2}$ where

g = the acceleration of gravity

r = the hydraulic radius,

S_e = the slope of energy gradient.

2. Field Measurements at Vinca.

The equation (26) indicates the necessity of determining the velocity of flow and its variation across the river as well as determination of other physical data. For this reason, the cross-section was measured and divided into sections 20 feet wide. Holes were drilled through the ice every 20 feet to measure depth, ice thickness and veloccity of flow. The ice thickness did not vary significantly, being between 15 and 17 inches. The number of stages for flow velocity measurements in each hole depended on the depth. The river is quite shallow and so three stages were taken in only three or four holes. An hydraulic current meter with several exchangeable propellers was used for the actual flow velocity measurements. The choice of various propellers suitable for various ranges of velocities enabled greater accuracy achieved.

The data was then summarized and used to calculate the dispersion coefficient D_L (Table B of Appendix). The correctness of the field measurements of flow was checked with the government record from the gauging station at the Low Level Bridge in Edmonton. The calculated flow of 2089 c.f.s. is very close to the government recorded flow of 2120 c.f.s. Since there are no significant tributaries between Edmonton and Vinca Bridge, and the small tributaries are frozen during the winter months, the difference is close to 1.5 percent.

The characteristic cross-section, with velocity contours interpolated from the velocities obtained, is shown in Figure 4. In this figure the sampling points used for the dye dispersion study at a later date are also shown.

The dispersion coefficient calculation is based on Fisher's formula (10) equation (15). The resulting value of the dispersion coefficient is 7040.5 $\text{ft.}^2/\text{sec.}$ Despite great care during the measuring procedure, this coefficient is not suitable for the time-concentration curves calculation for reasons described later in Chapter VI. The dispersion coefficient based on Glover's formula (9) equation (13) with the value 230 $\text{ft.}^2/\text{sec.}$ appeared to be more suitable for the river stretch being investigated.

TABLE IV

RHODAMINE W. T. CHARACTERISTICS

Dye Color	Basic Violet 10
Chemical Formula	$C_{28}H_{31}N_2O_3Cl$
Form Used	20% solution (by weight
Specific Gravity	1.12
Minimum Detectable Concentration	0.000046 mg/l in distilled water 0.000066 mg/l with background present
Photochemical Decay	50% concentration reduction
Physical Adsorption	moderate
Diffusivity	fair
Biodegradability	fair

CHAPTER V

DYE TRACER STUDY

1. Previous Studies.

Several studies have been carried out on the North Saskatchewan River, mainly to determine flow velocity in various reaches of the river. (R. D. Cameron (1) and D. Corrigan (2)) The results of those studies do not entirely reflect the present situation, because the ice formation varies from year to year. However, for rough estimation of the time of travel of dye, they provide valuable data.

2. Measuring Equipment and Fluorescent Dye Used.

In this study the dye was injected instanteously as a slug. Based on experience reported in previous studies where either 25% fluorescein or 40% rhodamine dye were used, Rhodamine W. T. dye was chosen as the most suitable. Table IV lists some important data concerning this dye.

A G. K. Turner Associates Model III fluorometer was used for actual concentration measurements. The fluorometer is basically an optical bridge, analogous to a Wheatstone bridge used in measuring electrical resistance.

The optical bridge measures the difference between the light emitted by the sample, which is proportional to the concentration of fluorescent material in the sample, and that from a separate calibrated light path. The quantity of light required in the calibrated light path to balance with that from sample is automatically indicated on a dial marked in 100 equal divisions. The fluorometer is equipped with four openings or appertures which emit light to the sample in the approximate ratio 1:3 : 10:30. This provides a means for examining a wide range of concentrations without changing the filter arrangements. The purpose of colour filters in a fluorometer is to limit the light reaching the photomultiplier, as far as possible, to that emitted by the dye.

The actual concentration of dye in a sample is determined by multiplying the dial readings by a calibration constant. The calibration constant is a ratio of the known concentration of the dye C to the reading obtained for this concentration D. Care must be exercised that the sample reading as well as the calibration constant are obtained within the same range.

All measurements were made using the general purpose ultraviolet lamp and the standard cuvette holder door supplied with the instrument. Cuvettes were borosilicate glass 12mm x 75 mm tubes. The zeroing cuvette was a round black 12 mm x 75 mm tube simulating a non-fluorescent sample.

3. Dye Dispersion Measurements.

As mentioned earlier, the suspected incomplete mixing of wastes from Fort Saskatchewan to Vinca established the need for this study in that locality. The main source of detectable chlorides, Dow Chemical Ltd. plant, determined also the first injection point for the dye. The sampling point for the passing dye cloud was then established at the Government sampling station approximately 2 miles upstream from Vinca Bridge. The net travel distance as measured along the river centreline is 70,600 feet.

In the second run the degree of mixing between Edmonton and Fort Saskatchewan was examined. The release of dye was below the Edmonton water treatment plant; sampling was at the Fort Saskatchewan Bridge.

In the first run, 5769 g of 20% Rhodamine W. T. was released into a manhole located about 100 feet from the river on a sewer outlet line from Dow Chemical Ltd. It was estimated that the dye would reach the river in one or two minutes because of a relatively high flow in the

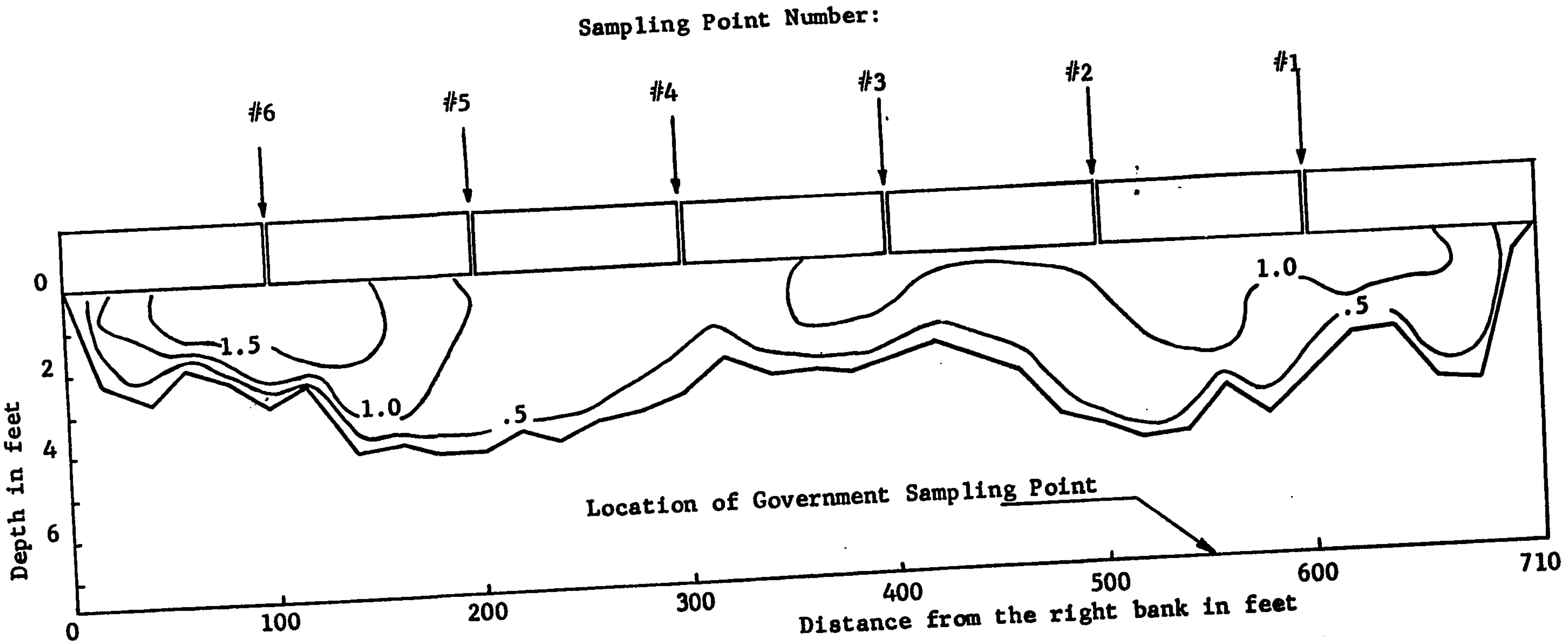

FIGURE 4 : River Cross-Section at Vinca Sampling Station Showing the Velocity Contours (ft/s).

sewer. The dye was released at 0:00 February 4th and measured in the cross-section 13 1/2 miles downstream between 11:30 A.M. and 3:40 P.M. on the same day. Time of travel as estimated in the previous studies was within the time range established by peak concentrations which arrived between 12:20 P.M. and 2:45 P.M. and were measured at six points across the river cross-section.

The actual sampling was carried out from six holes drilled through the ice. To ensure that the passing cloud of dye had arrived, a fluorometer was set for continuous operation on the hole where the strongest flow in the river was detected in previous measurements. Low air temperatures caused freezing of the pump supplying the fluorometer, but fortunately only after it had shown a sharp increase in concentration. The passage was then established from bottle samples taken at intervals of 10 to 15 minutes. The resulting curves are shown in Figures A1 to A6 of Appendix.

The second dye run was carried out between Edmonton and Fort Saskatchewan on Thursday, February 17th. 34.67 lbs. of 20% solution of Rhodamine W. T. was released at 10:20 A.M. just below the intake of Edmonton Water Treatment plant. The actual sampling took place on the following day between

10:30A.M. and 3:40 P.M. below Fort Saskatchewan Bridge from 4 holes in the ice. The time-concentration curve obtained (Figure 5) showed that the mixing from Edmonton to Fort Saskatchewan was sufficient to obtain a relatively uniform concentration across the river cross-section.

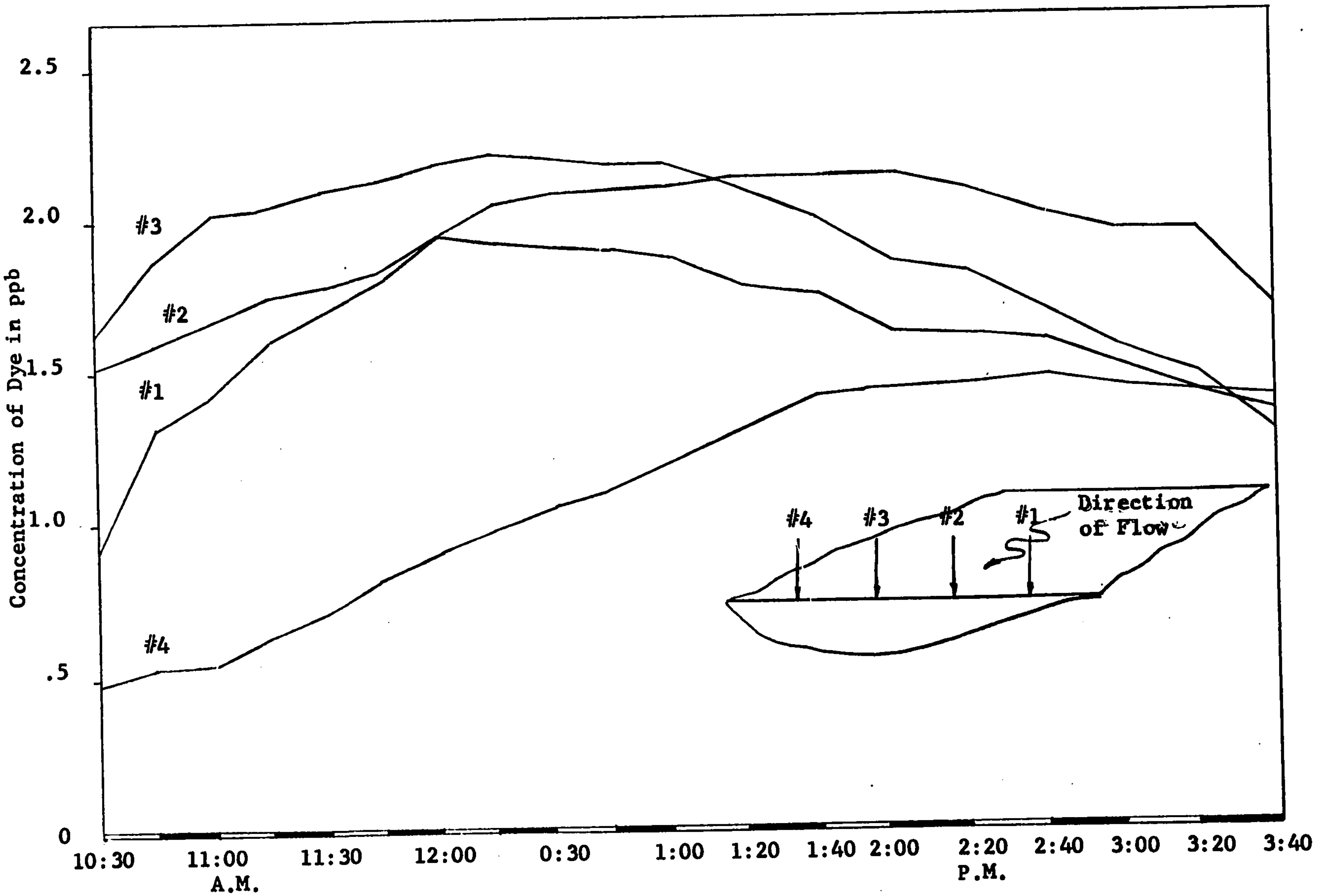

FIGURE 5 : Passage of Dye Cloud as Measured at Fort Saskatchewan (release of dye at Edmonton).

CHAPTER VI

APPLICATION OF ONE- AND THREE-DIMENSIONAL MODELS OF DISPERSION

1. One-Dimensional Model of Dispersion.

Equation (10) is the solution of the one-dimensional dispersion equation that satisfies all the necessary initial and boundary conditions required in the case of a natural stream. The concentrations for time-concentration curves were obtained from the first dye run, described in Chapter V, part 3. Using the dispersion coefficients determined in Chapter IV, an attempt has been made to calculate time concentration curves by equation (10). Since the one-dimensional model of dispersion applies only to mean concentrations in the cross-section, the mean concentrations had to be calculated for each time interval from our measured data and existing flow. This "dye" curve was then compared with the curves produced by the equation (10) using both dispersion coefficients. The data for all curves are shown in Table V and plotted in Figure 6.

It is apparent from Figure 6, that the calculated curve using the dispersion coefficient 7040.5 ft.^{2}/sec. (Chapter IV) is too flat as compared to the "dye" curve.

It suggests two important facts: 1) the dispersion coefficient used is too large, and 2) the one-dimensional dispersion model does not fit very well the situation where mixing within the cross-section is not uniform.

For the first possibility a coefficient based on Glover's formula (9) equation (13) has been used and the results obtained (shown also in the Table V and Figure 6) show closer resemblance with the "dye" curve.

Despite the fact that the expression used takes into account the detention of dye in dead zones, the tailing on the measured curve is much longer. Using the trial and error methods dispersion coefficient has been assumed D_L = 980 ft.^{2}/sec. The resulting curve, shown in Figure 6, gives the best approximation to the measured data.

This one-dimensional model, even if it produces a close approximation of the measured curve, is valid only for a cross-section a considerable distance downstream from the point of injection, where mixing is more uniform.

2. Three-Dimensional Model of Dispersion.

Equation (21) represents the solution of the three-dimensional dispersion equation. The same expression for the loss of dye as in the one-dimensional model has been

TABLE V

TIME-CONCENTRATION CURVES DATA INDICATING THE PASSAGE OF DYE AT VINCA

(BASED ON ONE-DIMENSIONAL MODEL OF DISPERSION)

Time	Concentrations			
	Measured	Calculated		
		D_L=7040.5 ft^2/s	D_L=230 ft^2/s	D_L=980 ft^2/s
hours	ppb	ppb	ppb	ppb
11:30	0.201	0.700	0.0279	0.310
11:40	0.261			
11:50	0.349	0.710	0.0785	0.396
12:00	0.404			
0:10	0.556	0.737	0.181	0.484
0:20	0.628			
0:30	0.678	0.745	0.328	0.566
0:40	0.691			
0:55	0.760	0.760	0.548	0.644
1:05	0.717	0.766	0.623	0.671
1:15	0.716			
1:30	0.732	0.741	0.732	0.732
1:40	0.721			
1:50	0.716	0.734	0.705	0.707
2:00	0.709			
2:15	0.717	0.712	0.572	0.681
2:25	0.687			
2:40	0.624	0.693	0.381	0.624

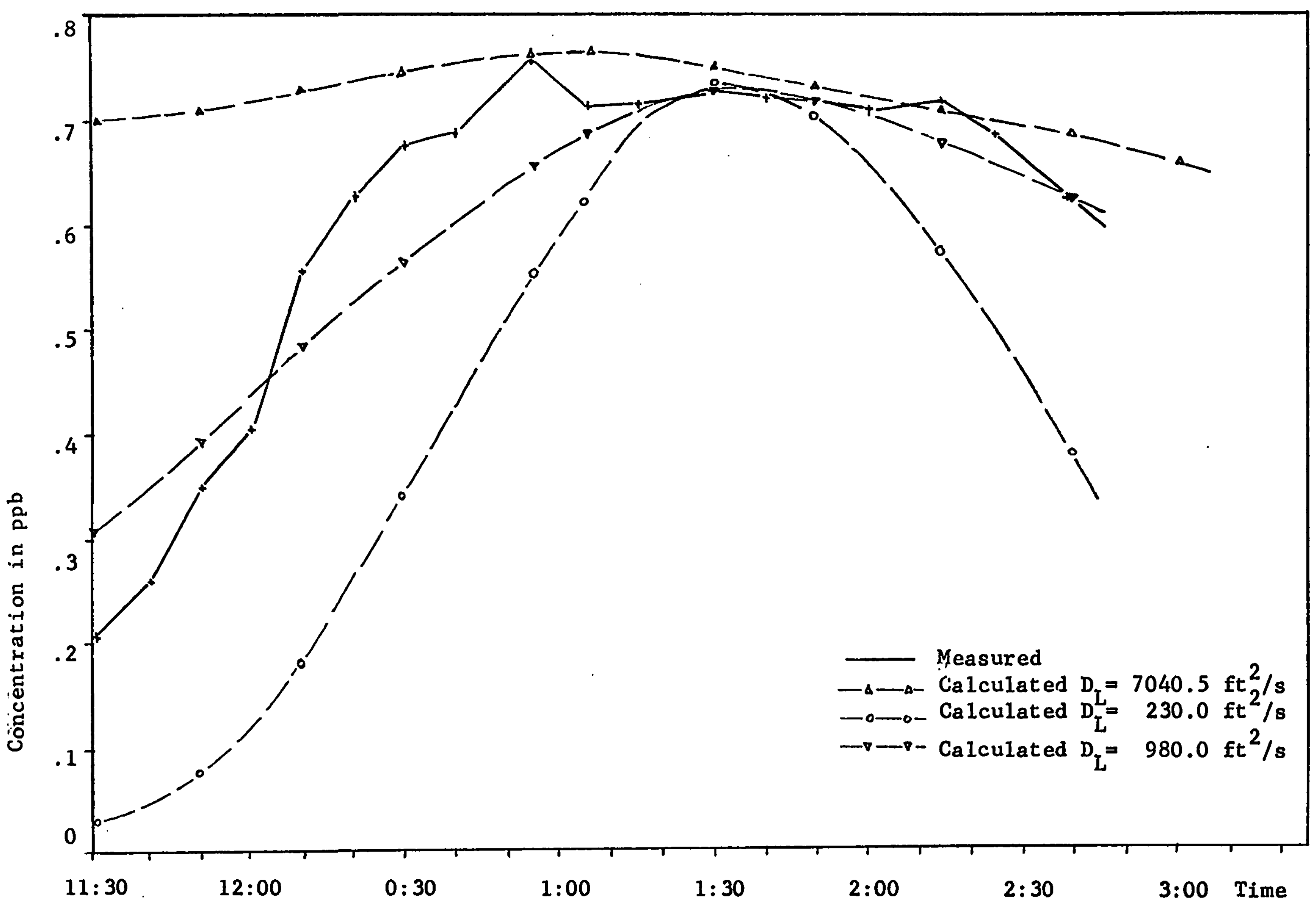

FIGURE 6 : Time-Concentration Curves Indicating Passage of Dye at Vinca (released at Fort Saskatchewan).

incorporated. It takes into account the loss of dye due to decay, adsorption and loss in lateral and vertical dead zones.

Near the point of injection the mixing of dye in y and z, or lateral and vertical directions, is not complete. This is also true in our case, even though our profile is located 13-1/2 miles downstream from the point of injection. The observed character of flow in this cross-section together with the measured time-concentration curves suggests that the centre of the axial system is 200 feet from the south bank. All the samples used for the time-concentration curve were taken from below the ice, close to the ice-water boundary, so the y z plane has been set also on this water level. The z dimension has therefore been considered to be 0 in the following calculations. The value of 1.62×10^{-5} has been assigned to the dispersion coefficient D_z in z direction as described in Chapter III, part 6. The time-concentration curves have then been calculated at the same locations as the measured ones. The spatial simulation of results obtained as shown in Figure 7 as compared with measured ones, Figure 8.

For better comparison the calculated vs measured time-concentration curves at appropriate locations are

TABLE VI

DYE CONCENTRATIONS AT VINCA RIVER CROSS-SECTION (ppb)

Time	Distance from right bank in feet											
	100		200		300		400		500		600	
	M	C	M	C	M	C	M	C	M	C	M	C
11:30	0.08	0.130	0.22	0.151	0.51	0.130	0.36	0.083	0.26	0.039	0.07	0.014
11:40	0.11		0.34		0.59		0.47		0.32		0.09	
11:50	0.12	0.321	0.53	0.372	0.84	0.321	0.63	0.207	0.40	0.099	0.09	0.035
12:00	0.17		0.76		0.98		0.80		0.55		0.09	
0:10	0.17	0.648	1.03	0.748	1.20	0.648	0.92	0.423	0.65	0.208	0.11	0.076
0:20	0.22		1.24		1.21		1.02		0.69		0.13	
0:30	0.32	0.984	1.38	1.130	1.27	0.984	0.95	0.648	0.69	0.325	0.13	0.123
0:40	0.39		1.43		-		0.83		0.69		0.15	
0:55	0.65	1.270	1.45	1.450	1.03	1.270	0.71	0.847	0.78	0.433	0.18	0.170
1:05	0.67	1.300	1.44	1.480	0.90	1.300	0.61	0.870	0.61	0.451	0.19	0.178
1:15	0.79		1.36		0.82		0.58		0.54		0.19	
1:30	0.99	1.140	1.25	1.300	0.69	1.140	0.53	0.777	0.52	0.410	0.20	0.165
1:40	1.07		1.13		0.81		0.44		0.44		0.18	
1:50	1.17	0.890	1.13	1.010	0.62	0.890	0.43	0.611	0.36	0.327	0.18	0.135
2:00	1.20		1.03		0.56		0.39		0.44		0.17	
2:15	1.39	0.511	1.02	0.578	0.49	0.511	0.35	0.355	0.28	0.193	0.14	0.082
2:25	1.26		0.89		0.45		0.31		0.24		0.14	
2:40	1.24	0.246	0.86	0.277	0.39	0.246	0.28	0.173	0.24	0.095	0.13	0.0415

M = measured

C = calculated

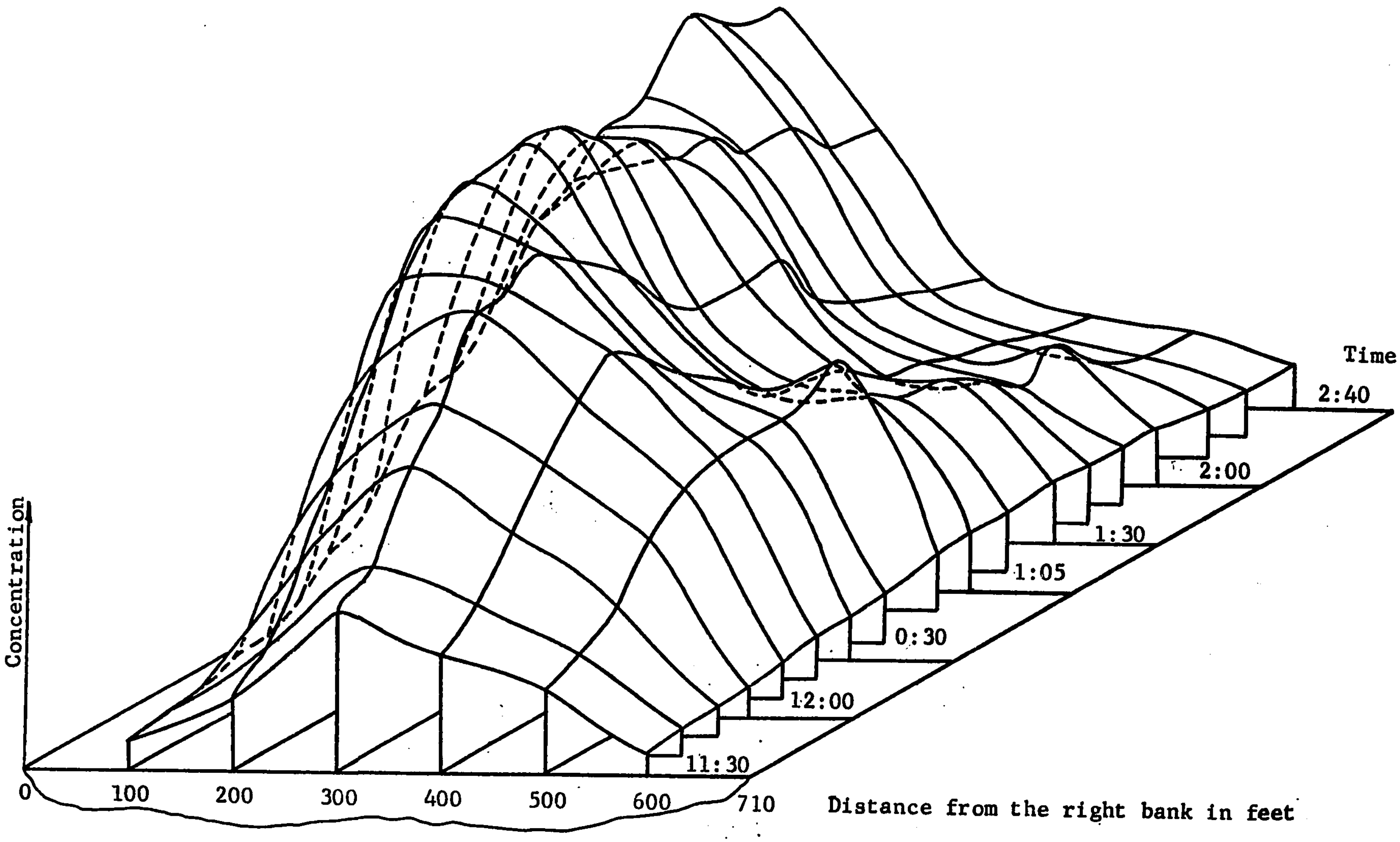

FIGURE 7 : Spatial Simulation of Dye Passage through the Cross-Section at Vinca. (as measured).

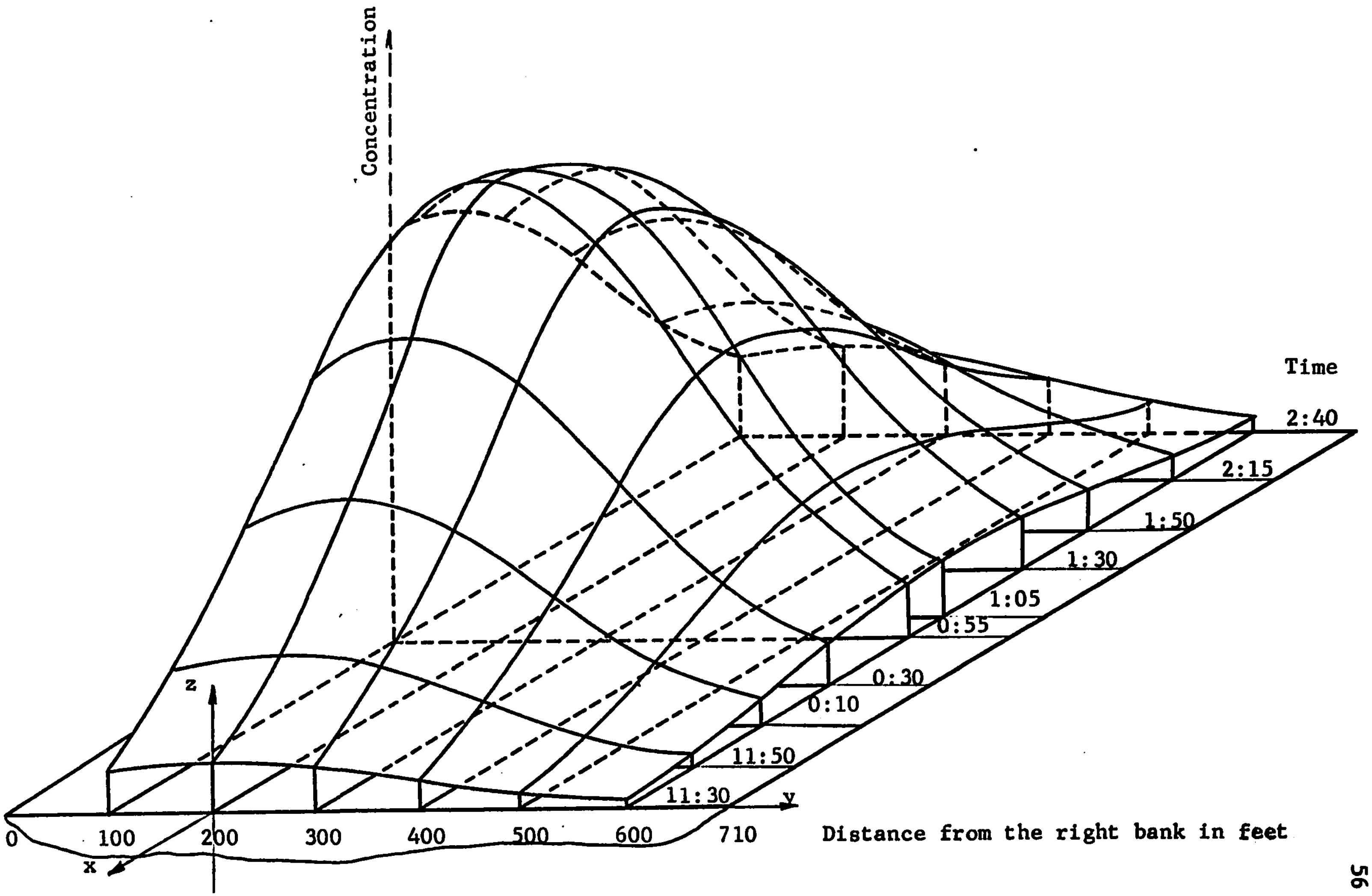

FIGURE 8 : Spatial Simulation of Dye Passage through the Cross-Section at Vinca (as calculated).

shown in Appendix A. Table VI shows the calculated results.

Again, as in case of the one-dimensional model, there is considerably larger tailing on the measured curve as compared with the calculated one. The peak values on both curves are approximately the same. For this case of a three-dimensional model of dispersion the longitudinal dispersion coefficient based on Glover's formula, equation (13), has been used.

CHAPTER VII

LABORATORY TESTS

1. Introduction.

During the winter period 1971-1972 an extensive sampling program was carried out both at Vinca and at Fort Saskatchewan in order to obtain information about waste levels in the river water. Series of samples were taken across the river to determine the variation in concentration.

Various tests were run on the samples obtained, but only a few indicated the suspected incomplete mixing at the Vinca Bridge sampling station. Results from samples taken at Fort Saskatchewan Bridge confirmed fairly good mixing of wastes from Edmonton. There was no significant variation in concentrations across the river at Fort Saskatchewan Bridge.

2. Laboratory Tests.

The study area is located in the vicinity of Edmonton and the effects of its industrial and domestic wastes on the river water quality are felt far downstream. Several tests were chosen to indicate the level of various pollutants from Edmonton and from some sources in Fort Saskatchewan.

The best results were obtained by determining chloride concentrations. Chlorides occur in natural waters in widely varying concentrations. In upland waters chloride content is usually quite low, riversand ground waters, however, show sometimes very high concentrations. In our case, since the North Saskatchewan River rises in the Rocky Mountains as a mountain stream as do its tributaries, it has a very low concentration of chlorides. As it descends into the plains and absorbs wastes from industries and municipalities, its chloride content rises, but the overall content of chlorides stays far below 250 mg/l, which is the recommended maximum level in a public water supply.

It has been estimated that average daily excretion of chlorides is about 6 g per person or about 2,760 kg/day from the City of Edmonton with its population of 460,000, which would cause an increase in the mean concentration of 0.5 mg/l. Industries also contribute to the total chloride content, so that another significant increase is found below outlet from Dow Chemicals' plant in Fort Saskatchewan. The Town of Fort Saskatchewan and Sherritt Gordon Mines' plant also contribute to the overall content of chlorides in the river in our study area, but their contribution is small in comparison with that of Dow Chemicals Ltd.

Another test applied in our study was for phosphates. Phosphates are added to the river via industrial waste discharges from plants using phosphates to control scaling in boilers, or via municipal waste discharges, where they occur as result of human metabolic breakdown of proteins or from household detergents. They occur as orthophosphates and polyphosphates, the latter being slowly transformed to orthophosphates. The speed of this transformation is greatly influenced by temperature.

An indicator related to the concentration of organic matter is the dissolved oxygen level, therefore the test for dissolved oxygen was chosen as another means to determine distribution in the river cross-sections.

Bacterial fauna in the process of decomposition uses oxygen from the water and the oxygen deficiency at any point is then a measure of the amount of organic matter previously decomposed in the stream. The ice cover, which prevents reoxygenation, favors this method.

A similar test, but one that gives more accurate results, is the test for total carbon (TC) and total organic carbon (TOC). This test was run by Federal Department of Health laboratory.

CHAPTER VIII

CONCLUSIONS AND RECOMMENDATIONS

1. General Conclusion.

The goal of this study, as formulated in the first chapter, has been achieved. There are, however, several points which need to be refined and further verified, but in the short time period of ice cover on the river, further reduced by bad weather conditions, it was not possible to accomplish them by existing means. It is assumed that further studies will be carried out on the river, either by the University of Alberta, Department of Civil Engineering, or by the Government of Alberta, Department of Environment and that this study will be of some help in this continuing program. Also the applicability, which is presently limited to low winter flow and perhaps only to this year's ice formation, will be extended.

2. Determination of the Dispersion Coefficient.

There are several methods used in this determination, but the one used in this study was expected to give the most precise solution. Even though real care was excercised during the field measurements, the dispersion coefficient obtained was not suitable for our situation. The coefficient based on Glover's formula, however, seems to give more reasonable results, but the best approximation of the measured data provides the coefficient D_L = 980 ft.^{2}/s, which was determined by trial and error method. Should there be any future study an attempt should be made to verify this coefficient for different flow conditions and possibly for various stretches of the river.

3. Concentration Distribution in the River Cross-Section at Vinca.

As is shown in Chapter VII, the best results, as far as the concentration distribution over the river cross-section at Vinca is concerned, are given by the test for chlorides. These results, as shown in Appendix C, indicate the highest concentration levels on the right side of the river. The data measured and calculated for the dye tracer run indicate that the ratio of peak concentrations at various sampling points within the cross-section to the amount measured at the approximate position of Government sampling point is as follows:

Ratios $\frac{C_n}{C}$ for dye released at Fort Saskatchewan (right bank) and measured at Vinca are given in the following table.

Distance from the right bank in feet:

	100	200	300	400	500	550	600	Mean
Measured	2.80	3.22	2.82	2.27	1.54	1.00	0.44	1.63
Calculated	4.56	5.21	4.56	3.04	1.55	1.00	0.61	1.84

C_n = concentration of the dye at the point n

C = concentration at the Government sampling point

n = distance from the right bank in feet

Looking at the plotted measured and calculated peak concentrations, Figure 9, we can see a very close resemblance, which is in contrast with the above tabulated data. The difference between corresponding measured and calculated values is very large because those ratios are based on concentrations (measured and calculated) at the point of Government sampling, where, unfortunately the difference between measured and calculated values is largest. The ratio of mean concentration to the base value is of special importance, since it can be used to approximate the mean concentration in the profile on the basis of the usual sample.

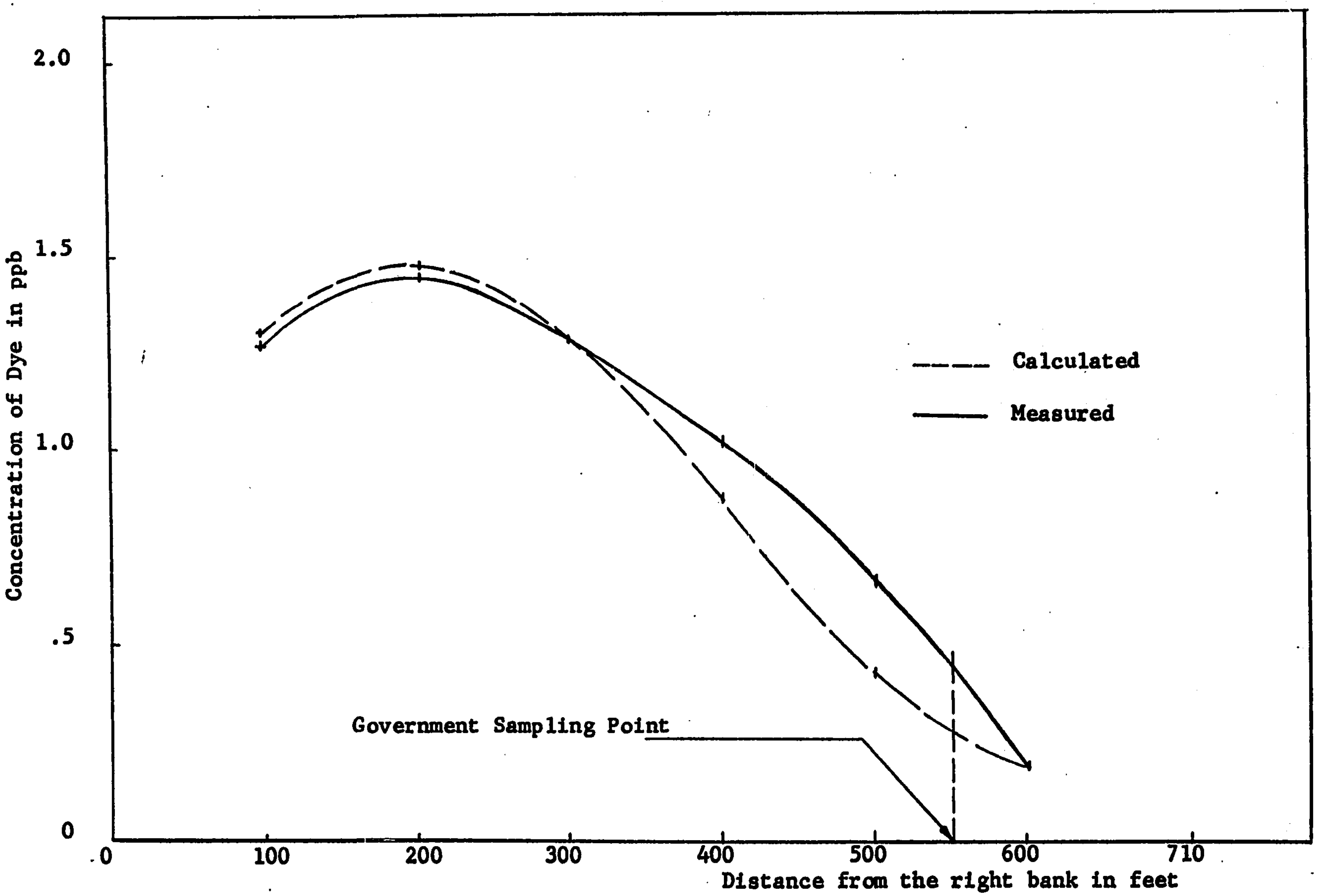

FIGURE 9 : Distribution of Peak Concentrations of Dye (released at Fort Saskatchewan) within the Cross-Section at Vinca.

4. Relation Between Values Obtained at the Government of Alberta, Department of Environment Sampling Point and Mean Concentration in the River.

For dye applications the ratio of values measured at the government sampling point to various concentrations in the cross-section, as well as mean concentration, is given in the table in the previous paragraph of this chapter. One must take into account many other factors to make practical use of those values. The approximate application to pollutants is possible only for chloride concentrations, and only after the mean concentration in the river above Fort Saskatchewan has been determined. Another important fact influencing the accuracy of this method is the discharge from Fort Saskatchewan lagoons and Sherritt Gordon plant.

The use for other pollutants remains virtually impossible mainly for two reasons: 1) The main source of incompletely mixed chlorides is Dow Chemicals, whereas sources of other pollutants might be as far upstream as Edmonton or further and their mixing is much more complete. 2) The level of their concentrations is too small for practical work.

5. Practical Application of Dye Study Data.

The two dye tracer runs as described earlier provide valuable information about the degree of mixing in two river cross-sections. The three-dimensional model of dispersion used to calculate concentrations throughout the cross-section could be also used to calculate amount of dye or pollutants released at Dow Chemicals. An attempt has been made to verify this calculations, but it appeared to be extremely difficult to estimate how much of the total amount of chlorides present is being brought by the river upstream. Because of continuous discharges of wastes a much simpler mixing equation can be used to serve the same purpose. Assuming that the concentration of pollutant remains constant throughout the day:

$$Q\,\bar{c} = q_1c_1 + q_2c_2 + q_3c_3 + \ldots\ldots + q_nc_n \qquad (27)$$

where

Q = river discharge

$\bar{c}$ = mean concentration in the river

q_1 = discharge of tributaries

c_1 = concentration of tributaries

Available data from our own and government tests were used to show an example calculation of concentration for the discharge from Dow Chemicals. Unfortunately available data did not quite correspond and effluent concentration from Fort Saskatchewan lagoons was not available and had to be estimated. The calculated value of 5550 mg/l could be considered to be in the same range as the measured concentration of 6250 mg/l obtained by government two days earlier.

6. Recommendations.

Bad weather and short time period did not allow more data to be obtained, which would provide a firmer basis for the conclusion. This fact itself suggests further verification of dispersion equation application and more detailed determination of the dispersion coefficient should be done for various discharges and flow conditions on the river. Further study of discharges and their concentrations is necessary in order to have a better picture of the overall pollution situation, which is now largely based on one or two grab samples analysis per month.

The government sampling station, which takes samples about 150 feet from the left bank at Vinca, should make use of the above mentioned coefficients in order to obtain mean concentrations in the river. The flow and dispersion patterms should be examined from time to time in order to update the information concerning the concentration distribution, which is valid only for winter flows and most probably this year's ice formation.

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APPENDIX A

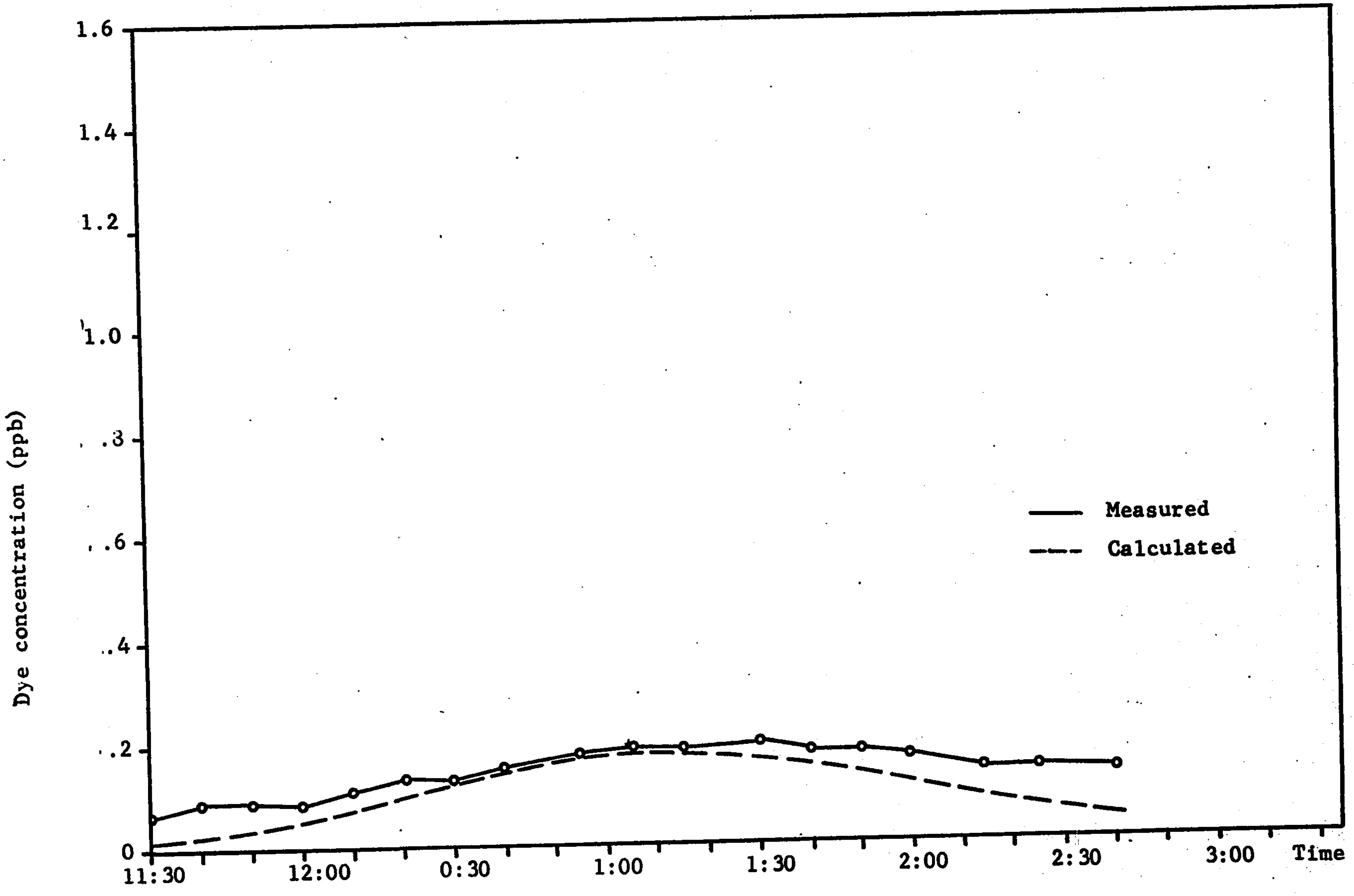

FIGURE A1 : Time-Concentration Curve for Sampling Point #1 in the Cross-Section at Vinca. (Dye Released at Fort Saskatchewan.)

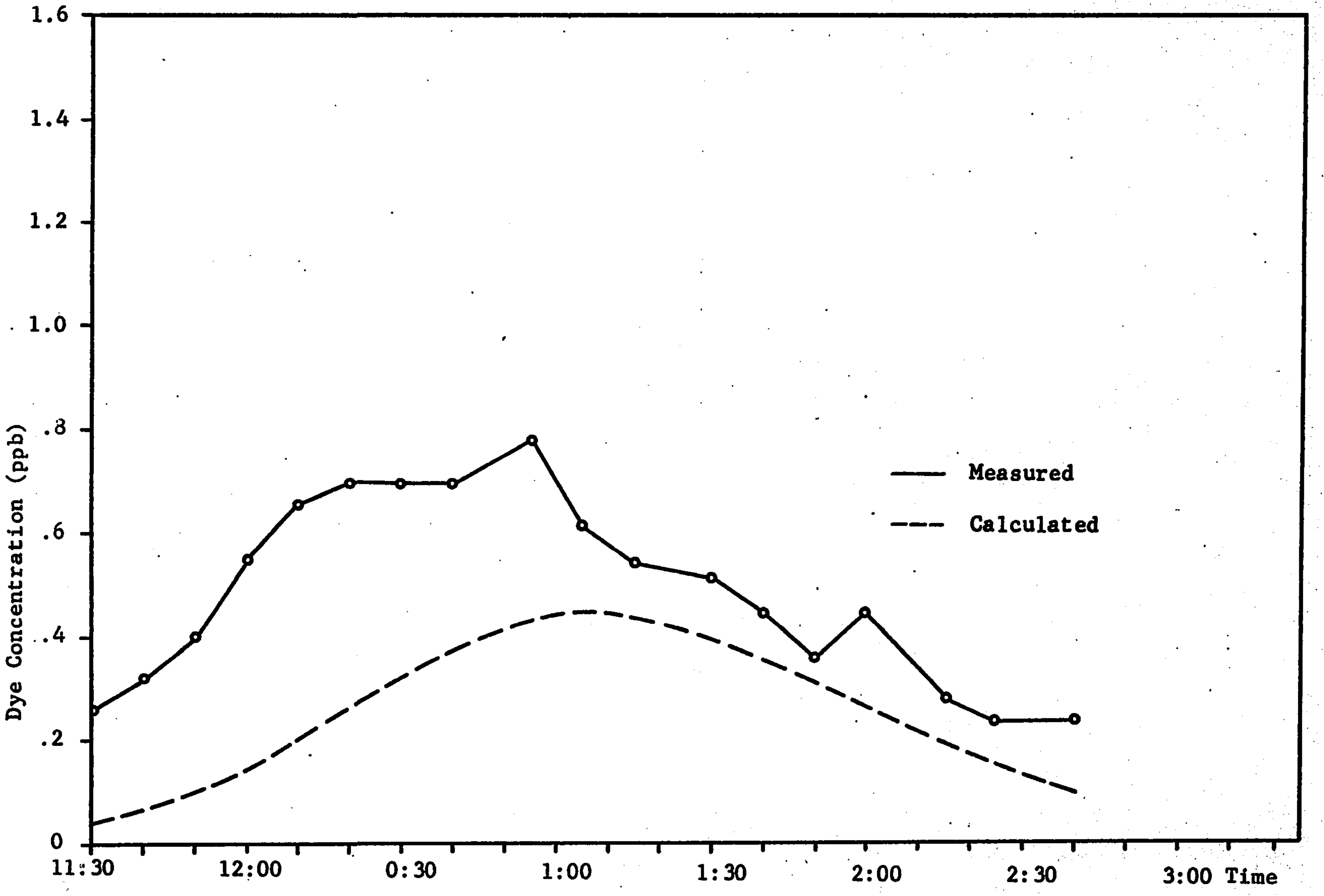

FIGURE A2 : Time-Concentration Curve for Sampling Point #2 in the Cross-section at Vinca.
(Dye Released at Fort Saskatchewan.)

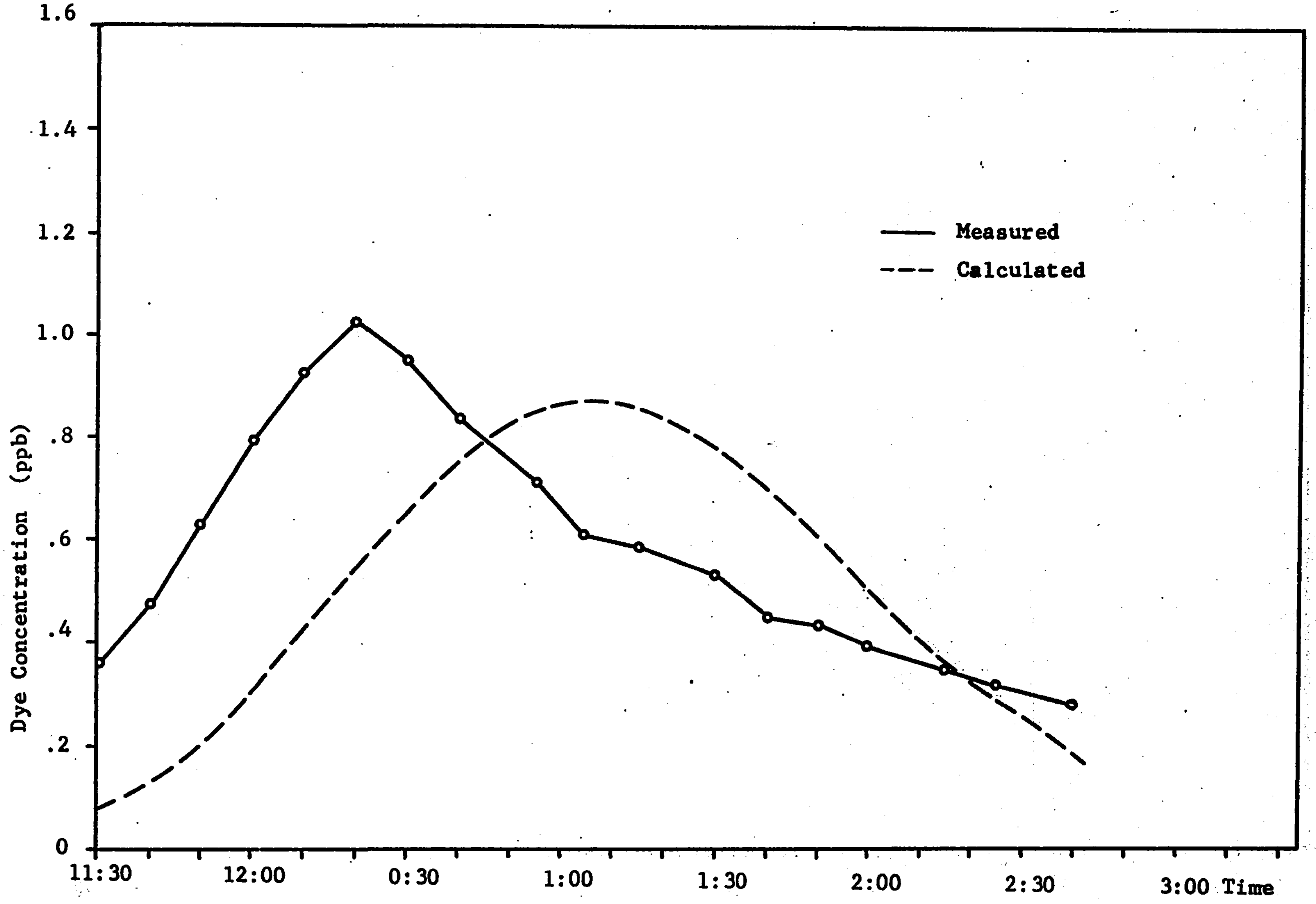

FIGURE A3 : Time-Concentration Curve for Sampling Point #3 in the Cross-Section at Vinca.
(Dye Released at Fort Saskatchewan.)

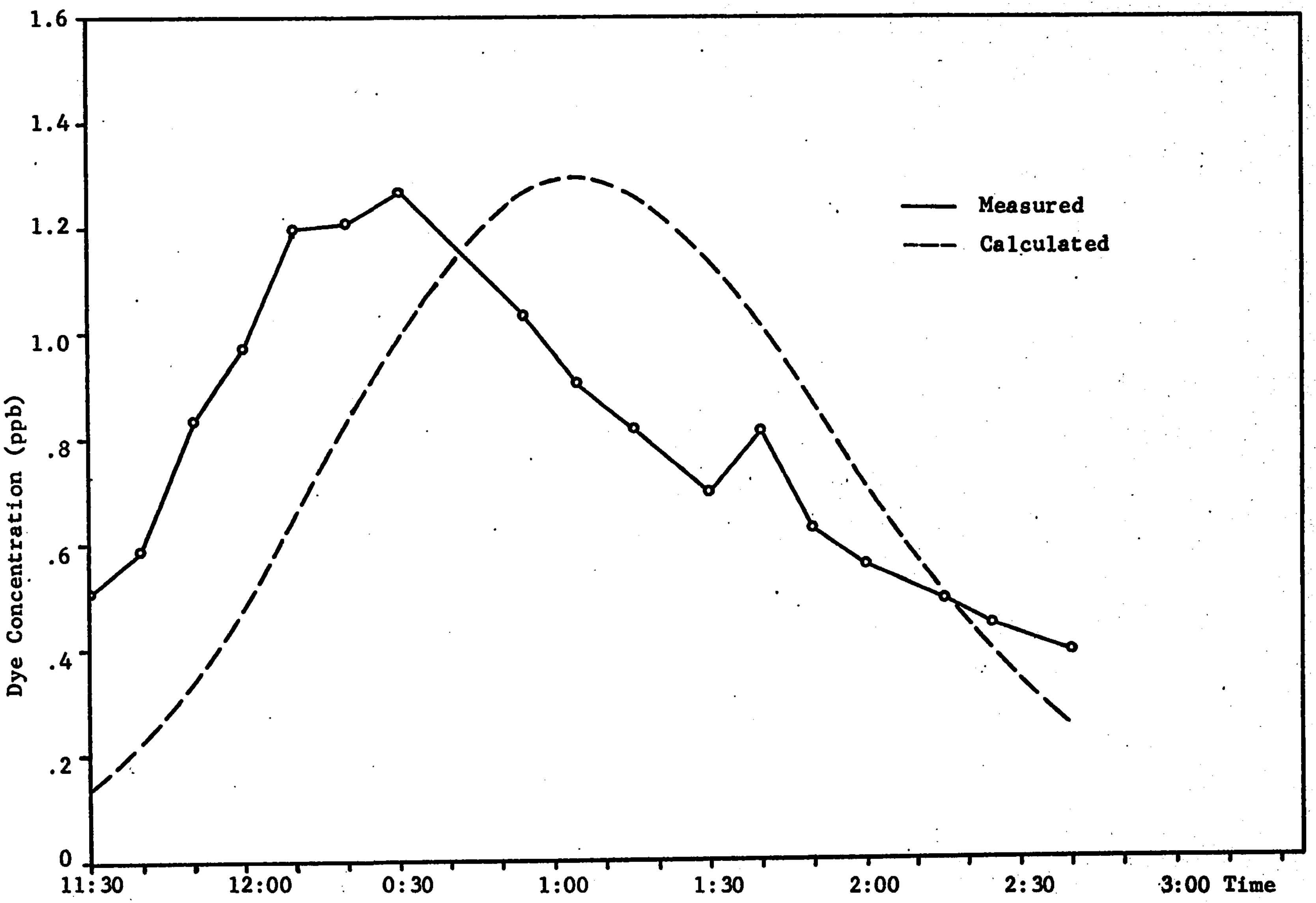

FIGURE A4 : Time-Concentration Curve for Sampling Point #4 in the Cross-Section at Vinca. (Dye Released at Fort Saskatchewan.)

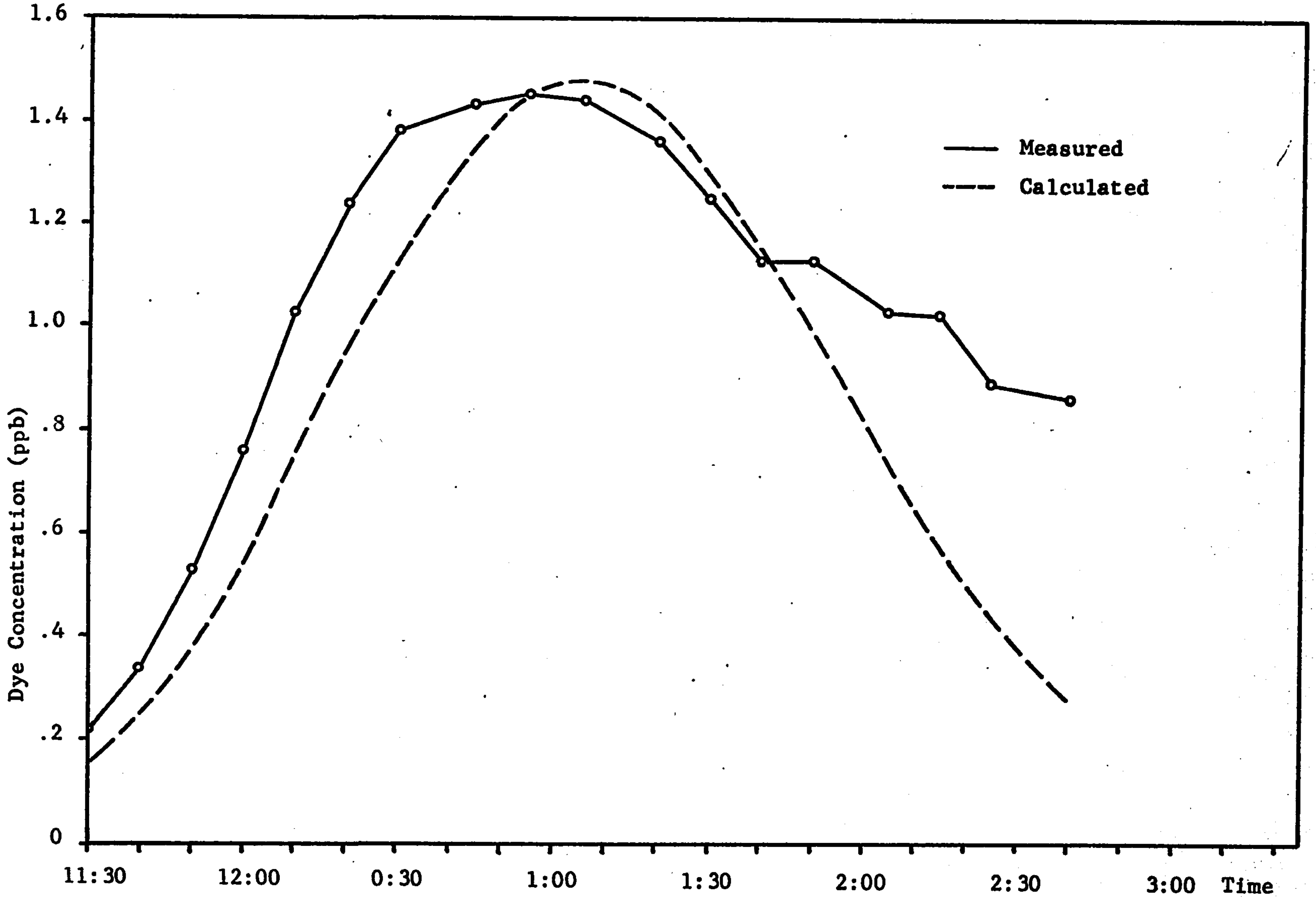

FIGURE A5 : Time-Concentration Curve for Sampling Point #5 in the Cross-Section at Vinca.
(Dye Released at Fort Saskatchewan.)

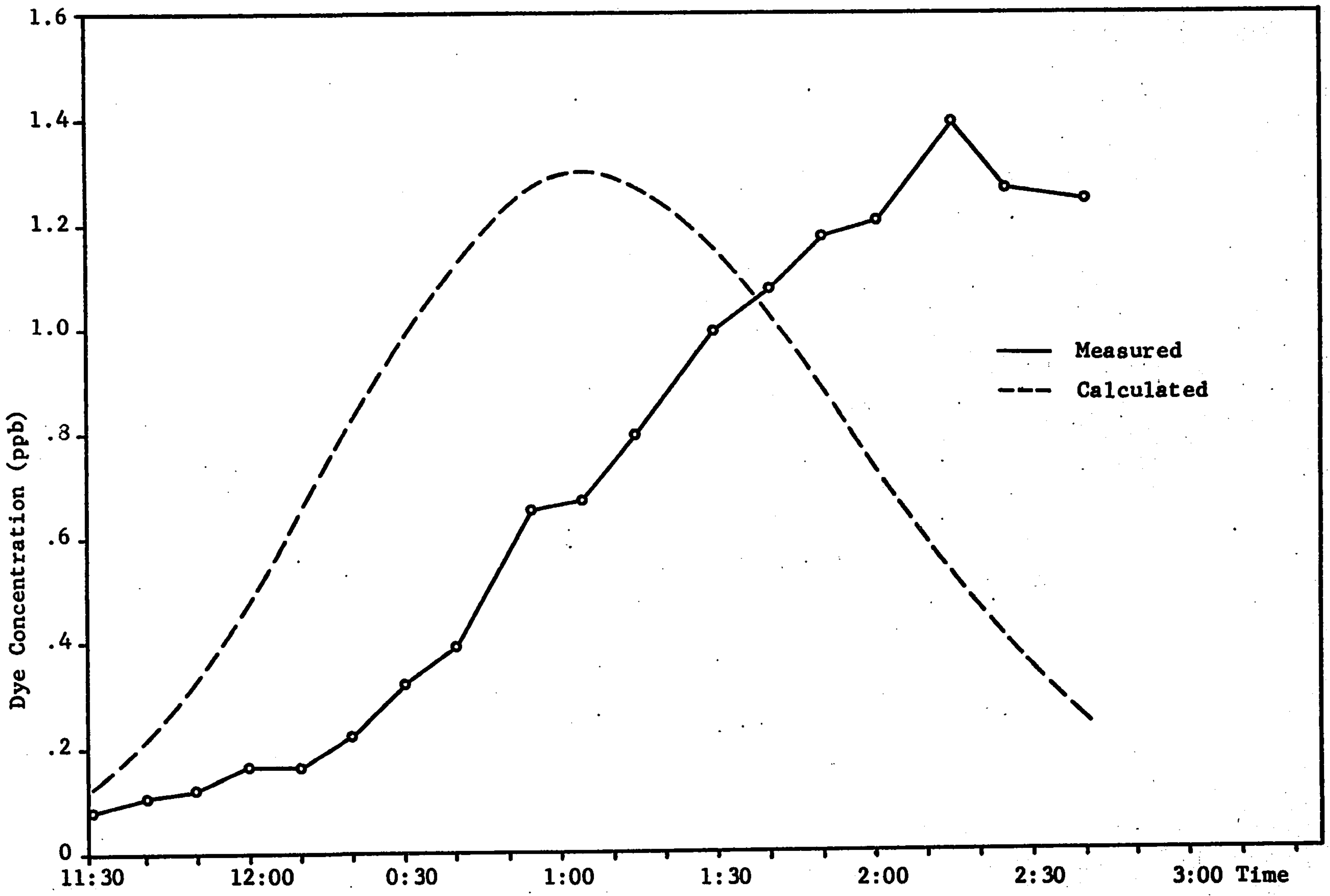

FIGURE A6 : Time-Concentration Curve for Sampling Point #6 in the Cross-Section at Vinca. (Dye Released at Fort Saskatchewan.)

APPENDIX B

TABLE B1

DISPERSION COEFFICIENT CALCULATION

Vertical slice No.	Distance from left bank to start of slice	Depth at left side of slice d_i (less ice)	Area of slice	Mean velocity u_i	Discharge through the slice Q_i	Relative velocity $u_i' = u_i - \bar{V}$	Cummulative relative discharge through the slice, relative to u_i' $q_i \Delta_z$	$\sum_{j=2}^{k} \frac{\Delta_z}{E_{z_j} d_j} \sum_{i=1}^{j-1} q_i' \Delta_{z_i}$	$\sum_{k=2}^{n} q_k' \Delta_z$ (column 9)
1	2	3	4	5	6	7	8	9	10
	Ft	Ft	Ft^2	Ft/Sec	Ft^3/Sec	Ft/Sec	Ft^3/Sec	Ft	Ft^4/Sec
1	0	0	1.5	0.30	0.45	-0.655	-0.98	-3180.0	+3 120
2	10	0.3	39.0	1.00	25.40	+0.045	+0.77	-2835.0	-960
3	30	3.6	71.0	0.85	66.00	-0.105	-7.10	-6215.0	+47 940
4	50	3.5	57.0	0.98	52.20	+0.020	-5.96	-6930.0	+40 040
5	70	2.2	45.0	1.07	46.20	+0.110	-1.01	-7041.0	+5 140
6	90	2.3	54.0	1.00	56.00	+0.040	+1.15	-6981.7	-9 960
7	110	3.1	73.0	0.85	67.50	-0.100	-6.15	-7185.7	+43 140
8	130	4.2	76.0	1.08	74.00	+0.120	+2.97	-7036.7	-21 060
9	150	3.4	79.0	0.89	78.00	-0.070	-2.56	-7110.4	+18 240
10	170	4.5	92.0	0.99	86.50	+0.03	+0.20	-7105.1	-1 360
11	190	4.7	90.0	0.90	85.00	-0.06	-5.20	-7269.1	+37 940
12	210	4.3	83.0	0.75	68.50	-0.21	-22.60	-8092.1	+178 940
13	230	4.0	69.0	0.56	45.50	-0.40	-50.20	-11592.1	+498 440
14	250	2.9	54.0	0.73	35.00	-0.23	-62.60	-17412.1	+714 440
15	270	2.5	46.0	0.65	32.00	-0.31	-76.90	-27562.1	+1 107 440
16	290	2.1	45.0	1.01	37.50	+0.05	-74.65	-35180.1	+1 028 340
17	310	2.4	51.0	1.05	52.50	+0.09	-70.06	-40770.1	+841 340
18	330	2.7	53.0	1.02	55.00	+0.06	-66.88	-46545.1	+693 340
19	350	2.6	53.0	0.75	46.50	-0.21	-77.98	-52755.1	+1 278 340
20	370	2.7	50.0	0.95	42.50	-0.01	-78.48	-61395.1	+1 309 037
21	390	2.3	54.0	0.39	34.00	-0.57	-109.28	-67965.1	+3 399 037
22	410	3.1	66.0	042	27.40	-0.54	-144.88	-74865.1	+6 069 037
23	430	3.5	71.0	0.58	35.50	-0.38	-171.88	-82565.1	+8 299 037
24	450	3.6	77.0	0.64	47.00	-0.32	-196.58	-89365.1	+10 409 037
25	470	4.1	80.0	0.90	62.00	-0.06	-201.38	-97055.1	+10 878 037
26	490	3.9	81.0	0.95	75.00	-0.01	-202.19	-103755.1	+10 962 037
27	510	4.2	84.0	1.02	82.00	+0.06	-197.15	-110275.1	+10 406 037
28	530	4.2	82.0	1.09	87.00	+0.13	-186.45	-117065.1	+9 153 037
29	550	4.0	82.0	1.53	107.50	+0.57	-139.75	-121695.1	+3 483 037
30	570	4.2	67.0	1.78	111.00	+0.82	-84.75	-129570.1	-3 646 963
31	590	2.5	55.0	1.53	91.00	+0.57	-53.35	-133015.1	-7 826 963
32	610	3.0	53.0	1.48	80.50	+0.52	-25.75	-135850.1	-11 576 963
33	630	2.3	42.0	1.70	67.00	+0.74	+5.35	-134984.1	-15 776 963
34	650	1.9	47.0	1.07	65.40	+0.11	+10.52	-134202.1	-16 470 963
35	670	2.8	51.0	1.05	54.00	+0.09	+15.11	-132541.1	-17 078 963
36	690	2.3	16.5	0.20	10.50	-0.76	+2.61	-131006.1	-15 439 963
37	700	1.0	3.0	0.10	0.30	-0.86	+00.03		
38	710	0	F= 2193.0		Q= 2089.35				

$R = \frac{F}{0} = \frac{2193}{1410} = 1.56$ ft

$E_{z_i} = 0.23\ d_i\ U^*$

$\bar{v} = \frac{208.94}{2193.0} = 0.955$ ft/sec

$U^* = \sqrt{g \times R \times S_c} = 0.149$ ft/sec

$D_L = \frac{-\Sigma \text{ col. } 10}{F} = \frac{+15439963}{2193} = 7040.5\ ft^2/sec$

APPENDIX C

CHEMICAL LABORATORY METHODS APPLIED

1. Test for Chlorides.

Chlorides in water may be detected by means of volumetric procedures. In this case the Mohr method employing silver nitrate as a titrant and potassium chromate as indicator was used.

As recommended in "Standard Methods" (18) 0.0141 N solution of silver nitrate was used. This normality of silver nitrate solution was chosen so that each milliliter is equivalent to 0.5 mg. of chloride ion. In the titration the chloride ion is precipitated as white silver chloride

$$Ag^{+} + Cl^{-} = \underline{AgCl}$$

To detect the endpoint an indicator must be present to demonstrate the excess of Ag^{+} ion. In our case potassium chromate was used as an indicator. As the concentration of chloride ion approaches extinction, the silver ion together with chromate ion begins to form a reddish brown precipitate of silver chromate.

$$2Ag^{+} + CrO_4^{--} = Ag_2CrO_4$$

Presence of this precipitate is evidence that all the chloride has been precipitated. Since an excess of silver ion is needed to produce a visible amount of silver chromate, the indicator error or blank must be determined and subtracted from all titrations.

If the silver nitrate solution used for titration is exactly 0.0141 N, the calculation for chlorides is then:

$$Cl^{-}(\text{in mg/l}) = \frac{(\text{ml } AgNO_3 - \text{blank}) \times 0.5 \times 1000}{\text{ml sample}}$$

2. Test for Phosphates.

Phosphorus compounds occur in several varieties, the most common are:

orthophosphates	- trisodium phosphate	Na_3PO_4
	- disodium phosphate	Na_2HPO_4
	- monosodium phosphate	NaH_2PO_4
	- diammonium phosphate	$(NH_4)_2HPO_4$
polyphosphates	- sodium hexametaphosphate	$Na_3(PO_3)_6$
	- sodium tripolyphosphate	$Na_5P_3O_{10}$
	- tetrasodium pyrophosphate	$Na_4P_2O_7$

All the polyphosphates gradually hydrolyze in aqueous solution and revert to the ortho form. The rate of reversion is a function of temperature and increases rapidly as the temperature approaches the boiling point. The rate is also increased by lowering the pH. Advantage is taken of both facts in determination of total phosphate concentration. In our study the same method was used to determine orthophosphates and total phosphates. Polyphosphates were calculated as a difference between those two concentrations.

The same colorimetric method was employed for both and the only difference was the pretreatment of samples for total phosphates by boiling for ninety minutes. By boiling the sample the polyphosphates are converted to orthophosphates and as such they are measured.

The stannous chloride method as described in 'Standard Methods' is based upon the fact that the phosphate ion combines with ammonium molybdate under acid conditions and forms a complex compound known as ammonium phosphomolybdate.

$$PO_4^{---} + 12(NH_4)_2MoO_4 + 24H^+ = (NH_4)_3PO_4 \cdot 12MoO_3 + 21NH_4^+ + 12H_2O$$

The molybdenum contained in ammonium phosphomolybdate is readily reduced to produce a blue colored sol that is proportional to the amount of phosphate present. Excess ammonium molybdate is not reduced and therefore does not interfere. As a reducing agent stannous chloride solution in glycerol was used because of certain advantages it has over other reducing agents.

$$(NH_4)_3PO_4 \cdot 12MoO_3 + Sn^{++} = \text{(molybdenum blue)} + Sn^{4+}$$

After 10 minutes of color developing its intensity was measured on spectrophotometer and calibration curve was then used to relate light transmission to actual concentrations.

3. Test for Dissolved Oxygen.

The Winkler method was used to determine dissolved oxygen levels in our samples. This method uses manganese sulphate ($MnSO_4$) and the alkali-iodine reagent (NaOH + KI). The oxygen present in sample oxidizes the manganese ion Mn^{2+} to a higher valence and manganese oxide then precipitates as a brown flocculant substance. This part is so called fixation of oxygen.

$$Mn^{++} + 2OH^{-} + \frac{1}{2}O_2 = MnO_2 + H_2O$$

The floc is allowed to settle and then concentrated sulfuric acid is added. Under resulting low pH conditions MnO_2 oxidizes I^- to produce I_2.

$$MnO_2 + 2I^{-} + 4H^{+} = Mn^{++} + I_2 + 2H_2O$$

The iodine in the sample is then titrated with 0.025 N sodium thiosulfate. Amount of titrated iodine is equivalent to the amount of oxygen that was present in the water.

$$4Na_2S_2O_3 + 2I_2 = 2Na_2S_4O_6 + 4NaI$$

Starch is used as an indicator for this titration. Added starch produces blue color which gradually disappears when all iodine is titrated.

4. <u>Biochemical Oxygen Demand Test.</u>

Biochemical oxygen demand (BOD) is usually defined as the amount of oxygen required by the bacteria while stabilizing decomposable organic matter under aerobic conditions. The BOD test is widely used to determine the pollutional strength of domestic and industrial wastes in terms of the oxygen that they will require if discharged into natural stream. By its use it is possible to determine the degree of pollution in stream at any time.

The BOD test may be considered as a wet oxidation procedure in which the living organisms serve as the medium for oxidation of the organic matter to carbon dioxide and water. A number of the organisms responsible for the stabilization of organic matter in natural waters are forms native to soil. Theoretically an infinite time is required for complete biological oxidation of organic matter, but for all practical purposes, the reaction may be considered complete in 20 days. However, a 20 day period is too long to wait for results in most instances. It has been found that a reasonably large percentage of the total BOD is exerted in 5 days, consequently the test has been developed on the basis of a 5 day incubation period. It should be remembered, therefore, that 5 day BOD values represent only a portion of the total BOD, usually 70 to 80%.

The BOD test is based upon determinations of dissolved oxygen levels. Samples whose BOD does not exceed 7 mg/l, do not require dilution, if they initially contain sufficient dissolved oxygen. The procedure for this type of sample is very simple. There are two or more samples taken for the test. The first is analyzed for dissolved oxygen immediately, the second is analyzed after incubation for 5 days at 20 degrees C. The 5 day BOD is then determined by subtraction of residual dissolved oxygen from the initial value.

5. Laboratory Tests Results.

All results of laboratory tests of water samples from the North Saskatchewan River taken at Vinca Bridge and Fort Saskatchewan Bridge are shown in Appendix C. The difference in chlorides in the river cross-section at Vinca is the best indication of the mixing occurring between Fort Saskatchewan and Vinca. The other tests as indicated by phosophates also confirm incomplete mixing, but because of their relatively low concentrations the uneven distribution throughout the river cross-section is far less apparent. Similar results are for the Total Carbon (TC), Dissolved Oxygen (DO), and Biochemical Oxygen Demand (BOD) tests.

Laboratory test results from samples taken at Fort Saskatchewan Bridge show quite good mixing. There is no significant difference between the values of phosphates at Vinca and Fort Saskatchewan. Small difference in the DO and BOD tests confirm DO utilization in the reach, which stays closed for the whole winter period with no reaeration possible.

All laboratory test results are tabulated and together with corresponding diagrams in the appendix, part C.

TABLE C1

CHLORIDES CONCENTRATIONS AT FORT SASKATCHEWAN (mg/l)

Date	Distance from the right bank in feet			
	100	200	300	400
03/10/71	2.0	1.0	1.0	1.5
18/10/71	1.5	1.5	1.5	1.0
29/10/71	4.5	-	-	-
10/11/71	4.5	4.5	4.5	-
26/11/71	3.0	2.5	3.0	3.0
16/12/71	4.5	5.0	5.0	4.5
10/03/72	5.5	3.0	2.0	2.0

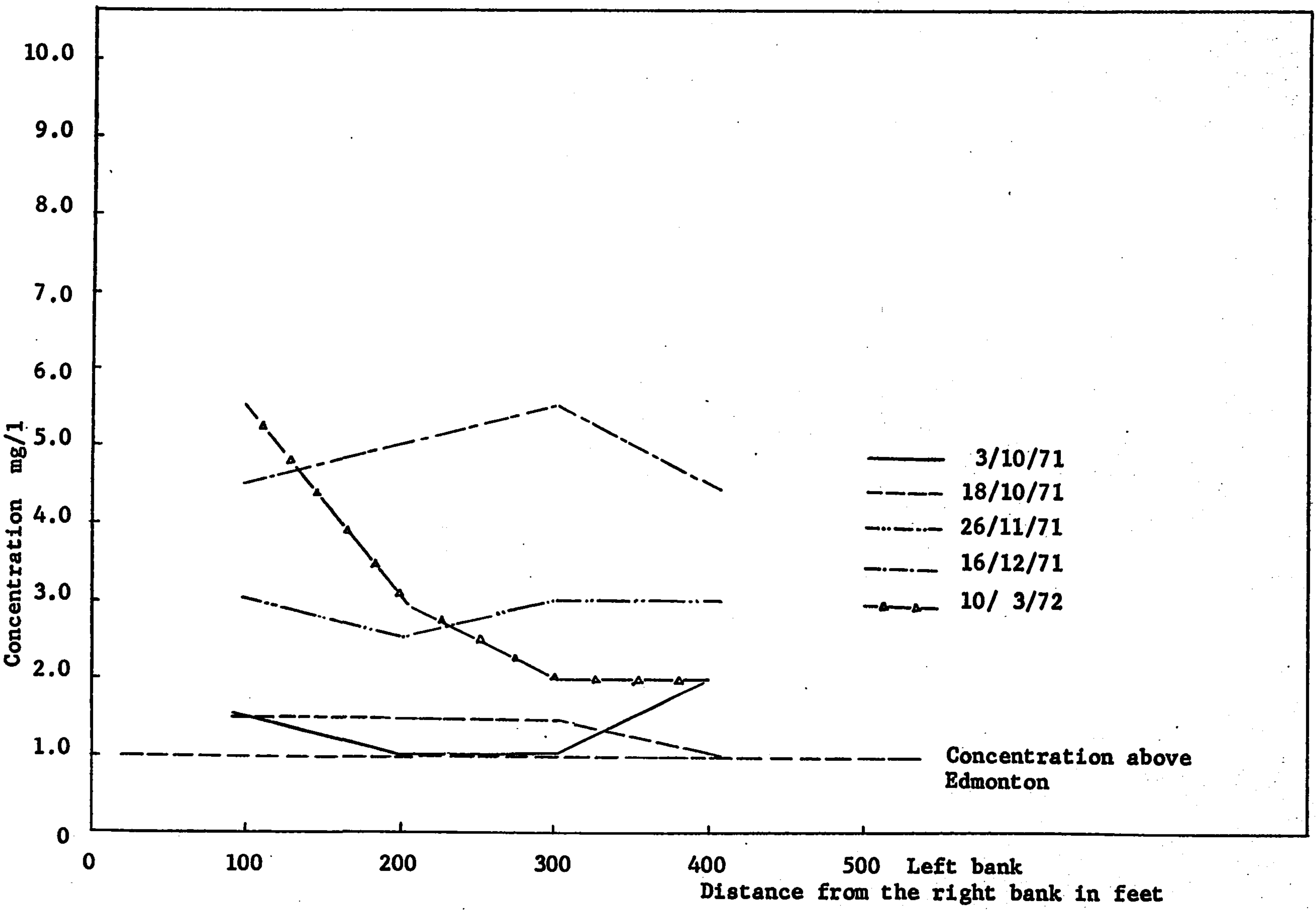

FIGURE C1 : Concentration Distribution of Chlorides in the Cross-Section at Fort Saskatchewan.

TABLE C2

CHLORIDES CONCENTRATIONS AT VINCA (mg/l)

Date	Distance from the right bank in feet				
	100	200	300	400	550
28/09/71	9.5	7.0	4.0	1.5	0.5
03/10/71	5.5	3.5	2.0	1.5	0.0
18/10/71	8.5	4.5	2.5	2.5	1.0
29/10/71	17.8	14.0	10.0	7.0	6.5
10/11/71	-	10.5	-	-	-
26/11/71	7.0	6.0	6.0	6.0	5.0
16/12/71	11.5	9.0	8.0	7.0	6.0
05/02/72	16.5	12.0	8.0	6.0	5.8
10/03/72	31.0	23.0	18.0	12.5	8.0

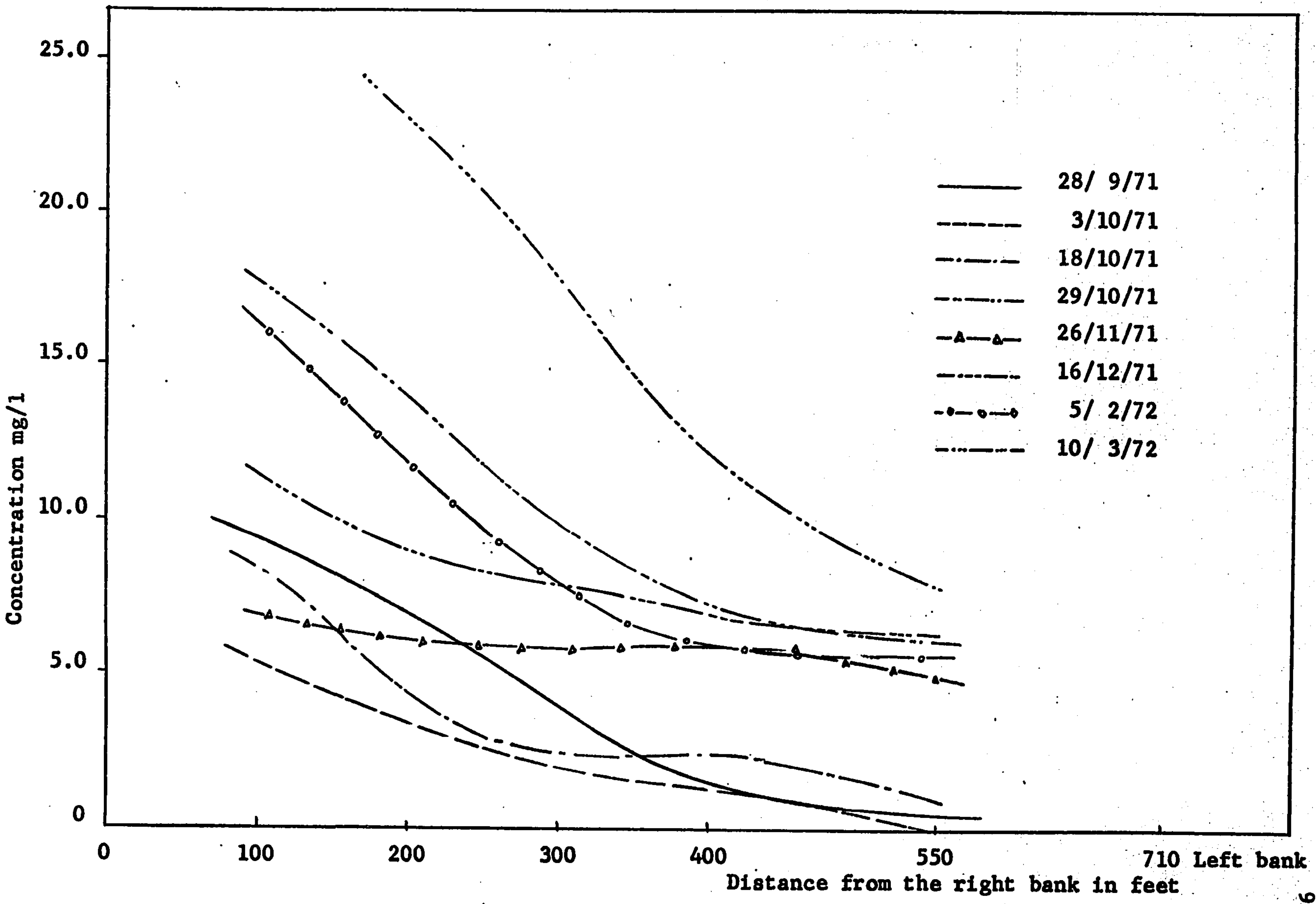

FIGURE C2 : Concentration Distribution of Chlorides in the Cross-section at Vinca.

TABLE C3

PHOSPHATES CONCENTRATIONS AT FORT SASKATCHEWAN (mg/l)

Date		Distance from the right bank in feet			
		100	200	300	400
03/10/71	O	0.36	0.28	0.22	0.13
	P	0.29	0.33	0.26	0.40
	T	0.65	0.61	0.48	0.53
18/10/71	O	0.37	0.28	0.21	0.21
	P	0.05	0.01	0.00	0.00
	T	0.42	0.29	0.21	0.21
29/10/71	O	0.54	-	-	-
	P	0.08	-	-	-
	T	0.62	-	-	-
10/11/71	O	0.20	-	-	-
	P	0.03	-	-	-
	T	0.23	-	-	-
26/11/71	O	0.70	0.55	0.48	0.48
	P	0.00	0.00	0.02	0.02
	T	0.70	0.55	0.50	0.50
16/12/71	O	1.50	1.20	1.05	1.00
	P	0.10	0.10	0.15	0.15
	T	1.60	1.30	1.20	1.15

O - orthophosphates

P - polyphosphates

T - total phosphates

TABLE C4

CONCENTRATIONS OF PHOSPHATES AT VINCA (mg/l)

Date		Distance from the right bank in feet				
		100	200	300	400	550
03/10/71	O	0.26	0.22	0.16	0.14	0.12
	P	0.21	0.18	0.16	0.16	0.14
	T	0.47	0.40	0.32	0.30	0.26
18/10/71	O	0.34	0.25	0.23	0.24	0.24
	P	0.05	0.05	0.00	0.00	0.00
	T	0.39	0.30	0.23	0.24	0.24
29/10/71	O	1.23	1.10	0.90	0.76	0.57
	P	0.00	0.00	0.10	0.00	0.11
	T	1.23	1.10	1.00	0.76	0.68
10/11/71	O	0.20	-	-	-	-
	P	0.00	-	-	-	-
	T	0.20	-	-	-	-
26/11/71	O	1.05	0.75	0.70	0.70	0.60
	P	0.05	0.10	0.10	0.10	0.05
	T	1.10	0.85	0.80	0.80	0.65
16/12/71	O	1.60	1.85	1.50	1.50	1.20
	P	0.60	0.15	0.10	0.00	0.00
	T	2.20	2.00	1.60	1.50	1.20
05/02/72	O	0.80	0.70	0.60	0.55	0.48
	P	0.35	0.15	0.15	0.15	0.22
	T	1.15	0.85	0.75	0.70	0.70

O - orthophosphates
P - polyphosphates
T - total phosphates

TABLE C5

DISSOLVED OXYGEN CONCENTRATIONS AT FORT SASKATCHEWAN AND VINCA CROSS-SECTIONS

D.O. - Ft. Saskatchewan

Date	Distance from the right bank in feet			
	100	200	300	400
18/10/71	12.3	12.3	12.3	12.3
26/11/71	12.0	12.1	12.0	12.0
16/12/71	11.8	11.8	11.8	11.8
08/03/71	9.6	9.7	9.8	9.8
10/03/72	9.6	9.6	9.8	9.8

B.O.D. - Ft. Saskatchewan

Date	100	200	300	400
08/03/72	3.2	3.4	3.0	3.0
10/03/72	2.1	2.2	2.1	2.0

D.O. - Vinca

Date	100	200	300	400	550
18/10/71	11.2	11.2	11.4	11.6	12.0
26/11/71	12.0	12.0	12.2	12.4	12.8
16/12/71	10.2	10.4	10.8	11.2	11.2
08/03/72	9.0	9.2	9.4	9.6	9.6
10/03/72	8.8	9.0	9.2	9.6	9.6

B.O.D. - Vinca

Date	100	200	300	400	550
08/03/72	3.2	5.0	4.0	3.7	3.2
10/03/72	3.2	3.0	2.6	2.4	2.2

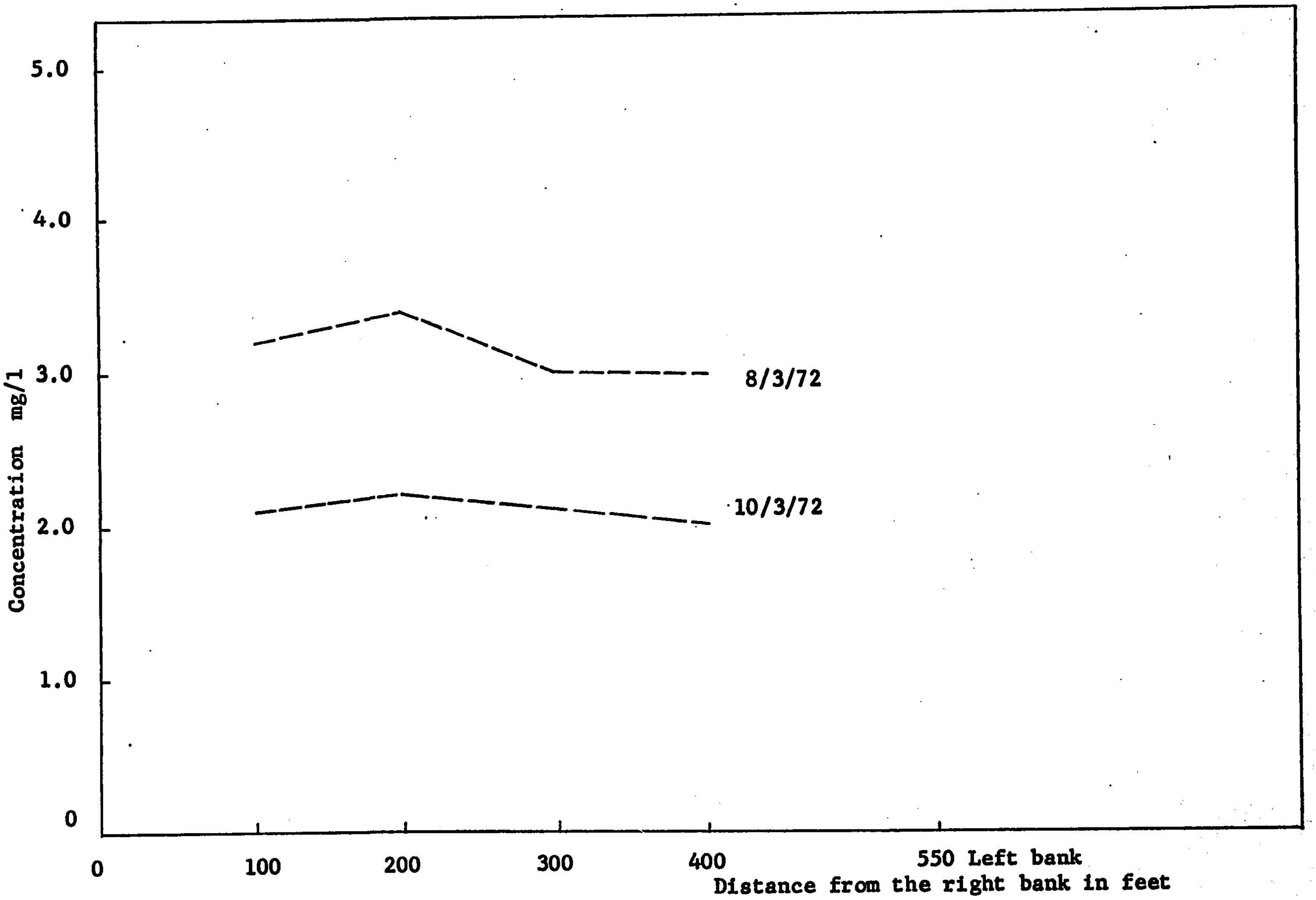

FIGURE C3 : B.O.D. Distribution in the Gross-section at Fort Saskatchewan.

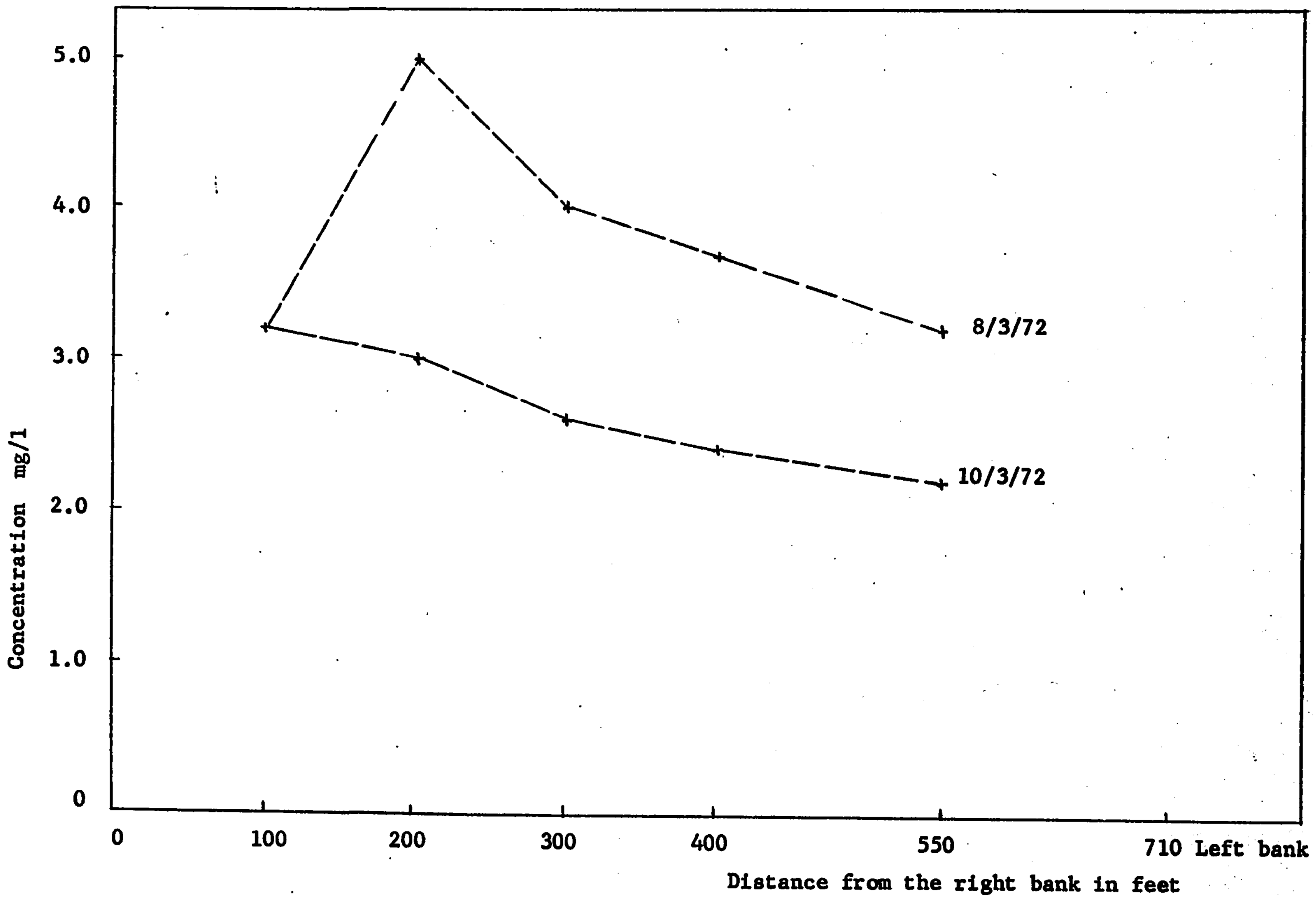

FIGURE C4 : B.O.D. Distribution in the Cross-Section at Vinca.