# METHODOLOGY FOR DEVELOPING A WATER QUALITY MODEL OF A NATURAL STREAM

by

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A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Applied Science

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February, 1972

# ABSTRACT

Those factors which affect the dissolved oxygen response in a natural stream were investigated. Field and laboratory experiments were conducted on the Rideau River to determine the magnitude of these stream constants and the methods of collecting data through these experiments were assessed. A mathematical expression was developed to simulate the effect of the stream constants on the biochemical oxygen demand, nitrogenous oxygen demand and the dissolved oxygen deficit on a 19.9 mile stretch of the Rideau River. The results of the simulation were compared with existing observed data.

A general methodology for developing a water quality model was suggested, applicable to any natural stream. Through analysis of experimental results, conclusions and recommendations were made regarding existing methods of data collection for determining stream constants.

# ACKNOWLEDGEMENT

The author wishes to express his sincere gratitude and appreciation to: his wife for her patience and encouragement during the last eighteen months, to Dr. E. E. Shannon and Dr. K. T. Brodersen for their advice and guidance during the project and to his fellow students for their suggestions and helpful discussions on the various subject investigated in this work.

Financial assistance received through a National Research Council of Canada bursary and a Department of University Affairs grant is gratefully acknowledged.

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# LIST OF SYMBOLS AND ABBREVIATIONS

| | |
|---|---|
| $A$ | Stream X-Section area |
| $A'$, $B'$ | Temperature dependent constants used in equation 2.21 |
| $a$, $b$ | Weir coefficients used in equation 2.17 |
| $Bd$ | Oxygen demand of bottom sediments |
| $b_N$ | nth Fourier coefficient of photosynthetic oxygen production |
| BOD | Biochemical oxygen demand |
| $BOD_5$ | Five day BOD |
| $C$ | Concentration |
| $\Delta c$ | Difference in concentration over a finite element |
| $C_A$, $C_4$ | Constants dependent on the Froude number, and used in equation 2.21 |
| $C_s$ | Saturation concentration of dissolved oxygen |
| $D$ | Dissolved oxygen deficit |
| $D_L$ | Longitudinal dispersion coefficient |
| $D_M$ | Molecular diffusivity of oxygen |
| $D_N$ | Dissolved oxygen deficit due to the nitrogeneous oxygen demand |
| DO | Dissolved oxygen |
| $D_o$ | Initial condition of dissolved oxygen |
| $g$ | Gravitational constant |
| $G.P_{AV}$ | Gross daily average photosynthetic production |
| $H$ | Mean stream depth |
| $h$ | Length of finite element |

| | |
|---|---|
| Hw | Height of weir |
| $K_1$ | Rate of oxidation of BOD constant for a stream (base e) |
| $K_2$ | Rate of atmospheric reaeration constant (base e) |
| $K_3$ | Rate of sedimentation of BOD constant for a stream (base e) |
| $k_2$ | Atmospheric reaeration rate (base 10) |
| $K_N$ | Rate of removal of NOD constant for a stream (base e) |
| L | Ultimate BOD at any time |
| $L_A$, $L_B$ | Ultimate BOD at upstream and downstream points in a stream |
| $L_a$ | Rate of addition of BOD to a stream by sediment diffusion, surface runoff, and groundwater accrual |
| $L_{aN}$ | Addition of NOD to a stream by sediment diffusion, surface runoff, and groundwater accrual |
| $L_c$ | Length of convective zone |
| $\ell$ | Characteristic length of a stream channel |
| $L_N$ | Ultimate nitrogeneous oxygen demand |
| M | Mass of tracer |
| n | Manning's roughness coefficient |
| $NH_3$-N | Ammonia nitrogen |
| NOD | Nitrogeneous oxygen demand |
| ORG-N | Organic nitrogen |
| p | Fraction of the day photosynthesis occurs |
| $P_M$ | Maximum rate of photosynthetic oxygen production |
| P(t) | Rate of photosynthetic oxygen production at any time t |

| | |
|---|---|
| Q | Stream flow |
| R | Algal respiration |
| $R_H$ | Hydraulic radius |
| S' | Slope of the energy gradient in ft per 1,000 ft |
| Se | Slope of the energy gradient |
| $\Sigma s$ | Sum of the sources and sinks |
| t | Time |
| $\bar{t}$ | Mean time of passage of a tracer past a monitoring point |
| T.O.N. | Total Organic Nitrogen |
| $t_s$ | Time at which photosynthetic oxygen production commences |
| $\bar{u}$ | Mean stream velocity |
| u* | Stream shear velocity |
| V | Volume |
| VS | Volatile Solids |
| x | Distance downstream |
| $\theta$ | Temperature coefficient |
| $\gamma_T$ | Ratio of oxygen deficit above a weir to the oxygen deficit below the weir at a water temperature of $T^{\circ}C$ |
| $\sigma^2$ | Variance of the time concentration curve |

# CHAPTER 1

# INTRODUCTION

## 1.1 Water Quality Modelling

The use of rivers and streams to dispose of domestic and industrial wastes has always been a necessity because it has not been technologically possible nor economically feasible to totally recycle or purify effluents before they discharge into a natural body of water. Discharges of these waste materials usually result in a deterioration of water quality in local areas and, if the quantities and concentrations are sufficiently high, may even affect a major portion of an entire river.

Since all domestic and most industrial effluents exert a biochemical oxygen demand (BOD) as well as nitrogeneous oxygen demand (NOD), the dissolved oxygen (DO) water quality parameter is a good indicator of the presence of oxidizable waste in a stream. In addition to oxygen being an indication of oxidizable material and also being relatively easy to measure accurately in situ, and since all stream flora and fauna are dependent upon it, the DO is one of the most important stream parameters to study. Thus, if increasing demands are made on the oxygen resources of major rivers, drastic and tragic ecological consequences may result. Although technology cannot yet economically eliminate the cause, it can reduce the effect that pollutants have on the aquatic environment through better water quality management.

To manage our water resources more effectively it is not sufficient to simply set universal effluent standards for industrial and domestic wastes since the response of stream functions will vary for each river, being dependent upon the hydrological, climatic, nutrient and biological conditions as well as the dilution factor of the stream and the nature of the waste itself. Consequently, each major river which serves a large industrial and urban centre should be studied individually so that effluent criteria may be determined for each river.

The task of setting such individual standards is immense and an efficient tool is required to produce accurate and precise information on water quality data with a minimum of data input and which will shed insight on the input-output relationships of the complex system of stream response. One such tool is the mathematical model which is now used by many investigators to perceive ways and means of improving the water quality of streams serving large urban and industrial centres. O'Connor et al (57) developed a mathematical model to simulate the behaviour of BOD, NOD and DO in the Delaware River Estuary and utilized the results to suggest methods of improving water quality through the amelioration of effluent discharge characteristics and low water flow augmentation.

However, in development of a mathematical model several stages must be considered which attempt to interrelate all model variables with various technological, economic, social and other factors. The stages which must be considered include:

1. Definition of the objectives of the model, e.g. whether it will be with regard to water quality, a dissolved oxygen or bacteria distribution model.
2. Observation of the system to be modelled and extraction of the most important and sensitive functions which will adequately describe the real world conditions.
3. Formulation of the mathematical expressions and inputting of the data collected from the real world.
4. Evaluation of the precision and accuracy of the model by comparison of the model predictions with real world conditions.

Attempting to validate the model often requires returning to the third stage and reapraising the inputted data or it may even require returning to the second stage and questioning the assumptions made in selecting the functions, (the stream constants in the case of a water quality model) as being the most sensitive and important. Generally, there is a continual feed back from the real world to the model resulting in refinement of the system constants and possibly the model itself. However, this trial and error or iterative process should not be construed as a simple manipulation of the model (such changes may simply duplicate the errors made in collecting the data or in constructing the model). In fitting the model to existing data, care must be taken so that it does not merely become a description of the events described by the data and thereby loses its ability to predict future conditions. In other words, the model must have a certain degree of generality.

## 1.2 Purpose and Scope

The purpose of this study was to outline and test a methodology for developing a mathematical water quality model for a natural stream. The model development was accomplished by formulating a mathematical expression, determining the values of the constants in the equations from data collected from a stream, selecting a method for solving the equations to obtain BOD, NOD and DO profiles and comparing predictions with observed data.

The study emphasized the manner in which the stream constants are evaluated since adequate and essentially identical forms of the equations for the BOD, NOD and DO profiles have been developed by several investigators (7,13,57). The existing methods of solving the equations all give approximately the same solutions differing only in analytical or numerical procedures.

In the final analysis of most water quality models, however, the overall validity of the model is found to be dependent upon the accuracy of the values assigned to the constants which in turn are dependent on the methods of collecting, analyzing and interpreting the data from the stream.

This investigation is part of an overall study to eventually model the Ottawa River. However, to reduce the amount of collected data required in determining a methodology for the development of a water quality model, a 19.9 mile stretch of the Rideau River was selected (see Figure 3.1 for map showing section of river studied). A major advantage in selecting the Rideau, apart from it having approximately one hundredth the flow of the Ottawa, was that a thorough survey of the cross section profiles of the river had been undertaken and completed in the summer of 1970, whereas similar extensive data does not exist for the Ottawa. Also, in regard to the Ottawa River, very little water quality and hydrologic data are available. Another major reason for selecting the Rideau River over the Ottawa is that personnel and financial resources greater than those available would be necessary to collect the extensive quantities of data required for simulation of the Ottawa, whereas such resources were relatively available for a study of the smaller Rideau. However, the overall hydrological and biochemical constants should be the same for both rivers although differing significantly numerically. The Ottawa is a relatively fast flowing river with low algal population, whereas the Rideau is a very sluggish stream (almost a series of impoundments) with numerous dams to control the water level for navigation, and very high populations of algae and rooted plants. In spite of these differences, it must be recalled that one of the requirements of any model is generality so that it can adequately simulate more than one set of conditions that may exist in a system. Thus, the formulation of a model for the Rideau and any recommendations that can be made regarding the methodology for the development of the model should be applicable to the Ottawa.

It must be emphasized that due to the scope of this study and the time and financial limitations involved, only sufficient data were collected to determine the dominant and most significant stream mechanisms and to estimate the relative numerical values of the various stream constants. Consequently, the Rideau was surveyed extensively only in reaches that typified the different conditions found in the river, e.g. values for dispersion were obtained only in the most and least sluggish reaches in the river.

# CHAPTER 2

# MODELLING STREAM RESPONSE

To simulate the DO water quality response of a stream receiving a pollutant, it is essential that all the factors which may influence that response be examined individually. Consequently, before any experimental work commenced, a review was made of existing research which had been undertaken to describe and evaluate the various stream mechanisms affecting stream DO. A review was also made of the analytical and numerical procedures for solving the equations which mathematically represent DO as a function of the stream mechanisms.

## 2.1 Factors Affecting Stream DO Response

The following sections contain a review of the existing literature on those stream characteristics which the DO water quality parameter is dependent upon, what they are contingent upon and the methods by which they are evaluated. These characteristics include bottom sediments, longitudinal dispersion, stream velocity, rate of organic removal, nitrification, weirs and impoundments, photosynthesis and respiration, and atmospheric reaeration.

### 2.1.1 Bottom Sediments

In lakes, reservoirs, and sluggish streams and during periods of low discharge in normally fast flowing rivers, suspended organic material may settle out and decompose upon the stream bottom. During spring runoff, scour may occur on these sludge banks, transporting material further downstream to more sluggish regions where it again settles. When low flow conditions return, settling may resume in the previously scoured areas. The occurrence of scouring and deposition continually changes and renews the composition of the bottom sediments.

If these sediments contain sufficient quantities of organic material, a substantial demand for oxygen on the overlying water can be exerted because of bacterial oxidation. Hanes and Irving (32) have reported that up to 50% of the total oxygen demand exerted on several streams and lakes was due to the sediments. In addition to creating problems with DO, a high degree of anaerobic benthic decomposition can produce methane and hydrogen sulphide resulting in not only odour problems, but also floating mats of sludge.

Organic decomposition in sediments occurs somewhat differently than the decomposition of organic material in the overlying water. Benthal decomposition is accomplished almost totally by anaerobic bacteria within the sediments with the exception of a very shallow upper layer of perhaps several centimeters which is aerobic. Products of anaerobic decomposition diffuse into the overlaying water and exert a chemical or biochemical oxygen demand or both.

Fair (19) stated that the most important factor affecting the benthic oxygen demand is the nature of the sediment itself. He concluded that the oxygen uptake is essentially independent of the oxygen concentration of the overlying water, provided it is aerobic, and is controlled by temperature and the rate of diffusion of oxidizable material from the interior of the deposits to the overlying water. Baity (2) and others (8,59,60) reached similar conclusions in their studies of stream sediments. Ogunrombi and Dobbins (59) in their work have emphasized that benthal decomposition must be expressed in terms of two distinct processes: oxygen consumed in the aerobic layer of the sediments and BOD released to the overlying water.

Other studies have shown that the activity of bottom dwelling invertebrates such as molluscs, insect larvae and sludge worms can constitute a major exertion of benthal oxygen demand. Edwards (17) concluded that oxygen uptake was essentially independent of sediment depth, but contrary to the above studies was dependent on the oxygen content of the overlying water. He determined that this was due to the activity of oxygen dependent invertebrates which burrow into the sediments and draw in currents of water for respiration. Later, Edwards and Rolley (18) concluded that the oxygen consumption was independent of depth, at depths greater than only 2 cm despite findings that animal life may exist to a depth of 20 cm in loose sediments (66).

The above are rather important observations, for McDonnell and Hall (49), in experiments similar to Edwards (17), determined that microbial respiration accounted for 45% to 48% of the benthal demand while invertebrate respiration accounted for 52% to 55% of the demand. The reason for the discrepancy between the two views on what influences the oxygen uptake in sediments appears to be the manner in which both groups of experiments were performed. Studies which concluded that the oxygen uptake rate was independent of oxygen concentration in the overlying water were performed using synthetic sludges. The other group of investigators used natural sediments or those seeded with macroinvertebrates.

Studies to determine the magnitude of the oxygen uptake rates on synthetic sludges, composed of organic and inert soil material have been undertaken in the laboratory. Fair (19) found the rates of benthal decomposition to be between 1% and 5% of the rates of bacterial oxidation which exist in polluted waters. In somewhat similar experiments Ogunrombi and Dobbins (59) calculated rates varying between 7% and 18%. From their data the benthal oxygen demand rates were calculated to be .0792 and .041 gms of oxygen per square meter of sludge surface per day for samples of 7.42 cm and 2.42 cm depth respectively.

Oldaker et al (60) on samples taken from natural river sediments at several distances below sewage outfalls computed the demand to be between 0.25 and 1.0 gm/sq.m/day depending on the depth and composition of the deposit. Quirk and Eder(64) measured oxygen uptake rates in the laboratory on natural sludges consisting mainly of paper mill solids. The average oxygen uptake rates of disturbed and undisturbed samples were 1.217 and 2.664 gm/sq.m/day, respectively.

All the above research was performed on synthetic sediments or on sediments removed from the stream bottom and probably did not accurately simulate *in situ* conditions. O'Connell (54) has developed an *in situ* benthic respirometer which covers a portion of sediment with a closed semi-cylinder, recirculates river water over the sediment, and by noting the change in oxygen concentration in the water with time, the uptake rate may be determined. The use of such a respirometer would probably give more realistic benthal rates than experiments on disturbed samples.

### 2.1.2 Longitudinal Dispersion

The manner in which a tracer is diluted and transported downstream is a function of two hydraulic characteristics of the stream: dispersion and convection. In a one-dimensional system, longitudinal dispersion is a function of velocity gradients, and molecular and turbulent diffusion. The latter two mechanisms constitute but 1% or less of the total dispersion in uniform turbulent flow (36). The magnitude of the convective transport is dependent on stream velocity.

To mathematically describe the behaviour of a conservative tracer subject to dispersion and convection, Taylor (74) developed the following one-dimensional equation:

$$\frac{\partial c}{\partial t} + \bar{u}\,\frac{\partial c}{\partial x} = D_L\,\frac{\partial^2 c}{\partial x^2} \qquad (2.1)$$

where $c$ = concentration of tracer

$t$ = time

$\bar{u}$ = mean stream velocity

$D_L$ = longitudinal dispersion coefficient

$x$ = distance

This equation was originally formulated to apply to conditions in a cylindrical pipe but has been used by many researchers to describe tracer behaviour in natural streams. Consequently, subsequent works on the study of the transport mechanisms in a natural stream have been based largely on equation 2.1. The solution for equation (2.1) for an initial tracer distribution concentrated in the plane x = 0 at time t = 0 is given by

$$c(x\,,\,t) = \frac{M}{A\sqrt{4\pi D_L t}}\; e^{\frac{(x-\bar{u}t)^2}{4D_L t}} \qquad (2.2)$$

where $M$ = total mass of tracer

$A$ = the cross-sectional area normal to $x$

However, some serious criticisms of equation (2.1) have been made based on some evident discrepancies between the time concentration curve, which is Gaussian or skewed right normal, predicted by equation (2.2), and that which actually results from tracer studies (see Figure 2.1). Thackston, Hays, and Krenkel (75) maintain that equation (2.1) does not accurately describe the mixing phenomena that occur in natural streams and feel that equation (2.2) can only approximate the time concentration curve. What equations (2.1) and (2.2) fail to predict is the long trail of tracer which occurs after the main slug of tracer has passed downstream. This effect, which shows up as a long tail on the observed time concentration curve of Figure 2.1 tends to increase the moment arm of the curve.

To simulate convection and dispersion in natural streams Hays (34) has developed the dead-zone model. This model accounts for the presence of sections of the river, outside the main stream, which receive tracer material when the main slug passes by and then slowly release it with time. However, Sayre (69) points out that there may be some difficulty in obtaining the mass transfer coefficients and geometry of the dead zones to predict their effect.

Another view of the transport mechanism is that held by Fischer (22,23,24) who states that after a tracer is released into a stream an initial period of convection exists during which there are considerable two and three dimensional variations. Furthermore, these multi-variations are not described by the equation of Taylor (74). The length of this convective period is defined by the following equation:

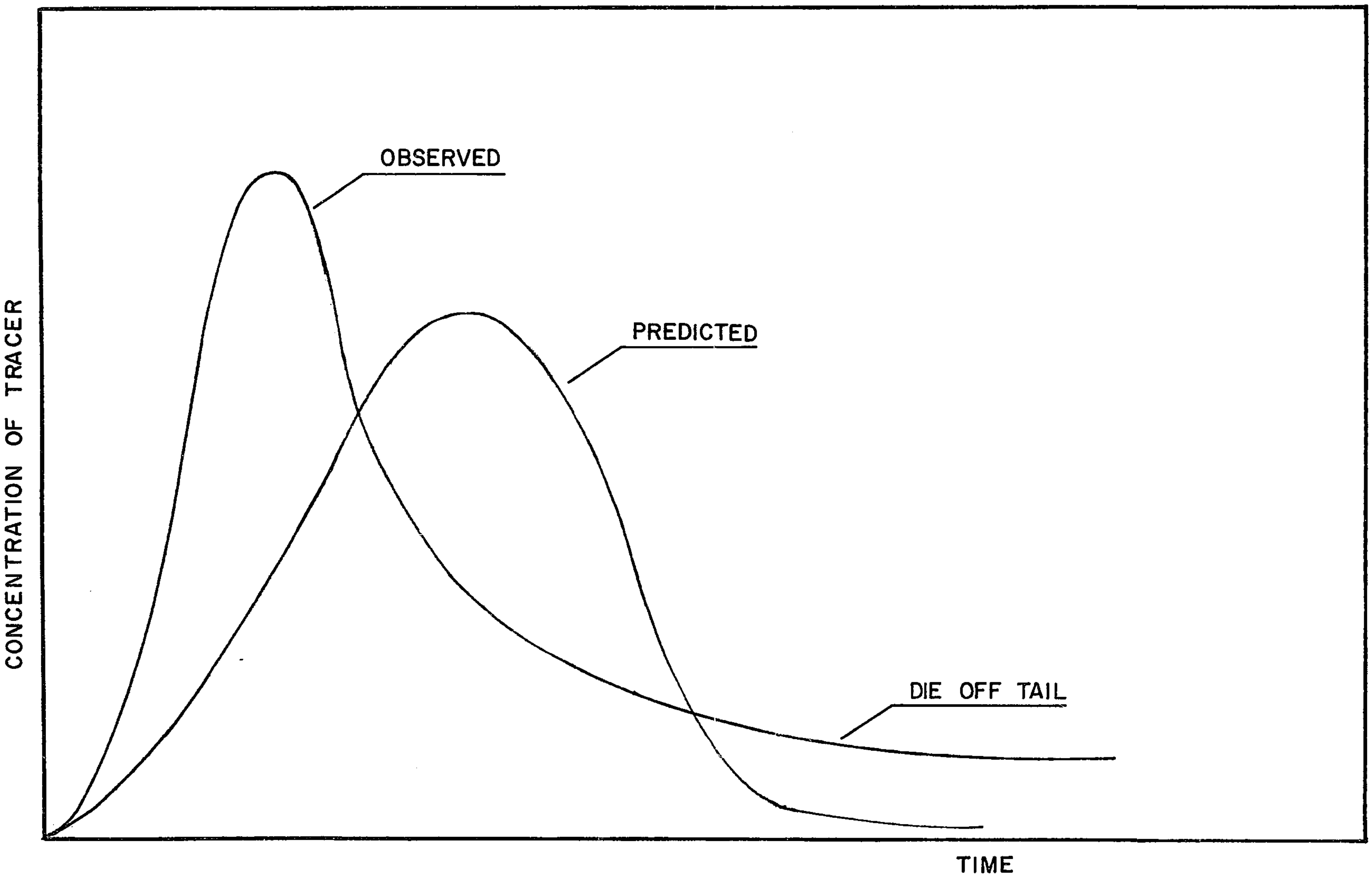

FIGURE 2.1 — PREDICTED AND OBSERVED TIME CONCENTRATION CURVES

$$L_c = 1.8 \frac{\ell^2}{R_H} \frac{\bar{u}}{u^*} \qquad (2.3)$$

where $L_c$ = the distance downstream

$\ell$ = the characteristic length of the channel (the distance from the point of maximum velocity to the most distant bank)

$R_H$ = the hydraulic radius

$u^*$ = the shear velocity

$\bar{u}$ = mean stream velocity

The shear velocity may be calculated by

$$u^* = \sqrt{gR_H Se} \qquad (2.4)$$

where $g$ = gravitational constant

$Se$ = slope of the energy gradient

After the convective period there is a period of diffusion and equation (2.1) is again valid for describing the mixing phenomena in this region.

Whether or not any of the methods that have been proposed give a correct dispersion coefficient can be checked by using a routing procedure suggested by Fischer (23), whereby the observed downstream time concentration curve is compared to a predicted curve using the dispersion coefficient. If a good fit does not result, the coefficient can be adjusted accordingly. However, the routing procedure can only be used for areas far enough downstream from the release of tracer to be in the convective zone and it assumes that the correct time concentration curve is Gaussian.

The many analytical methods for determining $D_L$ are based on one or more of the following assumptions:

i) that the time concentration curve is Gaussian (74);

ii) the effect of dead zones which produce the die-off tails in the observed concentration time curves will not significantly distort the results (22);

iii) that the solution to equation (2.1) is not significantly affected by the existence of a convective period (34).

To determine $D_L$ by analytical methods requires that some type of tracer study be conducted in the stream. However, these studies tend to be somewhat expensive and consequently, many empirical relationships, based on the basic hydraulic parameters of the stream, have been developed to circumvent the need for a tracer study. Bansal (3) summarizes formulae developed by various investigators and has himself suggested a semi-empirical model to evaluate $D_L$. Nevertheless, it is generally agreed in the literature that the following expression suggested by Krenkel is perhaps the best.

$$D_L = 6.39\ H^{1.34}\ E^{0.3} \qquad (2.5)$$

where $E = HSeg$

$H$ = mean depth of stream

It must be realized that no empirical equation can adequately represent all the parameters which affect dispersion.

Consequently, such formulations should be used only to obtain estimates of $D_L$.

### 2.1.3 Rate of Organic Removal

The rate of removal constant for BOD from a river, commonly designated $K_r$, is dependent on the mechanisms of sedimentation and oxidation. The rate constant for sedimentation, $K_3$, is primarily a function of stream velocity, particle size, and particle density. The rate constant for oxidation of BOD, $K_1$, is governed by a biochemical mechanism and is a function of temperature, stream turbulence, and the characteristics of wastes and microorganisms in the stream (16).

Immediately downstream of a waste input, suspended solids are usually present which will be removed from the streamflow, primarily by sedimentation rather than oxidation, and deposited on the bottom to decompose benthally. Beyond this zone of sedimentation, the removal of organics from the streamflow will occur primarily through oxidation. The rate of oxidation of organic material in a stream was originally thought to be the same as that determined through the standard BOD bottle tests. The stream values for the BOD reaction rate constant, $K_1$, were normally found to be not more than 0.1 at 20°C (40). However, Kittrell and Kochtitsky (40) observed that there was a great difference between the laboratory reaction rate and that which existed in a stream, with the stream reaction rate constant being much greater than the laboratory rate constant. The manner in which they calculated

$K_r$ consisted of determining the ultimate BOD at two or more sections downstream from a waste source. Using the monomolecular equation

$$\frac{dL}{dt} = -K_r L \tag{2.6}$$

it was found that

$$K_r = \frac{1}{t} \log \frac{L_A}{L_B} \tag{2.7}$$

where $L_A$ and $L_B$ are the ultimate BOD at an upstream and downstream station, respectively, and "t" is the mean time of travel of the pollutant between stations. Gannon (28) and Lordi and Heukelekian (44) in noting the difference between the laboratory BOD and river BOD rates suggested that the discrepancy was due to turbulent mixing.

Camp (8) suggested a method similar to that of Kittrell and Kochtitsky (40) but included terms to account for, not only the effects of the addition of BOD along the stretch, but also the loss of BOD by sedimentation. For steady state conditions, the BOD values between two points, A and B, in a river are related by the following equation:

$$L_B = L_A - \frac{L_a}{(K_1+K_3)} e^{-(K_1+K_3)t} - \frac{L_a}{K_1+K_3} \tag{2.8}$$

where $L_a$ is the rate of addition of ultimate BOD along the stretch. If $L_A$ and $L_B$ are determined from the standard BOD bottle tests and $L_a$ is solely due to benthic decomposition which can be measured by methods outlined in section 2.1.1,

$K_1$ and $K_3$ can be calculated. However, since $K_1$ is not the laboratory reaction rate and since it is virtually impossible to measure $K_3$, separate values for $K_1$ and $K_3$ are difficult to determine.

In addition to being affected by sedimentation and oxidation, $K_r$ is also temperature dependent. Streeter and Phelps (72) have found that the effect of temperature could be expressed by

$$K_r = K_{r20^\circ C}\theta^{(T-20^\circ C)} \tag{2.9}$$

where $K_{r20^\circ C}$ = the reaction rate at 20°C

$T$ = the stream temperature in °C

$\theta$ = the temperature coefficient

The range of values reported for $\theta$ vary between 1.00 and 1.075 for lower (4°C) to higher temperatures (30°C and above), respectively. An average value of 1.047 is generally used for temperatures near 20°C.

### 2.1.4 Nitrification

Nitrification is a series of reactions in which ammonia is oxidized to nitrite and in turn nitrite to nitrate by the nitrifying bacteria <u>Nitrosomonas</u> and <u>Nitrobacter</u>, respectively. Both genera of bacteria are strict aerobes and below an oxygen concentration of 3 ppm, the reactions become oxygen dependent (57). The stoichiometric relation of oxygen to ammonium nitrogen shows that 4.57 moles of oxygen are required for complete oxidation of one mole of ammonia to nitrate.

Ammonia may be discharged directly into a stream through industrial waste inputs and agricultural runoff or result from the bacterial degradation of proteins and urea in a domestic waste discharge. Therefore, in streams that receive domestic, industrial, or agricultural discharge, nitrogen compounds are present, assimilated by bacteria which require oxygen, and must be considered in calculating the oxygen balance of a stream.

Several methods are available to account for the effect of nitrogenous loadings on the oxygen balance of a stream. The simplest method considers the equivalent oxygen demand of the nitrogenous loadings as a BOD-like input into the dissolved oxygen equations and nitrification as a first order reaction. The nitrogenous oxygen demand (NOD) can be estimated by

$$NOD = 4.57\ (Org\text{-}N + NH_3 - N) \quad (45) \qquad (2.10)$$

where Org-N = total organic nitrogen

$NH_3$-N = ammonia nitrogen

This equation assumes that a nitrogenous waste is totally in the organic nitrogen and ammonia form and that the hydrolytic reaction of the organic nitrogen to ammonia is similar to the biochemical reactions of converting ammonia to nitrate. The nitrogenous river reaction rate can be calculated using a method similar to that for determining $K_r$ as outlined in section 2.1.3. In this case, only the second stage of the BOD curve at each section in the stream is considered. By conducting two sets of BOD determinations on one sample and adding methylene blue, a nitrifying bacteria inhibitor, to one set, two curves can be obtained (55). One curve would show the first stage BOD only and the other would give the second stage BOD. By subtracting the first stage curve from the second, the NOD can be found.

For one-dimensional non-steady state systems with constant coefficients the equations describing the distribution of NOD and DO deficit are given by

$$\frac{\partial L}{\partial t} = D_L \frac{\partial^2 L_a}{\partial x^2} - \bar{u} \frac{\partial L_N}{\partial x} - K_N L_N \qquad (2.11)$$

and

$$\frac{\partial D_N}{\partial t} = D_L \frac{\partial^2 D_N}{\partial x^2} - \bar{u} \frac{\partial D_N}{\partial x} - K_2 D_N + KL_N \qquad (2.12)$$

where $L_N$ = the ultimate NOD

$K_N$ = river reaction rate constant for the oxidation of NOD

$K_2$ = the reaeration coefficient

$D_N$ = oxygen deficit due to NOD

The derivation of these equations will be shown in section 2.2.

For a more intensive study of nitrification each reaction from total organic nitrogen through to nitrate formation should be considered individually. Thus, the description of each component of the nitrification process can be represented by an equation similar to equation (2.11) where $L_N$ would be replaced in succession by organic ammonia, nitrate, and nitrate nitrogen loadings, creating four simultaneous partial differential equations. If denitrification is assumed to be neglible ($NO_3 \rightarrow NO_2 \rightarrow N_2$) and that no forms of nitrogen are lost through the system, e.g. to the bottom sediments, three equations result and three separate reaction rates are required.

Wezernak and Gannon (79) have developed a method to predict the NOD in a stream by measuring _in situ_ the rates of reaction for $NH_3$ and $NO_2$. The method is very simple and requires sampling at only three stream stations. However, its validity has been questioned (47) since it uses the Robertson growth equation to describe the formation of oxidized products and assumes that initial bacterial concentration in a stream is insignificant.

Stratton and McCarty (71) have developed a method of determining reaction rates of formation of nitrite and nitrate. Their method is based on the Monod theory of the growth of biological organisms and although the method may be the most superior in theory, the various reaction parameters must be determined by laboratory batch tests. Thus it is questionable if the results represent conditions found in a flowing stream.

Pence et al (62) have used the following empirical formulations, derived by regression analysis, to approximate the nitrogen decay rate.

$$K_N = 0.00475 - 0.00184T + 0.000326T^2 - 0.000017T^3 + 0.000000479T^4 \qquad (2.13)$$

where T is the stream temperature in degrees centigrade. This formulation was developed and used in a study on the Delaware River Estuary.

### 2.1.5 Photosynthesis and Respiration

In very sluggish rivers in which organic decay exerts an oxygen demand, the major source of oxygen replenishment may come from the photosynthetic activity of the river flora. Not only can photosynthesis be the major source of oxygen, but because of its dependence upon light, can cause serious oxygen depletion during darkness when photosynthesis stops but the consumption of oxygen through plant respiration continues. Low oxygen levels because of plant respiration have resulted in fish kills in the Rideau River (65).

The rate at which the river flora produce oxygen is dependent primarily upon light intensity, nutrients, water temperature, and turbulence. Light intensity has been found to have the greatest effect on oxygen production. In fact, the rate of oxygen production versus time curve has the same shape as the incident light versus time curve (58). All of the above variables are in turn dependent upon seasonal and climatic conditions, waste input, land use, and hydraulic conditions. These factors, therefore, make it very difficult to model oxygen production by photosynthesis to cover all possible variable conditions. However, since light intensity is of a much greater significance than the other variables, most models consider it as the sole independent variable during steady state conditions when determining diurnal fluctuations in dissolved oxygen due to photosynthesis.

O'Connor and DiToro (55) have developed the following equation to predict photosynthetic oxygen production assuming that the photosynthetic source is representable by a half cycle sine wave which repeats periodically each day:

$$P(t) = P_m\{\frac{2P}{\pi} - \sum_{n=1}^{\infty} b_N \cos[2\pi n(t-t_s-P/2]\} \qquad (2.14)$$

$$\text{for } t_s - p < t < t_s - 1$$

and

$$P(t) = 0 \qquad (2.15)$$

$$\text{for } t_s - p < t < t_s - 1$$

$$b_N = \cos(n\pi p)\,\frac{4\pi p}{(\pi/p)^2 - (2\pi n)^2} \qquad (2.16)$$

where $P(t)$ = the rate of photosynthetic oxygen production

$P_m$ = the maximum rate of photosynthetic oxygen production

$t_s$ = time at which the source begins

$p$ = the fraction of the day over which the source is active.

The above equation is a Fourier series and $b_N$ is the Fourier coefficient of the nth term in the series .

If photosynthetic oxygen production is due primarily to rooted plants and periphyton (attached algae), $P_m$ may be found by modelling all the other parameters which affect stream dissolved oxygen and, by trial and error manipulation of $P_m$, fitting the calculated values with observed values.

In streams where pelagial (free floating) algae dominate the floral community to the exclusion of rooted plants, photosynthesis can be measured in situ and included in the dissolved oxygen model directly. The methods used to obtain oxygen production include measuring the oxygen change in light and dark bottles incubated in a stream over a period of time (67,70); measuring the amount of $carbon_{14}$ isotope in light and dark bottles incubated in a stream over a period of time, and determining the oxygen produced stochiometrically (67,70); and, measuring the chlorophyll content in the stream and relating it to oxygen production (67,70).

The $carbon_{14}$ method is the best where sensitivity is required and there is a low concentration of algae in a stream. However, it does require relatively expensive instruments and the preparation of $carbon_{14}$ isotope in solution. The method of direct oxygen measurement is the most inexpensive and gives good estimates of gross and net photosynthesis and respiration when algal concentrations are sufficiently high to change the oxygen concentration measurably over a short period of time, usually less than twelve hours.

Using the light and dark bottles for the two methods has disadvantages as noted by Hull (38). Turbulent stream conditions are neglected and the growth of periphyton results with the presence of the glass surface. It is also believed that heterotrophic organisms (bacteria and fungi) and protozoa may respire more quickly under high light intensities (76). These errors can be minimized to some extent by limiting the incubation period to four hours or to some period when the change in oxygen is measurable. Thus, instead of one incubation period during the photo period, several shorter periods could be used.

The determination of oxygen production through chlorophyll measurement is the least reliable method. Ryther (68) reported that Manning and Juday found that 1 mg of chlorophyll related to a mean production of 6.7 mg of oxygen per hour. However, one problem is that many plants develop more chlorophyll when grown in the shade than when exposed to bright light and different species of plants have different amounts of chlorophyll per unit biomass (68). Bain (1) has used this method of determining photosynthesis and respiration and obtained some degree of agreement between observed and calculated data.

### 2.1.6 Effects of Weirs and Impoundments

The portion of the Rideau River that was studied contains three, free type weirs where the water has an unbroken fall from the sill to a pool below. The existence of weirs act as a point source or sink of dissolved oxygen depending on whether the upstream water is undersaturated or supersaturated with oxygen. The following empirical equation has been developed by Gameson et al (27) to estimate the transfer of oxygen at a weir from the atmosphere to the stream or vice versa:

$$\gamma_T = 1.0 + 0.11\ ab(1 + 0.046T)H_w \qquad (2.17)$$

where $\gamma_T$ = ratio of upstream oxygen deficit to downstream oxygen deficit at a water temperature of $T^\circ C$

a = a water quality constant

b = a weir coefficient dependent upon the amount of turbulence created by the weir

$H_w$ = height which the water falls.

Values of b have been found by Gameson et al (27) to be unity for a free fall weir and for slightly polluted water, a has been found to be 1.25.

The effect of impoundments behind the weirs is to lessen the atmospheric reaeration rate considerably because of increased depth and lower velocities than in the sections upstream of the reservoir. However, with the long retention times nutrients carried in by the inflowing water and released by organic decay in the reservoir may stimulate algal productivity. Thus, oxygen replenishment may come mainly through photosynthetic activity. The effect of wind is also increased due to increased surface area. In most deep reservoirs, thermal stratification occurs during the summer months and if the outlet water from the reservoir is from the hypolimnion, downstream water quality may be adversely affected.

### 2.1.7 Reaeration

The only physical method by which a stream may replenish the oxygen resources that have been depleted through organic decay is by atmospheric reaeration. This important mechanism has been intensively studied and several formulations have been developed based on physical parameters of streams to predict the atmospheric reaeration coefficient, $K_2$.

O'Connor and Dobbins (56) were the first to predict $K_2$ using a method based on rational analysis. Two semi-empirical formulations were developed, one for isotropic turbulence assumed when the Chezy coefficient was greater than 17 and another for non-isotropic turbulence when the Chezy coefficient was less than 17. These formulae are given, respectively, as

$$k_2 = \frac{D_M(\bar{u})^{1/2}}{2.303\ H^{3/2}} \tag{2.18}$$

and

$$k_2 = 480\ \frac{{D_M}^{1/2}\ {Se}^{1/4}}{H^{5/4}} \tag{2.19}$$

where $D_M$ = the molecular diffusivity of oxygen

$k_2$ = atmospheric reaction rate to the base 10

Churchill <u>et al</u> (9) studied thirty different and relatively unpolluted streams in one geographic area (the Tennessee Valley) and using a method of statistical correlation analysis arrived at the following formulation:

$$k_2 = \frac{5.026\ \bar{u}^{0.969}}{H^{1.673}} \tag{2.20}$$

Dobbins (13) employing a similar rational approach to that used in his paper with O'Connor developed a more complex formulation which is written as

$$k_2 = \frac{0.12\ C_A A' E^{3/8} \coth}{C_4^{3/2}\ H} \left[\frac{B'E}{C_4{}^{1/2}}\right] \tag{2.21}$$

and $E = 30.0\ S'\ \bar{u}$

where $C_A$ and $C_4$ = constants dependent upon the Froude number

$A'$ and $B'$ = temperature dependent constants

$S'$ = slope of the energy gradient in ft per 1,000 ft.

Through laboratory studies and the use of data from field studies, Isaacs and Goudy (39) found that

$$k_{2(T^\circ)} = 3.739\ \frac{\bar{u}}{H^{3/2}}\ (1.0241)^{T-20} \tag{2.22}$$

where $k_{2(T^\circ)}$ = atmospheric reaeration rate to the base 10 at a water temperature of $T^\circ C$.

Thackston, Hays and Krenkel (75) derived semi-empirical relationships for $k_2$ by considering velocity and depth, longitudinal dispersion, shear velocity, energy expenditure, and the Froude number. These relationships were determined using field data and computing the constants for each relationship by a least squares method and employing the algorithm proposed by Marquardt (46). Thackston, Hays and Krenkel (75) felt that the most practical formulation and the one least affected by errors in hydraulic parameter measurement was

$$k_2 = 0.000125\left[1.0 - \left(\frac{\bar{u}}{\sqrt{gH}}\right)^{1/2}\right]\sqrt{\frac{Seg}{H}} \qquad (2.23)$$

Thackston, Hays and Krenkel's formulation appears to be the most accurate since it was found that the presence of dead zones, flow discontinuities and extra lateral shear had no apparent effect on the predicted value of $k_2$. Also the effect of an error in measuring $\bar{u}$ and H is minimized since the former appears to the one half power and the latter to the quarter power. However, the drawback to the equation is that at low Froude numbers associated with deep and sluggish streams, the constants developed in the formulation became indefinite.

As shown in Isaacs and Gaudy's equation, $k_2$ is also dependent on temperature and this relationship is usually given by

$$k_{2T^{o}} = k_{2\text{-}20^{o}C}\ \theta^{(T-20^{o})} \qquad (2.24)$$

Thus, with increasing temperature, $k_2$ will increase but not as rapidly as $K_r$, the rate constant of organic removal, which has a similar relationship to describe the effect of temperature change. Dobbins (13) and Metzger (50) maintain that θ is not constant as Isaacs and Gaudy presume, but is a function of stream turbulence and temperature range, with θ decreasing with increasing mixing conditions.

Other factors such as wind and surface active agents affect $k_2$ but high variability in their occurrence make their effect extremely difficult to simulate. Wind action is an especially important factor affecting reaeration rates in sluggish river sections and impoundments. The continual agitation of the water surface by the wind in these sections would produce a relatively high replenishment of the oxygen resources of the stream. But, an absence of wind, for a prolonged period, could result in critically low oxygen levels.

While the above procedures were developed to predict $k_2$ in streams, Tsivoglou _et al_ (76) have developed a method of measuring $k_2$ _in situ_. The method consists of injecting and measuring a fluorescent dye, tritium, and Krypton 85, a radioactive chemically inert gas, in a stream. The reaeration rate is found by finding the Krypton 85 loses and relating it to the relative transfer capabilities of oxygen and Krypton. Although this procedure would be too expensive in material and personnel to carry out on most stream studies, it is mentioned here because proper _in situ_ measurements are more reliable than values obtained from general formulae. This procedure is especially valuable for determining what $k_2$ would be under ice cover, a condition not covered by the above mentioned formulations.

## 2.2 The Stream Response Model

If all the factors which influence water quality are known, a mathematical expression can be formulated. A technique used by O'Connor et al (57) to develop such an equation for a one-dimensional system is to consider a mass balance about an elemental volume in a stream

$$\text{i.e. } V\Delta A = \text{Inflow-Outflow} \pm \Sigma S \qquad (2.25)$$

where $V$ = volume within the element

$\Delta C$ = change in concentration in the element over a period of time

$\Sigma S$ = sum of the source and sinks, e.g. if the concentration, $C$, represents oxygen some sources would be reaeration and photosynthesis and some sinks would be bacterial oxidation of BOD, benthal demand, and respiration.

Mass inflow and outflow result from the two transport mechanisms, convection and longitudinal dispersion. Both terms can be formulated mathematically and equation (2.23) can be expanded to

$$V\Delta C = Qc\Delta t - D_L\, A\frac{\partial c}{\partial x}\ \Delta t \qquad \text{[inflow convection and dispersion]}$$

$$-\left[Q(c-\frac{\partial c}{\partial x}\ \Delta x)\Delta t - D_L\ A\left(\frac{\partial c}{\partial x} - \frac{\partial}{\partial x}\ (\frac{\partial c}{\partial x})\right)\Delta x\ \Delta t\right] \qquad \text{[outflow convection and dispersion]}$$

$$\pm\ \Sigma S\ V\Delta t \qquad \text{[sources and sinks]} \qquad (2.26)$$

where $Q$ = stream flow

$A$ = stream cross section area

Noting that $V = A\Delta x$ and dividing equation 2.24 by $V$ and $\Delta t$ gives

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - \frac{Q}{A}\frac{\partial c}{\partial x} \pm \Sigma S \qquad (2.27)$$

as $\Delta t \rightarrow 0$ and $\Delta x \rightarrow 0$

Equation 2.27 describes any conservative or non-conservative water quality parameter. If this equation is to represent dissolved oxygen behaviour equation 2.27 could be expanded to give

$$\frac{\partial c}{\partial t} = D_L \frac{\partial^2 c}{\partial x^2} - \frac{Q}{A}\frac{\partial c}{\partial x} + K_2 (C_s - C) - K_1 L - K_N L_N + P_{AV} - R \pm B_d \qquad (2.28)$$

where $C_s$ = saturation concentration of DO, ppm

$L$ = BOD at any time t, ppm

$B_d$ = oxygen demand of bottom sediments, ppm per day

Similarly, BOD behaviour may be represented by equation 2.27 giving

$$\frac{\partial L}{\partial t} = D_L \frac{\partial^2 L}{\partial x^2} - \frac{Q}{A}\frac{\partial L}{\partial x} - (K_1 + K_3) L + L_a \qquad (2.29)$$

where $L_a$ = addition of BOD by diffusion from the bottom sediments and local runoff in ppm per day

By making the necessary simplifying assumptions as stated in Section 2.1.4, the behaviour of the NOD can be represented by

$$\frac{\partial L_N}{\partial t} = D_L \frac{\partial^2 L_N}{\partial x^2} - \frac{Q}{A}\frac{\partial L_N}{\partial x} - K_N L_N + L_{aN} \qquad (2.30)$$

where $L_{aN}$ = addition of NOD by diffusion from the bottom sediments and local runoff in ppm per day.

These basic equations describing the behaviour DO, BOD and NOD have been studied and used extensively in various modified forms by O'Connor et al (57), Pence et al (62), Dobbins (13) and others.

## 2.3 Solution of the Mathematical Model

Analytical solutions to the equations developed in Section 2.1 can be found only for steady state conditions where no variations with time are considered or, for certain simplified cases of unsteady state where dispersion is ignored. Dobbins (13), Camp (8) and O'Connor et al (57) have given solutions for these cases.

Parameters in streams are generally time varying as well as spatially varying. For these more complex systems the dissolved oxygen and BOD equations can only be solved using numerical procedures. Dresnack and Dobbins (14), Bella and Dobbins (5) and Pence et al (62) have used the method of finite differences to obtain solutions to the equations containing variable parameters and longitudinal dispersion. However, there are stability problems (48) as well as oscillation, skewness and dispersion errors (6). These errors may be eliminated or minimized by a judicious choice of the size of the spatial and temporal increments.

Guymon (30,31) has developed a finite element solution method for the equation of a conservative substance in flowing water. The method can be extended to include equations for non-conservative substances such as BOD and dissolved oxygen. The method is always stable but convergence is dependent upon the ratio of $\overline{u}h/D_L$, where h is the length of the finite elements. The smaller the ratio the slower the convergence to the exact solution. Thus, for small dispersion coefficients, h would have to be impractically small to retain acceptable accuracy. When dispersion is small and can be neglected, Di Toro (11) has found that the method of characteristics is the best for solving the BOD and dissolved oxygen equations. The basis of this method is that the partial differential equations can be reduced to two ordinary differential equations, one describing the position of the slug with time (plug flow must be accepted since dispersion is neglected), and the other describing the concentration with time, due to the action of the sources and sinks. The solution of the ordinary differential equations can be found using standard numerical integration techniques.

# CHAPTER 3

## EXPERIMENTAL METHODS AND CALCULATION OF THE STREAM CONSTANTS

Having discussed the factors which influence stream response, it now remains to determine the magnitude of the stream constants. Consequently, experiments for determining the oxygen demand and BOD diffusion rates from the sediments, dispersion, mean stream velocity, deoxygenation rate constant, photosynthesis, and respiration were performed in situ on the Rideau or in the laboratory. Values for the other stream constants, atmospheric reaeration rate, effect of weirs and impoundments, and nitrification were taken from the literature sources reviewed in the previous section.

### 3.1 Sediment Evaluation

An in situ measurement of the effect of the bottom sediments on the dissolved oxygen and BOD concentration is no doubt superior to carrying out tests on disturbed sediments. However, because of time and financial restraints, it was not possible to have an in situ respirometer constructed for the study and tests were made on disturbed samples in the laboratory.

Samples of the river sediments were taken with an Eckman dredge throughout the section being studied, except where the bottom was too rocky or the sediment too coarse for the dredge to pick up. On each sediment sample the five day BOD, dry solids, volatile solids, total organic nitrogen, and ammonia nitrogen were determined. Test procedures were followed as outlined in Standard Methods (70) with the exception of the BOD determinations: the sediments in the bottle were not continuously stirred and kept in suspension. The description of the sediments and their composition are given in Tables A-1 to A-4 of Appendix A.

In order to determine benthal oxygen demand and diffusion of BOD from the sediments to the overlying water, four sediment samples were taken from the reaches between Black Rapids Dam and Mooney's Bay for analysis in the laboratory. Samples were taken near the inlet and outlet to Mooney's Bay, at the outlet of Nepean Creek and several hundred yards above Uplands sewage treatment plant (see Figure 3.1 for map location). The sediments obtained, ranging from very coarse sand to extremely fine silt, were believed to be representative of the sediment material existing throughout the stretch of the river being studied.

To measure the benthal oxygen demand and the BOD diffusion, an experimental apparatus was set up as shown in Figure 3.2. A portion of each sediment was placed in an air tight plexiglass cylinder to a depth of approximately two inches and aerated water pumped through. The fact that there was complete mixing in the cylinders was ascertained by observing the diffusion of dye that was introduced into each cylinder before any sediment samples had been placed inside.

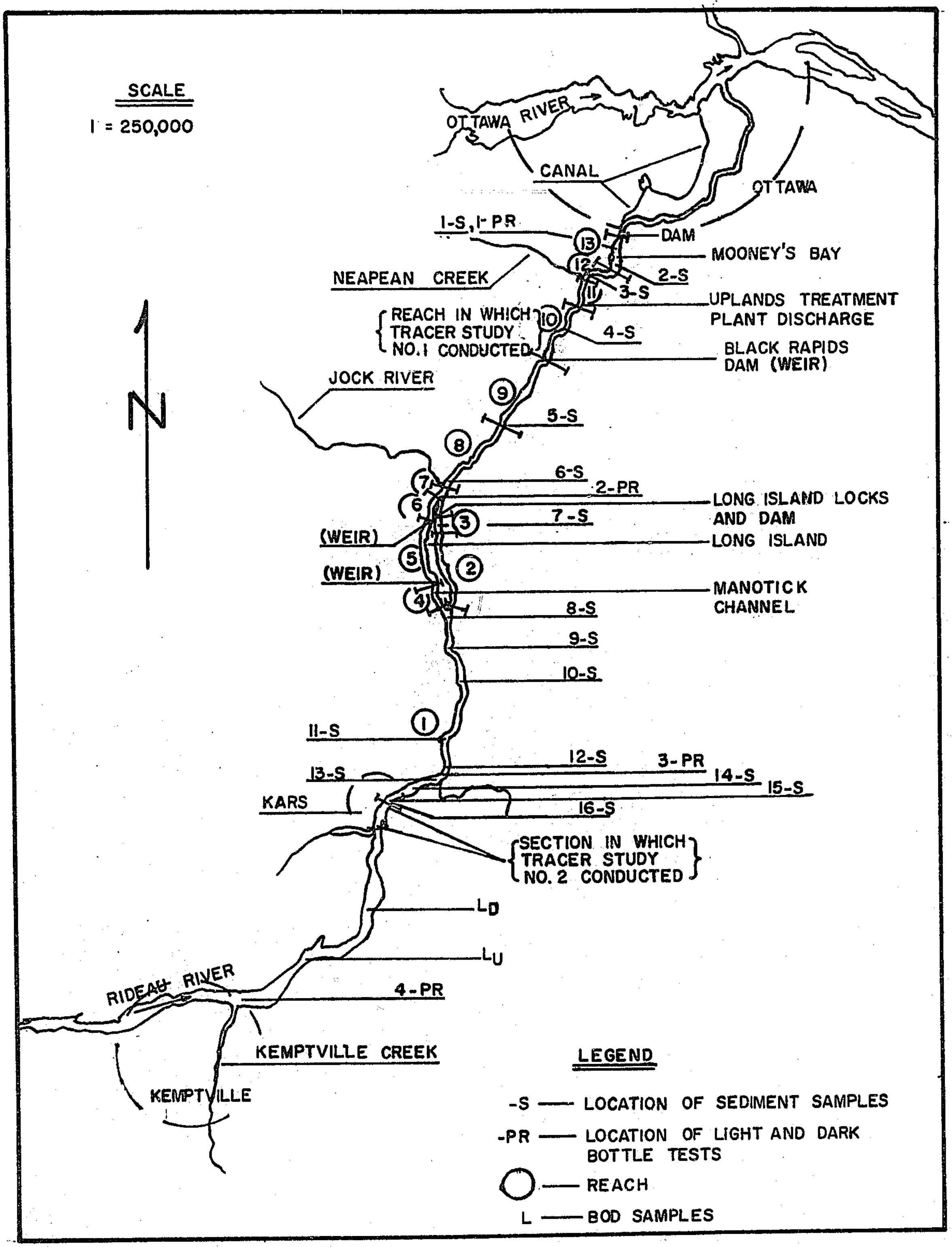

FIGURE. 3.1 — SECTION OF RIDEAU RIVER SIMULATED SHOWING SAMPLE LOCATIONS AND AREAS OF TRACER STUDIES

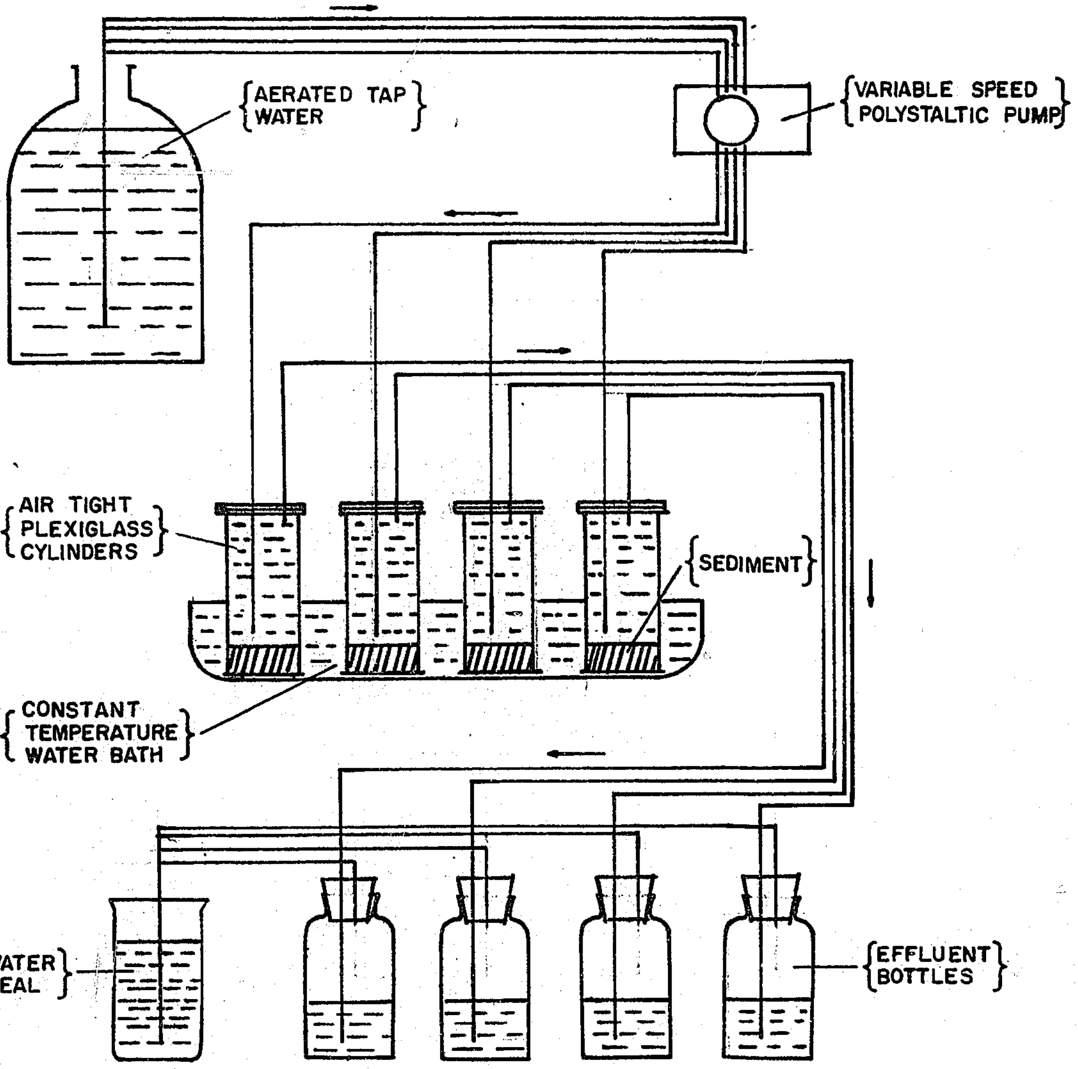

FIGURE 3.2 — SCHEMATIC DIAGRAM OF APPARATUS FOR SEDIMENT EVALUATION

Initially, the dissolved oxygen and BOD of the influent and effluent were determined daily, but the large quantity of BOD determinations made daily analysis unwieldly and, consequently, tests were performed every second day. Although testing on alternate days resulted in a longer period of microbial activity in the BOD bottles than desirable, it was thought that these effects would be minimal.

Readings for the first two days were not recorded in order to negate influences that any suspended material might have had on the BOD results. After two days it was felt all the suspended material had been flushed out of the cylinders and tests were then conducted for eighteen days. The results are given in Tables A-6 to A-10 of Appendix A. Oxygen uptake rates were obtained by plotting the cumulative oxygen consumed by the sediments with time. The slope of the resulting line was taken as the oxygen uptake rate (see Figure 3.3). A method similar to that used to determine the uptake rate was employed to determine the rate of diffusion of BOD. However, a more asymptotic curve resulted (see Figure 3.4). Because they were disturbed samples, the initial period was felt to be one of adjustment and the latter period of constant slope was taken as being more representative of what was occurring in the actual stream regarding BOD diffusion. The oxygen uptake rates and the rates of BOD diffusion of the samples are given in Table 3.1.

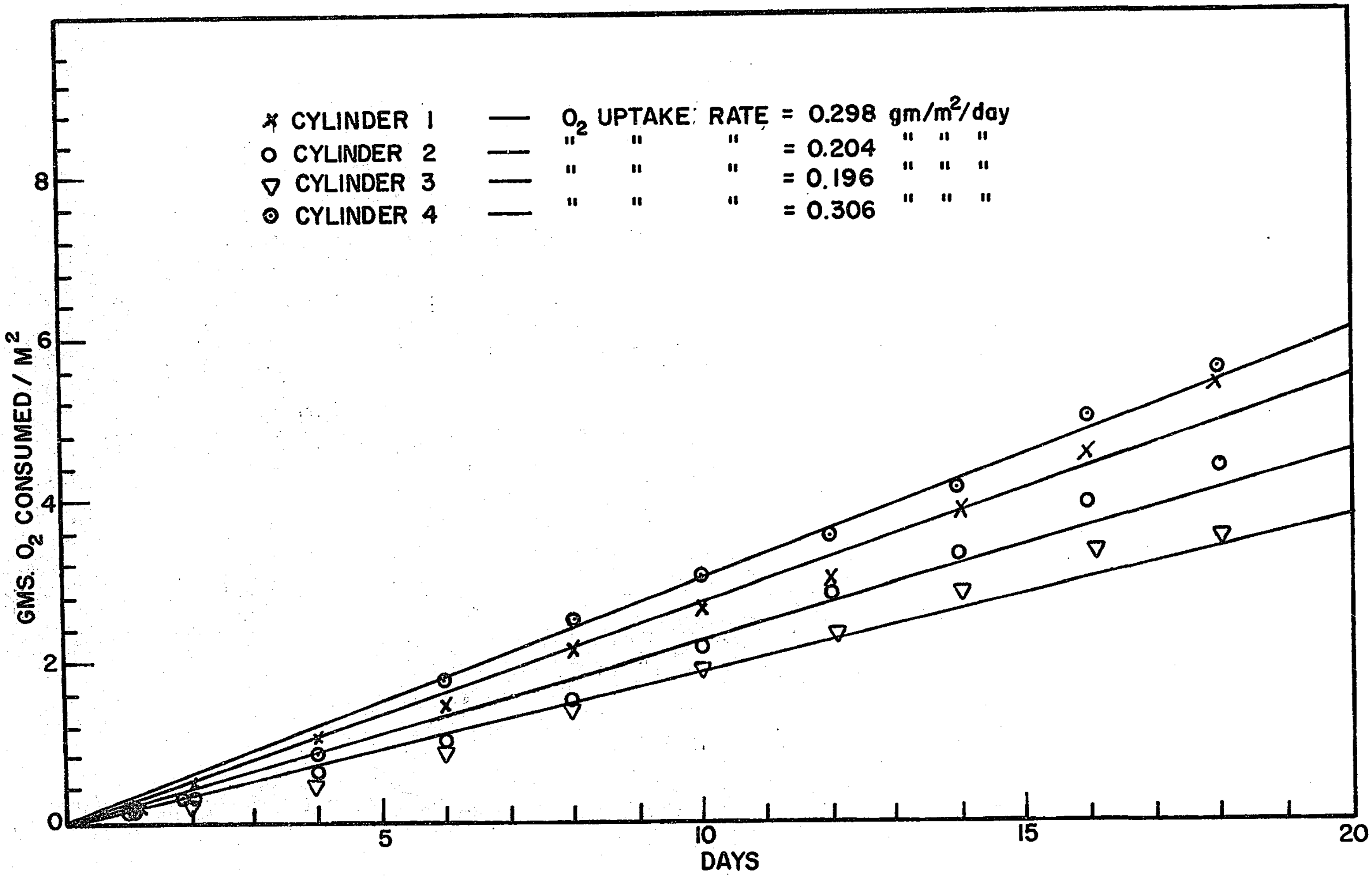

FIGURE 3.3 — DETERMINATION OF OXYGEN UPTAKE RATES OF SEDIMENTS

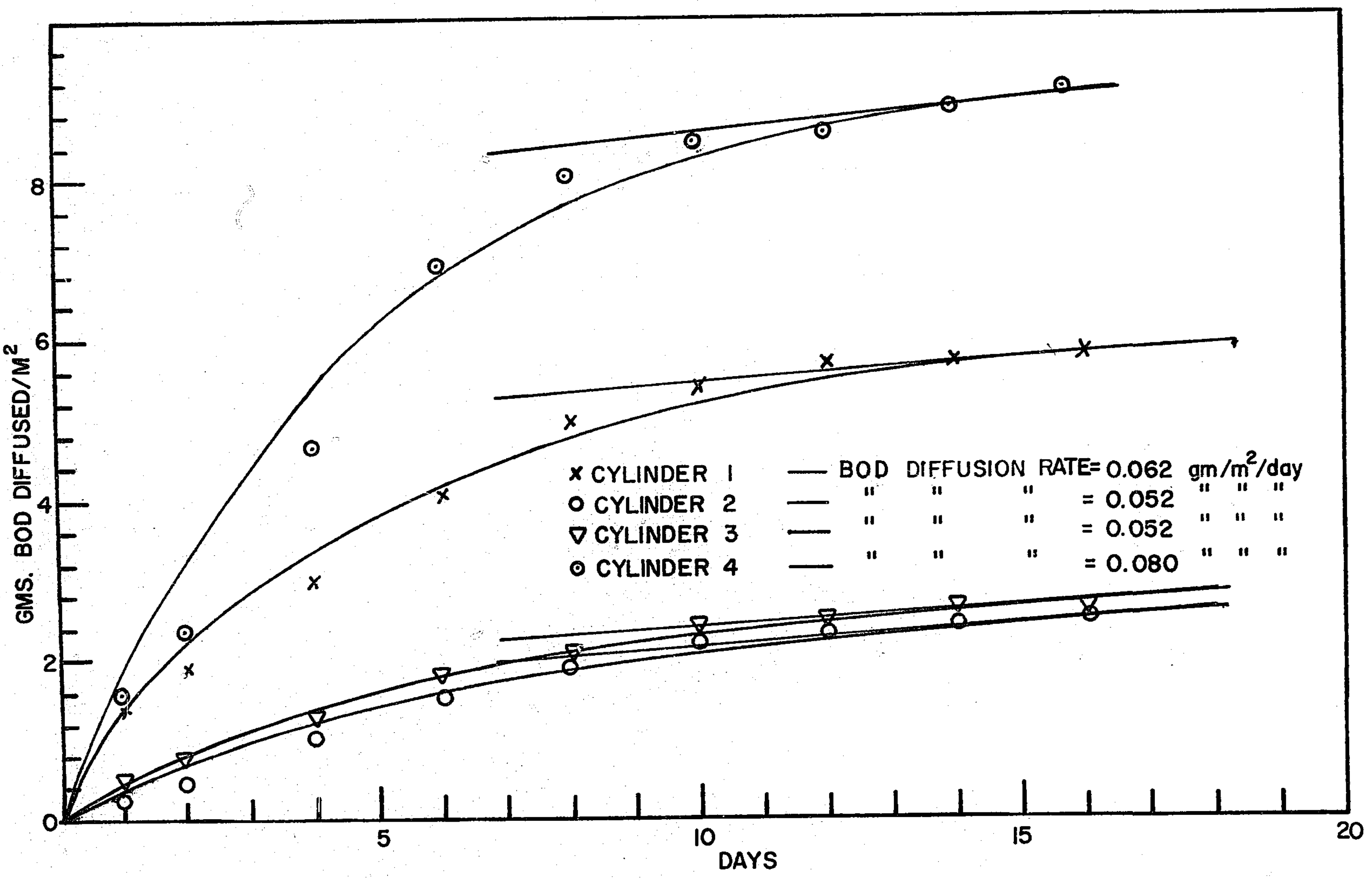

FIGURE 3.4 — DETERMINATION OF BOD DIFFUSION RATES OF SEDIMENTS

| Sample No. | $BOD_5$ gms $O_2$ per kgm V.S. | Volatile Solids % Dry Wt | $O_2$ Uptake gm/sq.m/day | BOD Diffusion gm/sq.m/day |
|---|---|---|---|---|
| 1-S | 119.0 | 2.35 | 0.298 | 0.062 |
| 2-S | 39.9 | 0.76 | 0.204 | 0.052 |
| 3-S | 72.6 | 0.87 | 0.196 | 0.052 |
| 4-S | 13.3 | 0.62 | 0.306 | 0.08 |

TABLE 3.1 - $BOD_5$, Volatile Solids, $O_2$ Uptake and BOD Diffusion Values of Rideau River Sediments

It was thought that the higher the five day BOD of the sediment, the greater would be the oxygen uptake rate and rate of BOD diffusion. As shown in Table 3.1 this was not verified. Sample 4-S had the highest uptake and diffusion rates. Sample 3-S, with a higher five day BOD than sample 2-S, had a lower oxygen uptake rate. The variation in the data from test to test may be due to a number of factors. After placing sample 4-S in the cylinder it was probable that the porosity was very high resulting in a deep aerobic layer and hence affecting the oxygen uptake rate. Another contributing factor to the variation may be due to significantly different invertebrate activity in each sample. Numerous molluscs were observed in all four samples.

The intention of the above tests was to relate the benthal oxygen demand and the diffusion of BOD to the sediment characteristics that were determined for all the sediments, i.e. five day BOD, volatile solids, etc. However, based on the above results and on those obtained by other researchers cited in Section 2.1.1, it would appear that data obtained using disturbed samples cannot be related to in situ sediments with a great deal of accuracy. The manner of deposition and invertebrate activity, two important factors affecting uptake rates, cannot be duplicated in laboratory tests. The oxygen and BOD values obtained are, nevertheless, useful in obtaining the relative magnitude of the oxygen demand of different types of sediment found in the Rideau River and they compare favourably with values in studies quoted in Section 2.1.1.

The oxygen demand and diffusion rates of the sediments in the other reaches were estimated by comparing the physical appearance of the dredged samples to those that were studied in the laboratory.

## 3.2 Longitudinal Dispersion and Mean Stream Velocity

Dobbins (13) has stated that in most natural streams dispersion can be neglected when modelling BOD and dissolved oxygen without causing appreciable error. However, it was felt that dispersion could be significant relative to the extremely low mean flow velocities found in the Rideau River. It was also thought that the mean flow velocity would be appreciably different from the discharge velocity (Q/A) and should therefore be determined by current meter measurement or a tracer study.

Two sections of the river were selected for the tracer studies (see Figure 3.1). One section, having a narrow channel and sharp bends, was located between Mooney's Bay and Black Rapids Dam while the other, located just below Kars, had a wide channel with a gradual bend. These stretches of river typified the morphology of the entire river section studied.

Three fluorescent dyes were considered: pontacyl brilliant pink B, rhodamine B and rhodamine WT. Based on quality and cost comparison of the dyes as stated by several sources, (25,37,81) rhodamine WT was selected for use in the tracer studies. Wilson (81) and Hudspith (37) give detailed descriptions of the procedures for fluorometric dye tracing.

The fluorometer used to measure the dye tracer was a Turner, Model 111, equipped with a 50 cc flow-through door. Transparent vinyl garden hose (0.5" I.D.) was connected to the inlet and outlet of the flow-through door. Both the inlet and outlet hose were covered with three to four feet of black tape from the door to prevent sunlight from entering the fluorometer. The far UV lamp and the No. 540 primary filter and No. 590 secondary filter were used as recommended for rhodamine WT (25).

To continuously monitor the fluorometer readings, a Bausch and Lamb 10 mv VOM5 variable speed chart recorder was employed. Since all measurements were taken in a boat, a 2500 watt gasoline generator was required to power the pump and instruments. The inlet and outlet hoses were attached to the fluorometer so that the flow was pulled rather than pushed through the fluorometer to eliminate interference due to bubbles. Figure 3.5 shows a schematic layout of a typical monitoring station set up.

On the recommendation of Hudspith (37) a 240 volt amp constant voltage transformer was used to damp out any voltage fluctuations to the recorder and fluorometer. Despite the use of a transformer of this size, the chart speed was found to vary, indicating that the transformer was not able to keep a constant voltage. The variation in chart speed of this recorder was not noticed during laboratory use. To overcome this problem, the correct time was marked on the chart every ten minutes of operation.

Two fluorometers were used in the study: one was employed in the field while the other remained in the laboratory. The laboratory fluorometer was equipped with a single sample cell and had been calibrated prior to use. Figure 3.6 shows the calibration curve for the single cell sample fluorometer. To determine the concentrations of the dye from field recordings, grab samples were taken every ten or fifteen minutes during tracer measurement on the river and the time and chart readings noted. The concentration of the grab samples were determined with the laboratory fluorometer. A correlation curve between chart readings and grab sample concentration for each monitoring point was then made

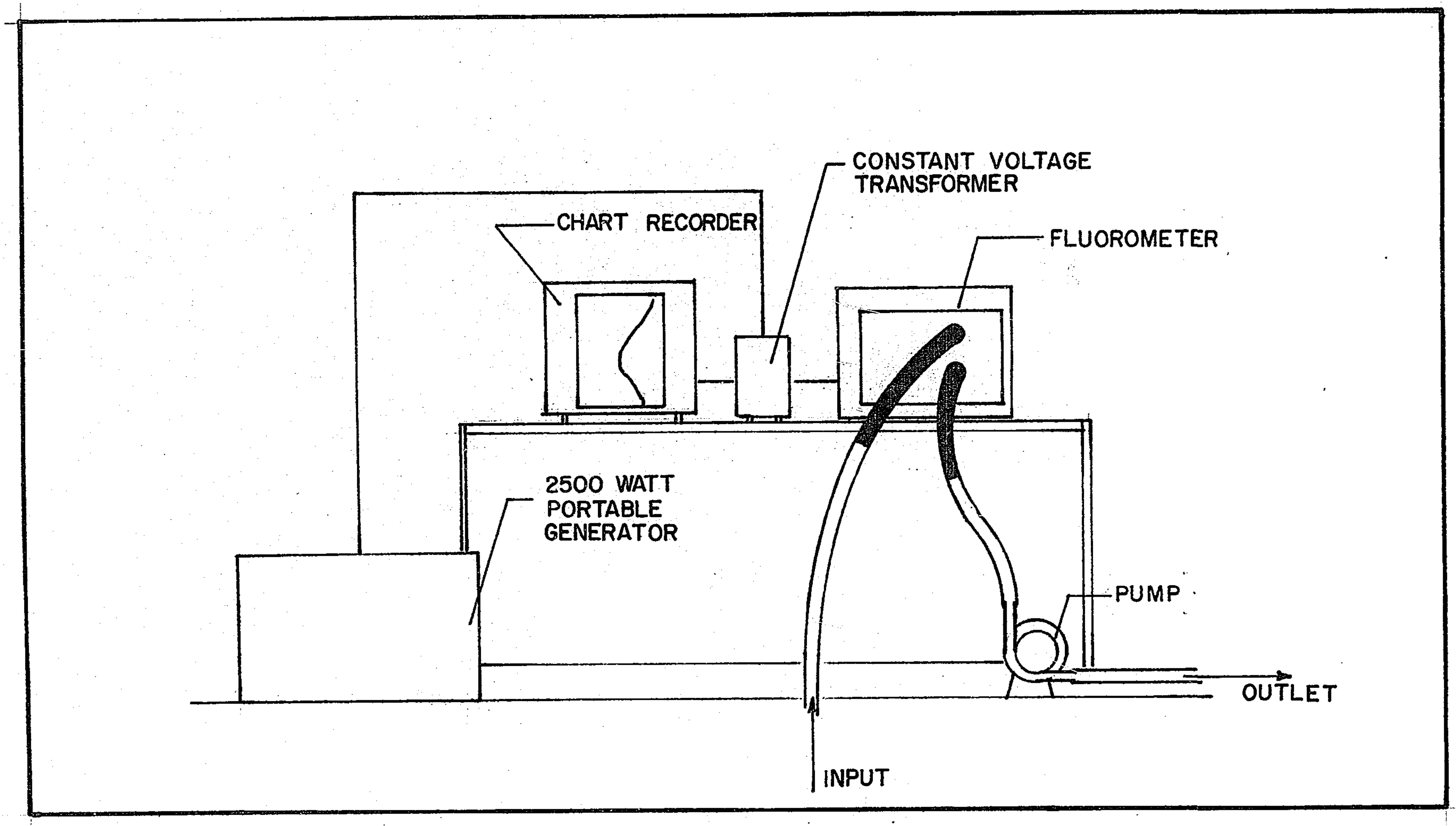

FIGURE 3.5 — MONITORING APPARATUS

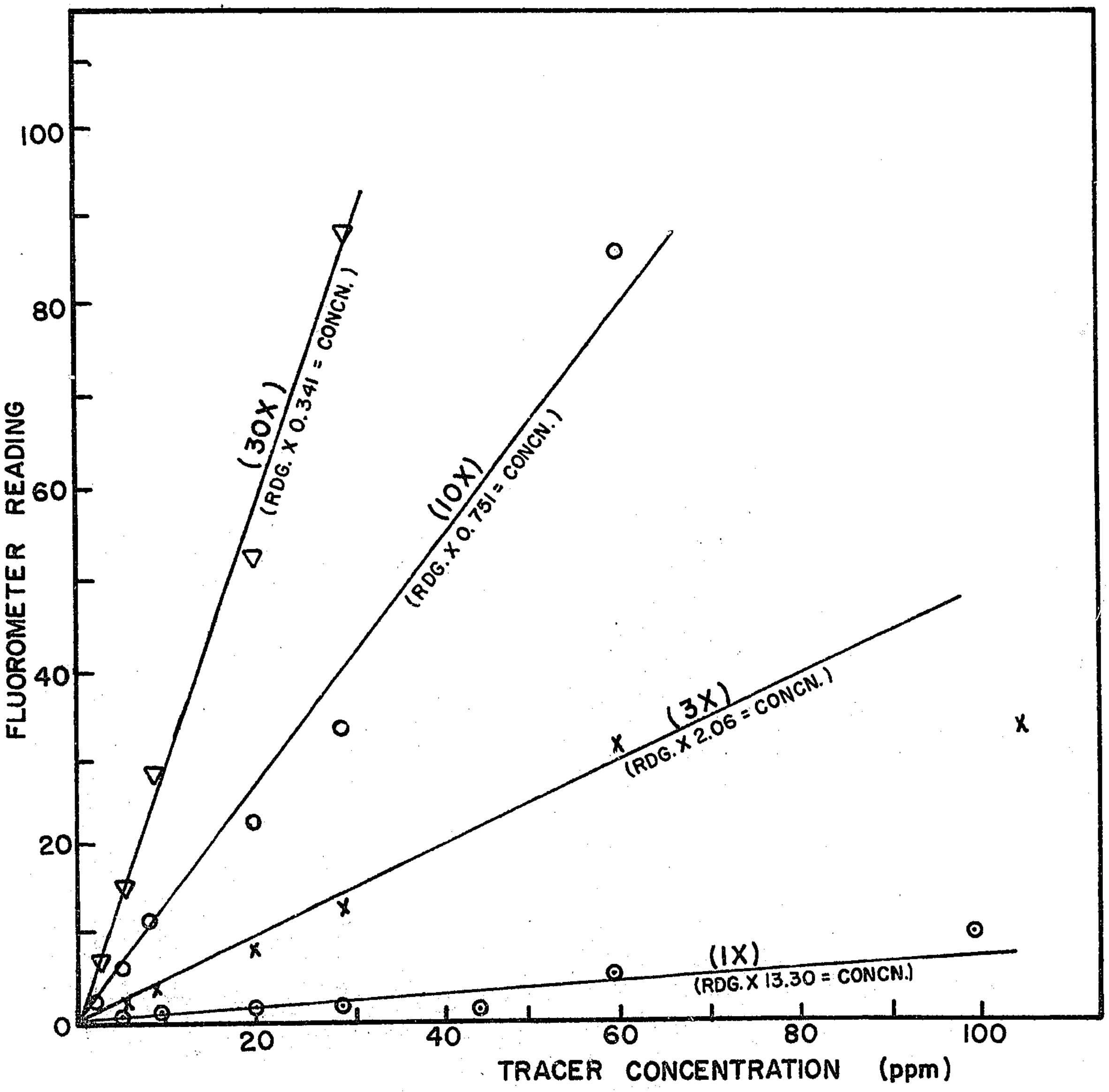

FIGURE 3.6 — CALIBRATION CURVES FOR FLUOROMETER WITH SINGLE SAMPLE CELL

(Figures 3.7 and 3.8). This procedure was used because it was felt that the field fluorometer would be subject to jarring and sudden shutdowns and start ups during power stoppages to refuel the generator, thus affecting the calibration and readings of the instrument. The drawback, however, with this procedure was that rhodamine WT could not be measured at concentrations less than approximately 2 ppb with a single sample cell, whereas with a 50 cc flow-through door, much lower concentrations could be detected.

As suggested by Wilson (81), the fluorometer was the last instrument to be turned on and always had a warm up time of not less than two hours before any portion of the injected tracer began to flow past a monitoring point.

The amount of dye required for each study was determined using the following formula developed by O'Connell (29).

$$M = \frac{CA(nx)^{1/2}H^{5/12}}{1.1 \times 10^{3}} \qquad (3.1)$$

where M = mass of dye in grams

C = expected concentration at the furthest downstream station in ppb

n = Manning's coefficient of stream roughness

x = distance in feet between the point of dye injection and the monitoring point furthest downstream

H = mean stream depth in feet

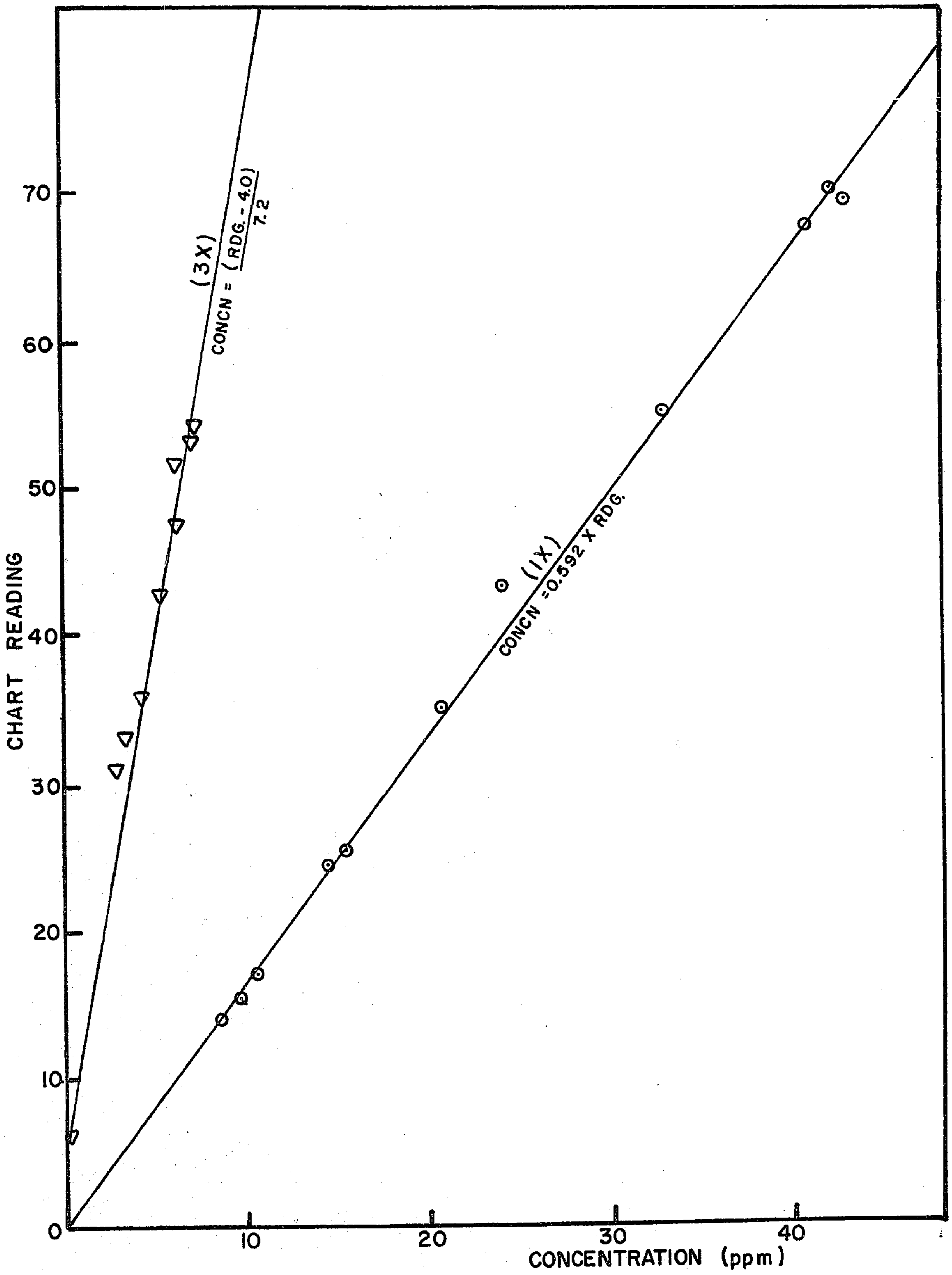

FIGURE 3.7— CALIBRATION OF CHART READINGS WITH GRAB SAMPLE CONCENTRATIONS — STUDY NO. 1

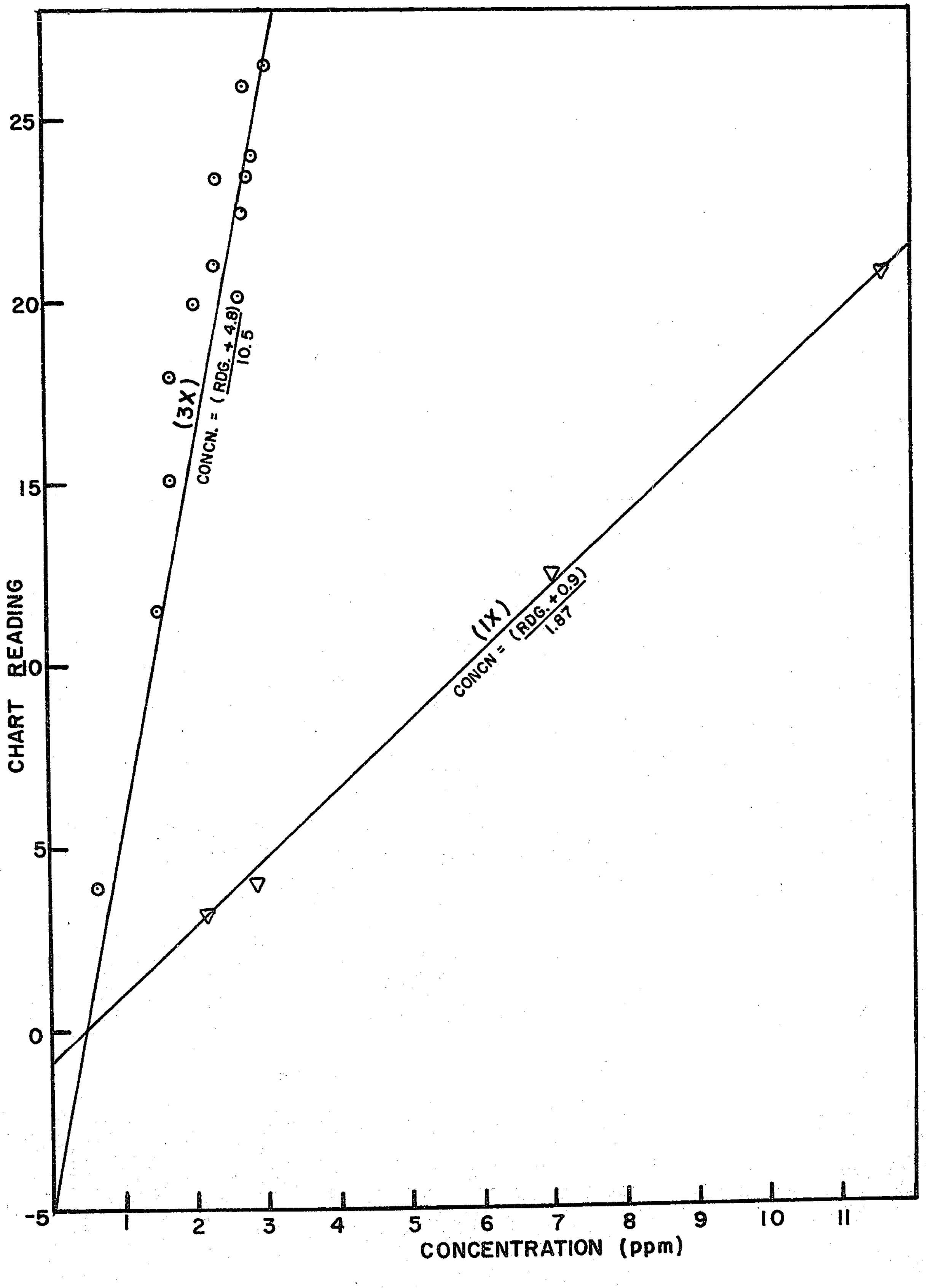

FIGURE 3.8 — CALIBRATION OF CHART READINGS WITH GRAB SAMPLE CONCENTRATIONS — STUDY NO. 2

A = cross-section area of the stream at injection point in square feet.

The calculated dye quantity was diluted to several gallons with tap water and released as a line source by discharging it from a boat moving at a constant speed across the river and as close to perpendicular to the stream flow as possible. The release points and the two measuring points in each study were chosen so that they could be pinpointed on existing topographic maps and the distances between them determined.

Only one point in the cross section was monitored for dye at each station. The two monitoring stations set up in each section were 0.296 and 1.1 miles from the injection point in Study No. 1 and 0.454 and 0.770 miles from injection point in Study No. 2. $D_L$ and the mean velocity of tracer, $\overline{u}$, were determined by the method of moments developed by Fischer (23) and described in Section 2.1.2. Despite the criticism of Thackston, Hays and Krenkel (75) that the method will likely give high $D_L$ values, the method is extremely easy to use, well suited for digital computation and should give a reasonable approximation of the order of magnitude of $D_L$. With two concentration time curves from two monitoring points, it is possible to check the value of $D_L$ by the routing method and alter it accordingly, to give a more accurate correlation between the observed and predicted downstream curve.

The mean time of travel of the tracer cloud was calculated from the following equation:

$$\overline{t}_A = \frac{1}{\Sigma c_i} \sum_{i=1}^{n} c_i t_i \qquad (3.2)$$

where $\overline{t}_A$ = mean time of passage past the monitoring point A

$n$ = number of points considered on the time concentration curve

$c_i$ = concentration in ppb recorded at time $t_i$.

The following equation gives the variance of the time concentration curves:

$$\sigma_A^2 = \frac{1}{\Sigma c_i} \Sigma t_i^2 c_i - \overline{t}_A^2 \qquad (3.3)$$

where $\sigma_A^2$ is the variance of the time concentration curve for monitoring point A.

The mean stream velocity $\overline{u}$ was determined by dividing the distance between stations by the difference in times of passage. The dispersion coefficient, $D_L$, was computed from

$$D_L = \frac{\overline{u}^2}{2} \frac{\sigma_A^2 - \sigma_B^2}{\overline{t}_A - \overline{t}_B} \qquad (3.4)$$

where $\sigma_A^2$ and $\sigma_B^2$ = variances of the time concentration curves at the upstream and downstream stations, respectively

$\overline{t}_A$ and $\overline{t}_B$ = mean time of passage of the tracer cloud past each station.

The time concentration curves for each monitoring station are plotted in Figures 3.9 and 3.10. The shape of the curves clearly shows the effect of dead zones within the river. For example, the curve at station 3 has a major and minor peak. The cause of the minor peak was assumed to be due to a relatively large slug of dye entering a dead zone and then quickly released back into the main stream lagging behind the principal mass of dye by several minutes. The rather undulating nature of curves 2 and 3 also indicate the effect of dead zones. Curve 1 is quite close to Gaussian probably because there were no major dead zones between the monitoring station and the injection point.

The computer programme used to evaluate $D_L$ and $\bar{u}$ is given in Appendix B. The computed values of $D_L$ and $\bar{u}$ are given in Table 3.2.

| Section | Discharge Velocity Q/A mi/day | $\bar{u}$ mi/day | $D_L$ mi$^2$/day |
|---|---|---|---|
| 1-T | .699 | 2.824 | .0245 |
| 2-T | .384 | 1.704 | .01514 |

TABLE 3.2 Dispersion and Convection Values

Once $\bar{u}$ was found, the length of the convective period was determined to check whether the monitoring points were in the diffusive length. Using equation 2.3 the lengths of the

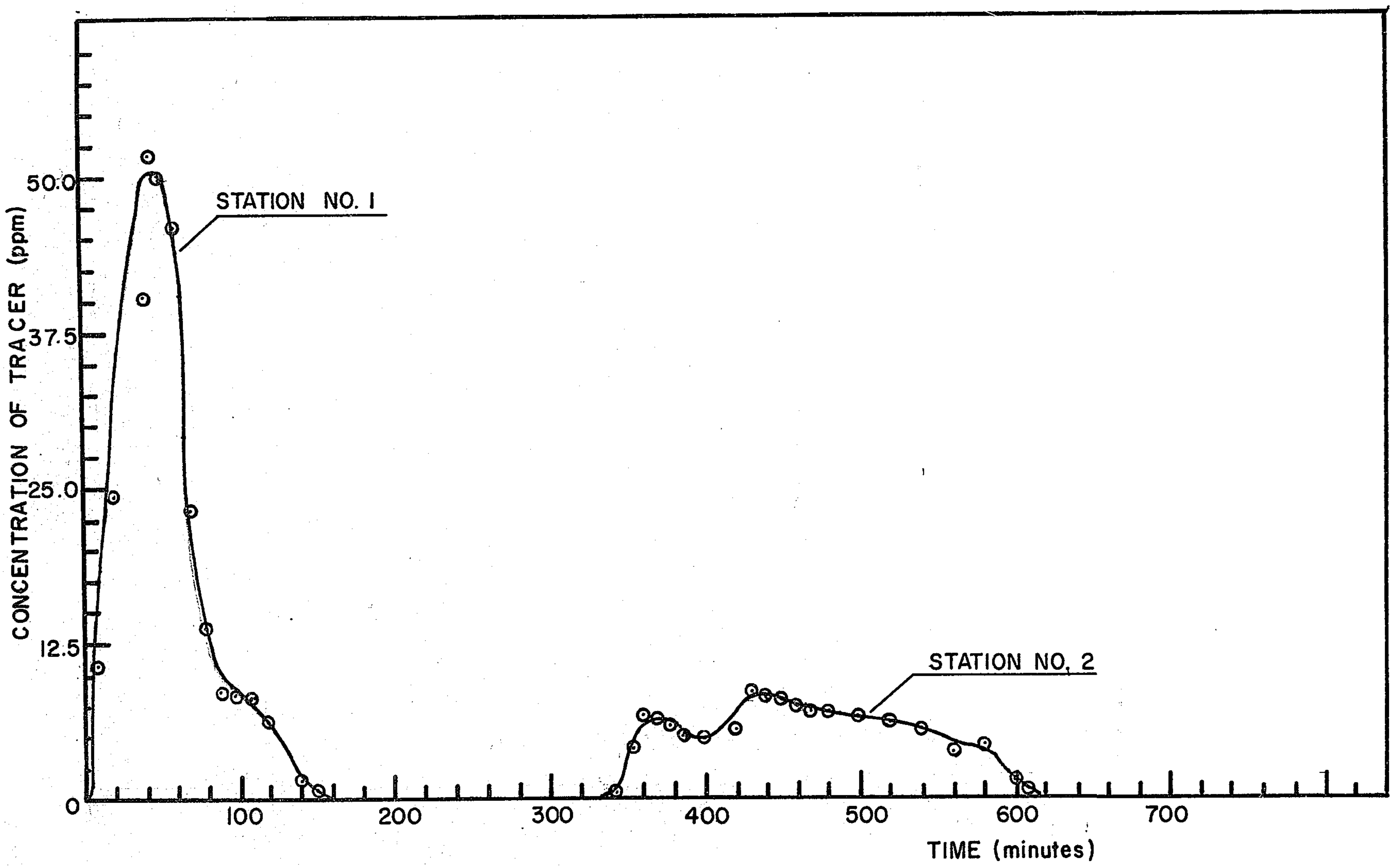

FIGURE 3.9 — TIME CONCENTRATION CURVES.
STUDY NO. I

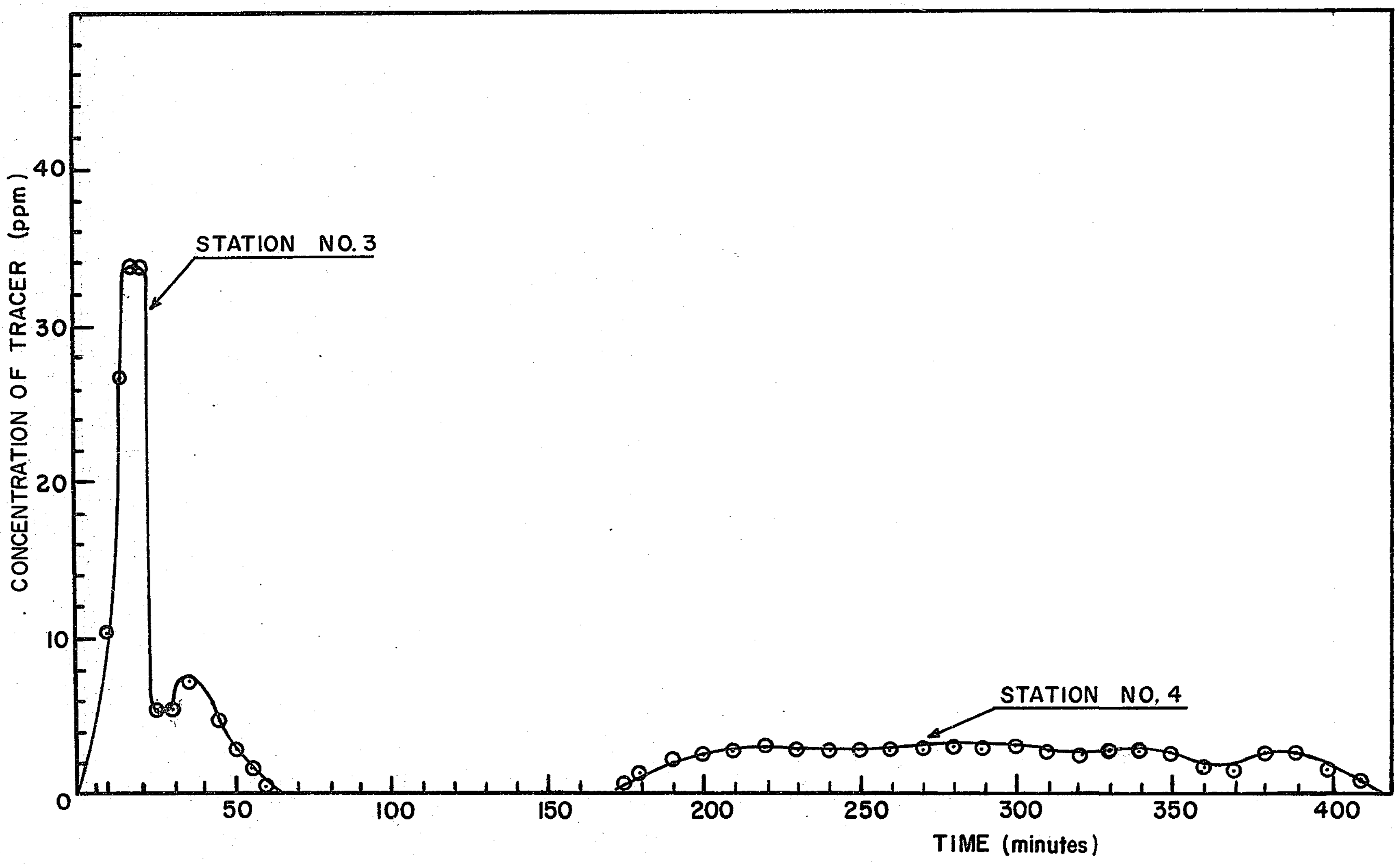

FIGURE 3.10 — TIME CONCENTRATION CURVES.
STUDY NO. 2

convective periods in both sections were determined and are shown in Table 3.3.

| Section | n | Rh<br>ft | $u^*$<br>ft/min | $\bar{u}$<br>ft/min | $\ell$<br>ft | $L_c$<br>mi |
|---|---|---|---|---|---|---|
| 1-T | 0.02 | 10.65 | $19.8 \times 10^{-2}$ | 10.356 | 150 | 9.41 |
| 2-T | 0.03 | 11.79 | $10.25 \times 10^{-2}$ | 6.266 | 250 | 16.20 |

TABLE 3.3 Lengths of Convective Periods with Hydraulic Values Used in its Determination

The high values of L and the difference between the mean velocities and the daily discharge velocities is believed to be due to the numerous dead zones in the sections and very low velocity gradients in the lateral and vertical directions. The effect of these dead zones could be seen as the tracer approached the first monitoring stations in each section. Figure 3.11 shows the outline of the tracer slug as it approached the first monitoring point in the first section, approximately two hours after injection, and as it approached the second station several hours later. It can be seen that the effective area of flow is considerably less than the average area of the section. The discharge velocities were calculated to be 24.8% and 22.6% of the mean velocities of the tracer cloud found in sections one and two, respectively. Consequently, to determine the mean stream velocity of other reaches using stream flow and cross section area, the average discharge velocity was divided by 0.248

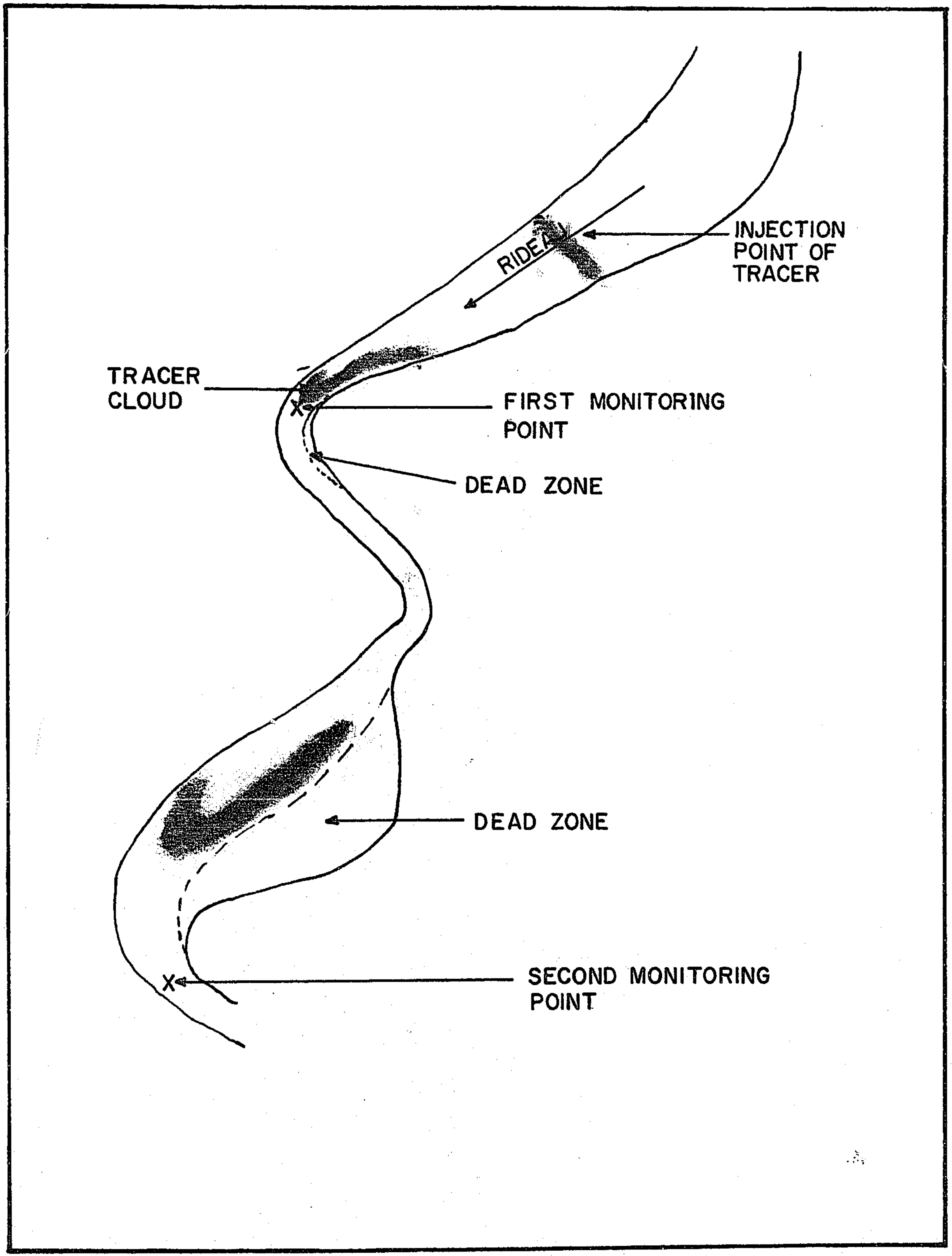

FIGURE 3.11 —— OBSERVED TRACER PATTERN
STUDY NO. 1

except in the reach around Kars where the discharge velocity was divided by 0.226.

O'Connor (45) has indicated that if the quantity $K_r D_L/\bar{u}^2$ is between 0.0 and 0.1, dispersion may be neglected. For the sections studied, these ratios were found to be .000596 and .000872. Since they were very much less then 0.1, dispersion was assumed to be insignificant, inspite of earlier beliefs to the contrary.

The magnitudes of $D_L$ that were determined were felt to approximate the dispersion characteristics found in the Rideau even though both monitoring points were in the convective zones. To accurately measure dispersion, it would have been necessary to measure vertical and lateral points in the river at each station which was not possible under the equipment and personnel limitations of this study.

### 3.3 River Reaction Rate Constant

To determine $K_r$, water samples were taken at two stations downstream from the town of Kemptville. The sections were chosen sufficiently close together so that the addition of BOD between stations was insignificant, the biochemical characteristics of the stream load remained constant, and the stations were far enough downstream from the Kemptville area so that removal by sedimentation was assumed to be complete and that all BOD removal between stations resulted solely from oxidation.

Samples at each station were taken only minutes apart, the mean time of travel having not yet been determined by dye studies. However, it was felt that the BOD profile between the two points was relatively constant. The samples were collected and taken to the laboratory and stored in a cold room overnight prior to analysis. The following day the samples were subjected to the standard BOD tests with one to five day BOD's being determined. Using this data and the method of moments developed by Moore et al (52) the ultimate BOD at the upstream station was computed as 3.35 ppm and at the downstream station, 2.34 ppm (see Appendix C for BOD results).

The mean travel time was determined by dividing the distance between stations, 2.37 miles, by the mean stream velocity which was estimated by

$$\bar{u} = Q/A \times 1/.226 \qquad (3.5)$$

where Q, the stream flow, is 150 cfs; A, the average cross section area between stations, is $9.1 \times 10^3$ sq ft; and, the value .226 was determined by dye tests to be the ratio of cross-section velocity to mean stream velocity near Kars. Mean travel time is therefore 1.990 days. Using equation 2.6 in Section 2.1.3

$$K_r = \frac{1}{1.99} \log 3.35 - \log 2.34 \qquad (3.6)$$

Hence, $K_r$ = .175 per day to the base e.

## 3.4 Measurement of Photosynthesis and Respiration

To obtain an approximation of the magnitude of oxygen production through photosynthesis in the Rideau River, the light and dark bottle technique (70) was used in four locations. The locations selected were at Mooney's Bay, below the Long Island locks where the river was relatively fast flowing, shallow and free of rooted plants; approximately one mile upstream of Kars where the water was sluggish, in a deep channel with shallow areas containing an abundance of rooted plants; and at the mouth of Kemptville Creek where the channel was choked with weeds (see Figure 3.1 for map location).

At each station the bottles were placed at four depths. Since the zone of highest production usually occurs in the top three feet of the euphotic zone, samples were placed at depths of half a foot, one and a half feet, and three and a half feet. The fourth set of bottles was placed near the bottom of the euphotic zone.

The depth of the euphotic zone was found by multiplying the Seechi disc reading by two. Verduin (78) has quoted sources which give values for the multiplication factor varying from 2.5 to 5.0. However, these values were found in studies on lakes where algal concentrations are not homogeneous. In the Rideau it was assumed that the turbulence was great enough to give a homogeneous algal distribution.

A Meyer sampler was used to collect samples at the four different depths at which the light and dark bottles were incubated. To obtain the initial and final dissolved oxygen concentrations in the bottles, the Winkler method as outlined in Standard Methods (70) was employed. All samples were fixed in the field and brought back to the laboratory for titration.

Only one light and one dark bottle were used at each depth and were left in the water for 24 hours to ensure that the oxygen production and respiration would be measureable. This was not necessary and in fact magnified any erros caused by conditions cited in Section 2.2.4.

The results from these field tests are given in Appendix D. The respiration and gross photosynthetic oxygen production are plotted versus depth. It is assumed that there is zero oxygen production beyond the euphotic zone but that respiration is constant throughout the cross section because of a uniform algal concentration due to turbulence. To determine the average daily photosynthetic oxygen production, $G.P_{AV}$, and respiration, R, the curve was integrated with depth. Table 3.4 gives the calculated values.

| Section | $G.P_{AV}$ ppm | R ppm | $G.P_{AV}/R$ |
|---|---|---|---|
| Mooney's Bay (1-PR) | 0.455 | 0.845 | 0.539 |
| Below the Long Island (2-PR) | 2.46 | 0.99 | 2.48 |
| Upstream of Kars (3-PR) | 0.298 | 0.504 | 0.591 |
| Near Kemptville Creek (4-PR) | 0.15 | 0.205 | 0.731 |

TABLE 3.4 Average Daily Photosynthetic Oxygen Production and Respiration

It is interesting to note that the $G.P_{AV}/R$ ratio is 2.48 below Long Island while at Mooney's Bay it is .539. The low oxygen production at Mooney's Bay may be caused by the pumps continually flushing out the beach areas and producing convection currents in the bay which transport the algae in and out of the euphotic zone. Since the aphotic zone is much greater in area than the euphotic zone the respiration rate should be higher than the photosynthetic rate.

The other two sections studied were in areas where there was a large concentration of rooted plants. The low rates of oxygen production and respiration indicate small algal concentrations. Thus it would seem that either rooted plants or algae dominate an area to the relative exclusion of the other. For a first approximation of $G.P_{AV}$, the values found below the Long Island Locks were taken to hold for the entire river under study except for Mooney's Bay where the value obtained through field data was used.

The values obtained for the ratio of $G.P_{AV}$ to R in the Rideau compare favourably with values obtained by O'Connor and Di Toro (55) from studies on several rivers in the United States and Europe. Although the rivers studied were much smaller than the Rideau and rates for $G.P_{AV}$ and R were generally much higher, the ratio of these two values varied between 0.32 and 2.0.

## 3.5 Selection of the Other Stream Constants

As previously stated, those constants that were not evaluated through laboratory or field experiments, were determined by the use of semi-empirical formulations discussed in the sections of Chapter 2 dealing with the factors which affect stream response.

Since no data was collected to obtain reaction rates for nitrification, equation 2.13, developed by Pence <u>et al</u> (62) from their study on the Delaware River Estuary, was used in the model.

To describe the effect of weirs, equation 2.17 was employed. The effects of a thermocline were neglected in the model. No thermocline was observed in Mooney's Bay, due to the large recirculating pumps installed by the City of Ottawa to flush beach areas with cleaner water from the middle section of the bay. There was a thermocline at the Long Island impoundment at approximately a depth of twelve feet; but, since the average depth in the impoundment was 14.33 feet, it was thought that its existence did not significantly affect water quality. Values of 1.0 and 1.25, respectively, have been assumed for the empirical constants b and a found in equation 2.17 which was used to estimate the transfer of oxygen at the weirs.

The atmospheric reaeration rate, $k_2$, was determined by equation 2.23 developed by Thackston, Hays and Krenkel (75). The terms in the equation, such as mean stream velocity and depth, were obtained through the field studies.

# CHAPTER 4

# THE WATER QUALITY MODEL FOR THE RIDEAU RIVER

The identification and evaluation of the stream constants of the Rideau River have been determined, a mathematical expression describing their effect on the oxygen response of the river has been developed, and methods for solving the equation discussed. The next step is to synthesize this information and develop a specific model for the Rideau River, generate water quality data, and evaluate its validity through comparison with existing data.

## 4.1 Mathematical Representation of the Rideau River

The stream flow and water levels of the Rideau River are closely controlled by the Federal Department of Transport for the purpose of navigation. Consequently, there are three different hydrologic periods during the year. To increase the upstream reservoir capacity for spring runoff, the water levels are lowered during the fall producing low water levels with low stream flow. During spring runoff the water levels and stream flow are high and in the summer the levels are maintained at sufficient height for navigation. Extremely low but constant flows predominate during the summer period, with the occasional short periods of higher flows due to storms. To model the Rideau River for year round conditions, it would be necessary to collect the required physical, chemical, and biological data during the different periods of flow. In this study, data was collected during the summer and consequently, only summer conditions were simulated.

The data from the Department of Transport gauging stations at Merrickville, 21 miles above the town of Kars, and at Long Island indicate that the stream flow during the summer varies between 150 cfs and 200 cfs. Thus, tributary inflow only balances evaporation loses between Merrickville and Long Island. Since the only tributary of significance between Long Island and Mooney's Bay is the Jock River, which is almost dry during the summer with an estimated flow of 3 cfs, it was assumed that the flow in this section remained the same as above Long Island. Water quality data on the Rideau River is very meager. The Ontario Water Resources Commission (OWRC) does collect monthly data which include dissolved oxygen, BOD, temperature, total kjeldahl nitrogen, ammonia, nitrite and nitrate nitrogen measurements. Within the section of the river being studied, there are three locations where sampling is done: at the town of Kars, 6.3 miles downstream of Kars, and at the Black Rapids dam. No attempt was made by the OWRC to measure the same slug of water at these stations since there is only two hours between the time of sampling at each station, and the actual time of travel is in the order of approximately 2.5 days.

It was assumed that the BOD and NOD concentrations at Kars resulted from discharges in the Kemptville area, seven miles upstream, and the waste loads were well mixed throughout the main stream flow. The concentrations at Kars were assumed to be steady. Having assumed steady state conditions, and dispersion to be insignificant, the solutions to equations 2.28 to 2.30 can be determined analytically and have been found by Dobbins (13) and Camp (8) to be:

i) for BOD

$$L = Loe^{-K_r t} + \frac{L_a}{K_r}(1 - e^{-K_r t}) \qquad (4.1)$$

ii) for NOD

$$L_N = Lo_N e^{-K_N t} + \frac{L_{a_N}}{K_N}(1 - e^{K_N t}) \qquad (4.2)$$

iii) for DO deficit

$$D = Doe^{-K_2 t} + \frac{K_r}{K_2 - K_r}\left(Lo - \frac{L_a}{K_r}\right)(e^{-K_r t} - e^{-K_2 t})$$

$$+ \frac{K_r}{K_2 K_r}(1 - e^{-K_2 t}) + \frac{K_N}{K_2 - K_N}\left(Lo_N - \frac{L_{a_N}}{K_N}\right)(e^{-K_N t} - e^{-K_2 t})$$

$$+ \frac{K_N L_{a_N}}{K_2 K_N}(1 - e^{-K_2 t}) + \frac{P_{AV}}{K_2}(1 - e^{K_2 t})$$

$$- \frac{R}{K_2}(1 - e^{-K_2 t}) + \frac{B_D}{K_2}(1 - e^{-K_2 t}) \qquad (4.3)$$

In the above formulation Lo, $Lo_N$, and Do are the initial BOD, NOD, and dissolved oxygen deficit. The other terms are as defined in Section 2.2.

## 4.2 Segmentation of the Rideau River

The 19.9 miles of the main channel of the Rideau River and the 3.1 miles of the Manotick Channel around Long Island were divided into thirteen reaches. The physical, chemical, and biological characteristics were assumed to be uniform within each reach. The river was sectioned wherever there was a discontinuity in one of the stream characteristics. Thus, a new reach began where a source or sink of dissolved oxygen originated (at a weir), at an input of BOD and NOD loading (Uplands treatment plant), and where the oxygen demand of the sediments changed abruptly (see Figure 3.1, for map location of reaches).

To obtain the average cross section area and average depth of each reach, sounding rolls which were from a study undertaken by the Canadian Hydrographic Service in the summer of 1970 were acquired. These soundings showed the complete cross section profile of the river at intervals of several hundred feet or less. The average cross section area for each reach was simply taken as the average of the areas computed from the soundings contained within each section. The discharge velocity was taken as the flow divided by the average cross section area of each reach. To calculate the mean stream velocity, the discharge velocities were divided by a factor of 0.226 in the first reach and 0.248 in the remainder. A summary of the other stream characteristics for each reach of the model is given in Tables 4.1 to 4.3.

| Reach | Length (Miles) | Average Cross-Section Area (Sq. Ft.) | Average Depth (Ft.) | Flow[3] (cfs) | Mean Stream Velocity (Miles/day) |
|---|---|---|---|---|---|
| 1 | 6.993 | 4,789 | 12.36 | 150.00 | 2.27 |
| 2 | 2.245 | 3,132 | 10.05 | 91.50[2] | 1.93 |
| 3 | 0.602 | 8,211 | 14.33 | 91.50[2] | 0.73 |
| 4[1] | 0.869 | 2,295 | 7.53 | 58.50[2] | 2.64 |
| 5[1] | 2.155 | 391 | 3.00 | 58.50[2] | 9.87 |
| 6 | 0.680 | 1,466 | 6.34 | 150.00 | 2.63 |
| 7 | 0.284 | 3,371 | 9.00 | 150.00 | 2.94 |
| 8 | 2.765 | 4,118 | 10.81 | 150.00 | 2.40 |
| 9 | 2.305 | 5,250 | 12.18 | 150.00 | 1.89 |
| 10 | 1.711 | 3,971 | 11.43 | 150.00 | 2.49 |
| 11 | 0.485 | 2,869 | 11.22 | 151.13 | 3.45 |
| 12 | 0.934 | 2,621 | 8.76 | 151.13 | 3.78 |
| 13 | 0.885 | 15,328 | 15.76 | 151.13 | 0.65 |

[1] Manotick Channel Reaches.

[2] Flow divided into channels by ratio of areas of Reaches 2 and 4.

[3] Flow data taken from Department of Transport (Canada) records for Long Island gauging station.

TABLE 4.1 STREAM CHARACTERISTICS FOR EACH REACH

| Reach | $K_N$-23° (per day) | Average Daily Photosynthesis ppm/day | Average Daily Respiration ppm/day | $O_2$ Uptake Rates of Sediments gms/sq. m./day | BOD Diffusion Rate of Sediments gms/sq. m./day |
|---|---|---|---|---|---|
| 1 | 0.062 | 1.75 | 0.99 | 0.350 | 1.000 |
| 2 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 3 | 0.062 | 1.75 | 0.99 | 0.298 | |
| 4 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 5 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 6 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 7 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 8 | 0.062 | 1.75 | 0.99 | 0.000 | 0.000 |
| 9 | 0.062 | 1.75 | 0.99 | 0.080 | 0.052 |
| 10 | 0.062 | 1.75 | 0.99 | 0.080 | 0.052 |
| 11 | 0.062 | 1.75 | 0.99 | 0.080 | 0.052 |
| 12 | 0.062 | 1.75 | 0.99 | 0.080 | 0.052 |
| 13 | 0.062 | 0.455 | 0.845 | 0.298 | 0.062 |

TABLE 4.2 STREAM CHARACTERISTICS FOR EACH REACH

| Reach | Kr (per day) | BOD from Local Runoff ppm/day | Direct Waste Input Flow (cfs) | BOD of Waste Input ppm | NOD of Waste Input ppm | DO of Waste Input ppm |
|---|---|---|---|---|---|---|
| 1 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 2 | 0.175 | 1.0 | 0 | 0 | 0 | 0 |
| 3 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 4 | 0.175 | 1.0 | 0 | 0 | 0 | 0 |
| 5 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 6 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 7 | 0.175 | 1.0 | 0 | 0 | 0 | 0 |
| 8 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 9 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 10 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 11 | 0.175 | 0.0 | 1.125[4] | 40.0[5] | 7.5[5] | 2.0[5] |
| 12 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |
| 13 | 0.175 | 0.0 | 0 | 0 | 0 | 0 |

[4] Value obtained through personal communication with Mr. L. Kamp, Environment Canada, Ottawa.

[5] Averaged from data collected by Environment Canada at the Uplands Treatment Plant, Ottawa.

TABLE 4.3 STREAM CHARACTERISTICS FOR EACH REACH

```
               REACH N O.     1


AREA=            4789 .000           SQFT
DEPTH=             12 .360           FT
VELOCITY=           2 .268           MI/DAY
BODA=               0 .028           MG/L/DAY
VOLUME=  5006959787 .769             L
AREA OF SED=1413898 .657             SQ.M
RN=                 0 .062           1/DAY
ENERGY GRADIENT=    0 .000079101     FT/FT
OXSED=              0 .350           GMS/SQ.M/DAY
DOSAT=              8 .498           MG/L/DAY
SEDR=               0 .100           GMS/SQ.M/DAY
REAERATION COEF.=   0 .00522         1/DAY
BD=                 0 .099           MG/L/DAY


DISTANCE       BOD         NOD          DO DE FICICIT

MILES          MG/L        MG/L          MG/ L

0.699          0.948       1.050         -0. 557
1.399          0.900       1.030         -0. 616
2.098          0.854       1.010         -0. 680
2.797          0.811       0.991         -0. 748
3.497          0.771       0.972         -0. 820
4.196          0.733       0.954         -0. 895
4.895          0.698       0.936         -0. 974
5.594          0.664       0.918         -1. 057
6.294          0.633       0.901         -1. 143
6.993          0.603       0.884         -1. 231
```

TABLE 4.4 SIMULATION RESULTS – REACH NO. 1

LIST OF SYMBOLS

AREA=Average x-section area of reach

DEPTH=Average depth of reach

VELOCITY=Mean stream velocity in reach

BODA=Addition of BOD from sediments, surface runoff, and groundwater accrual

VOLUME=Volume of water in reach

AREA OF SED=Area of bottom sediments

RN=NOD reaction rate constant

ENERGY GRADIENT=Slope of the energy grade line

OXSED and BD=Oxygen demand of sediments

DOSAT=DO saturation value

SEDR=Addition of BOD from sediments only

REAERATION COEF=Atmospheric re-aeration rate coefficient

```
          REACH N O.     2


AREA=             3132 .000          SQFT
DEPTH=              10 .050          FT
VELOCITY=            1 .928          MI/DAY
BODA=                1 .000          MG/L/DAY
VOLUME=  1051244742 .763             L
AREA OF SED= 365329 .588             SQ.M
RN=                  0 .062          1/DAY
ENERGY GRADIENT=   0 .000075378      FT/FT
OXSED=               0 .000          GMS/SQ.M/DAY
DOSAT=               8 .498          MG/L/DAY
SEDR=                0 .000          GMS/SQ.M/DAY
REAERATION COEF.=  0 .00565          1/DAY
BD=                  0 .000          MG/L/DAY


DISTANCE       BOD        NOD         DO DE FICICIT

MILES          MG/L       MG/L          MG/ L

7.218          0.704      0.877         -1. 273
7.442          0.803      0.871         -1. 312
7.667          0.900      0.865         -1. 349
7.891          0.994      0.858         -1. 384
8.116          1.086      0.852         -1. 417
8.340          1.176      0.846         -1. 448
8.564          1.264      0.840         -1. 477
8.789          1.350      0.834         -1. 505
9.013          1.434      0.828         -1. 531
9.238          1.516      0.822         -1. 555
```

TABLE 4.5   SIMULATION RESULTS - REACH NO. 2

```
          REACH N O.    3


AREA=             8211 .000         SQFT
DEPTH=              14 .330         FT
VELOCITY=            0 .735         MI/DAY
BODA=                0 .015         MG/L/DAY
VOLUME=    739023556 .088           L
AREA OF SED= 177668 .900            SQ.M
RN=                  0 .062         1/DAY
ENERGY GRADIENT=     0 .000006708   FT/FT
OXSED=               0 .298         GMS/SQ.M/DAY
DOSAT=               8 .498         MG/L/DAY
SEDR=                0 .062         GMS/SQ.M/DAY
REAERATION COEF.=    0 .00141       1/DAY
BD=                  0 .072         MG/L/DAY


DISTANCE      BOD         NOD         DO DE FICICIT

MILES         MG/L        MG/L         MG/ L

9.298        1.492       0.818        -1. 567
9.358        1.469       0.814        -1. 581
9.419        1.446       0.809        -1. 595
9.479        1.424       0.805        -1. 609
9.539        1.402       0.801        -1. 624
9.599        1.380       0.797        -1. 639
9.659        1.359       0.793        -1. 654
9.720        1.338       0.789        -1. 670
9.780        1.318       0.785        -1. 687
9.840        1.297       0.781        -1. 704
```

TABLE 4.6   SIMULATION RESULTS - REACH NO. 3

```
              REACH N O.    4


AREA=            2291 .000          SQFT
DEPTH=              7 .530          FT
VELOCITY=           1 .685          MI/DAY
BODA=               1 .000          MG/L/DAY
VOLUME=     297653232 .844          L
AREA OF SED= 136113 .174            SQ.M
RN=                 0 .062          1/DAY
ENERGY GRADIENT=    0 .000083049    FT/FT
OXSED=              0 .000          GMS/SQ.M/DAY
DOSAT=              8 .498          MG/L/DAY
SEDR=               0 .000          GMS/SQ.M/DAY
REAERATION COEF.=   0 .00685        1/DAY
BD=                 0 .000          MG/L/DAY


DISTANCE      BOD          NOD            DO DE FICICIT

MILES         MG/L         MG/L            MG/ L

0.087        0.648        0.881           -1. 250
0.174        0.693        0.878           -1. 269
0.261        0.737        0.875           -1. 287
0.348        0.781        0.872           -1. 305
0.435        0.824        0.870           -1. 322
0.521        0.867        0.867           -1. 339
0.608        0.909        0.864           -1. 355
0.695        0.951        0.861           -1. 371
0.782        0.993        0.858           -1. 387
0.869        1.034        0.856           -1. 402


DO DEFICIT BELOW WE IR AT MANOTICK=  -0.0000 0
```

TABLE 4.7 SIMULATION RESULTS - REACH NO. 4
(MANOTICK CHANNEL)

```
                REACH N O.    5


AREA=             391 .000          SQFT
DEPTH=              3 .000          FT
VELOCITY=           9 .872          MI/DAY
BODA=               0 .000          MG/L/DAY
VOLUME=   125976567 .265            L
AREA OF SED= 144117 .807            SQ.M
RN=                 0 .062          1/DAY
ENERGY GRADIENT=    0 .009689016    FT/FT
OXSED=              0 .000          GMS/SQ.M/DAY
DOSAT=              8 .498          MG/L/DAY
SEDR=               0 .000          GMS/SQ.M/DAY
REAERATION COEF.=   0 .11946        1/DAY
BD=                 0 .000          MG/L/DAY


DISTANCE      BOD        NOD          DO DE FICICIT

MILES         MG/L       MG/L           MG/ L

1.085         1.029      0.855          -0. 007
1.300         1.025      0.853          -0. 014
1.515         1.020      0.852          -0. 020
1.731         1.016      0.851          -0. 027
1.946         1.011      0.850          -0. 034
2.162         1.007      0.849          -0. 041
2.377         1.003      0.848          -0. 048
2.593         0.998      0.846          -0. 055
2.808         0.994      0.845          -0. 061
3.024         0.989      0.844          -0. 068
```

TABLE 4.8 SIMULATION RESULTS - REACH NO. 5
(MANOTIC CHANNEL)

```
          REACH N O.    6


AREA=            1466 .000          SQFT
DEPTH=              6 .340          FT
VELOCITY=           6 .751          MI/DAY
BODA=               0 .000          MG/L/DAY
VOLUME=    149041983 .344          L
AREA OF SED=  81359 .326          SQ.M
RN=                 0 .062          1/DAY
ENERGY GRADIENT=  0 .001688819     FT/FT
OXSED=              0 .000          GMS/SQ.M/DAY
DOSAT=              8 .498          MG/L/DAY
SEDR=               0 .000          GMS/SQ.M/DAY
REAERATION COEF.= 0 .03400         1/DAY
BD=                 0 .000          MG/L/DAY


DISTANCE      BOD        NOD          DO DE FICICIT

MILES         MG/L       MG/L           MG/ L

 9.908        1.175      0.805          -0. 030
 9.976        1.172      0.805          -0. 033
10.044        1.170      0.804          -0. 036
10.112        1.168      0.804          -0. 039
10.180        1.165      0.803          -0. 042
10.248        1.163      0.803          -0. 045
10.316        1.161      0.802          -0. 048
10.384        1.158      0.802          -0. 051
10.452        1.156      0.801          -0. 054
10.520        1.154      0.801          -0. 057
```

TABLE 4.9   SIMULATION RESULTS - REACH NO. 6

```
DO DEFICIT BELOW WE IR AT LONG ISLAND=  -0.0 0000

 PARAMETERS AFTER M IXING BELOW LONG ISLAND DAM

9.840          1.177 2          0.806          -0.027
```

TABLE 4.10 STREAM PARAMETERS AT THE JUNCTION OF THE MANOTICK CHANNEL AND THE WEIR AT LONG ISLAND

```
              REACH N O.    7


AREA=           3371 .000          SQFT
DEPTH=             9 .000          FT
VELOCITY=          2 .936          MI/DAY
BODA=              1 .000          MG/L/DAY
VOLUME=   143134007 .445           L
AREA OF SED=  54687 .464           SQ.M
RN=                0 .062          1/DAY
ENERGY GRADIENT=  0 .000198438    FT/FT
OXSED=             0 .000          GMS/SQ.M/DAY
DOSAT=             8 .498          MG/L/DAY
SEDR=              0 .000          GMS/SQ.M/DAY
REAERATION COEF.= 0 .00971         1/DAY
BD=                0 .000          MG/L/DAY


DISTANCE       BOD         NOD          DO DE FICICIT

MILES          MG/L        MG/L          MG/ L

10.548         1.161       0.800         -0. 059
10.577         1.168       0.800         -0. 062
10.605         1.176       0.799         -0. 065
10.634         1.183       0.799         -0. 068
10.662         1.191       0.798         -0. 071
10.690         1.198       0.798         -0. 074
10.719         1.205       0.797         -0. 076
10.747         1.213       0.797         -0. 079
10.776         1.220       0.796         -0. 082
10.804         1.227       0.796         -0. 085
```

TABLE 4.11  SIMULATION RESULTS - REACH NO. 7

```
          REACH N O.    8


AREA=           4118 .000         SQFT
DEPTH=            10 .810         FT
VELOCITY=          2 .403         MI/DAY
BODA=              0 .000         MG/L/DAY
VOLUME=  1702343575 .646          L
AREA OF SED= 546006 .639          SQ.M
RN=                0 .062         1/DAY
ENERGY GRADIENT=  0 .000105292    FT/FT
OXSED=             0 .000         GMS/SQ.M/DAY
DOSAT=             8 .498         MG/L/DAY
SEDR=              0 .000         GMS/SQ.M/DAY
REAERATION COEF.= 0 .00644        1/DAY
BD=                0 .000         MG/L/DAY


DISTANCE       BOD          NOD           DO DE FICICIT

MILES          MG/L         MG/L           MG/ L

11.080        1.199        0.790          -0. 119
11.357        1.172        0.785          -0. 154
11.633        1.145        0.779          -0. 190
11.910        1.119        0.774          -0. 227
12.186        1.093        0.768          -0. 264
12.463        1.068        0.763          -0. 302
12.739        1.044        0.757          -0. 341
13.016        1.020        0.752          -0. 380
13.292        0.997        0.746          -0. 420
13.569        0.974        0.741          -0. 461
```

TABLE 4.12  SIMULATION RESULTS - REACH NO. 8

```
          REACH N O.    9


AREA=           5250 .000          SQFT
DEPTH=            12 .180          FT
VELOCITY=          1 .885          MI/DAY
BODA=              0 .015          MG/L/DAY
VOLUME=  1809239127 .017           L
AREA OF SED= 514904 .883           SQ.M
RN=                0 .062          1/DAY
ENERGY GRADIENT=   0 .000055232    FT/FT
OXSED=             0 .080          GMS/SQ.M/DAY
DOSAT=             8 .498          MG/L/DAY
SEDR=              0 .052          GMS/SQ.M/DAY
REAERATION COEF.=  0 .00439        1/DAY
BD=                0 .023          MG/L/DAY


DISTANCE      BOD         NOD          DO DE FICICIT

MILES         MG/L        MG/L          MG/ L

13.799        0.952       0.735         -0. 502
14.030        0.931       0.730         -0. 544
14.260        0.910       0.724         -0. 587
14.491        0.890       0.719         -0. 630
14.721        0.870       0.713         -0. 674
14.952        0.851       0.708         -0. 719
15.182        0.832       0.703         -0. 764
15.413        0.813       0.697         -0. 810
15.643        0.795       0.692         -0. 856
15.874        0.778       0.687         -0. 903


 DO DEFICIT BELOW W EIR AT BLACK RAPIDS=  -0 .00000
```

TABLE 4.13   SIMULATION RESULTS - REACH NO. 9

```
          REACH N O.   10


AREA=            3971 .000          SQFT
DEPTH=             11 .430          FT
VELOCITY=           2 .492          MI/DAY
BODA=               0 .016          MG/L/DAY
VOLUME=  1015817370 .029          L
AREA OF SED= 310776 .015          SQ.M
RN=                 0 .062          1/DAY
ENERGY GRADIENT=  0 .000106315    FT/FT
OXSED=              0 .080          GMS/SQ.M/DAY
DOSAT=              8 .498          MG/L/DAY
SEDR=               0 .052          GMS/SQ.M/DAY
REAERATION COEF.= 0 .00630        1/DAY
BD=                 0 .024          MG/L/DAY


DISTANCE       BOD         NOD          DO DE FICICIT

MILES          MG/L        MG/L           MG/ L

16.045         0.768       0.684          -0. 027
16.216         0.759       0.681          -0. 053
16.387         0.750       0.678          -0. 081
16.558         0.740       0.675          -0. 108
16.729         0.731       0.672          -0. 135
16.901         0.723       0.670          -0. 163
17.072         0.714       0.667          -0. 190
17.243         0.705       0.664          -0. 218
17.414         0.696       0.661          -0. 246
17.585         0.688       0.658          -0. 274
```

TABLE 4.14  SIMULATION RESULTS - REACH NO. 10

```
PARAMETERS AT UPLA NDS TREATMANT PLANT:

DISTANCE      BOD        NOD           DO DE FICICIT

MILES         MG/L       MG/L            MG/ L

17.585        0.980 6        0.709           -0.224
```

TABLE 4.15 STREAM PARAMETERS AFTER MIXING OF THE EFFLUENT DISCHARGE FROM THE UPLANDS SEWAGE TREATMENT PLANT

```
          REACH N O.   11


AREA=            2869 .000          SQFT
DEPTH=             11 .220          FT
VELOCITY=           3 .450          MI/DAY
BODA=               0 .017          MG/L/DAY
VOLUME=    208035774 .972          L
AREA OF SED=  66172 .860          SQ.M
RN=                 0 .062          1/DAY
ENERGY GRADIENT=  0 .000214532    FT/FT
OXSED=              0 .080          GMS/SQ.M/DAY
DOSAT=              8 .498          MG/L/DAY
SEDR=               0 .052          GMS/SQ.M/DAY
REAERATION COEF.= 0 .00904        1/DAY
BD=                 0 .025          MG/L/DAY


DISTANCE       BOD        NOD          DO DE FICICIT

MILES          MG/L       MG/L          MG/ L

17.633         0.978      0.709         -0. 229
17.682         0.976      0.708         -0. 233
17.730         0.973      0.707         -0. 238
17.779         0.971      0.707         -0. 243
17.827         0.968      0.706         -0. 247
17.876         0.966      0.705         -0. 252
17.924         0.963      0.705         -0. 257
17.973         0.961      0.704         -0. 262
18.021         0.958      0.704         -0. 267
18.070         0.956      0.703         -0. 271
```

TABLE 4.16   SIMULATION RESULTS - REACH NO. 11

```
          REACH N O.   12


AREA=             2621 .000          SQFT
DEPTH=               8 .760          FT
VELOCITY=            3 .776          MI/DAY
BODA=                0 .021          MG/L/DAY
VOLUME=     365998778 .001           L
AREA OF SED= 145108 .193             SQ.M
RN=                  0 .062          1/DAY
ENERGY GRADIENT=     0 .000344860    FT/FT
OXSED=               0 .196          GMS/SQ.M/DAY
DOSAT=               8 .498          MG/L/DAY
SEDR=                0 .052          GMS/SQ.M/DAY
REAERATION COEF.=    0 .01299        1/DAY
BD=                  0 .078          MG/L/DAY


DISTANCE       BOD          NOD           DO DE FICICIT

MILES          MG/L         MG/L            MG/ L

18.163         0.951        0.702           -0. 279
18.257         0.947        0.701           -0. 286
18.350         0.943        0.700           -0. 293
18.444         0.939        0.699           -0. 300
18.537         0.935        0.698           -0. 307
18.630         0.931        0.697           -0. 315
18.724         0.926        0.695           -0. 322
18.817         0.922        0.694           -0. 329
18.911         0.918        0.693           -0. 337
19.004         0.914        0.692           -0. 344
```

TABLE 4.17 SIMULATION RESULTS - REACH NO. 12

```
              REACH N O.   13


    AREA=             15328 .000          SQFT
    DEPTH=               15 .760          FT
    VELOCITY=             0 .646          MI/DAY
    BODA=                 0 .013          MG/L/DAY
    VOLUME=  2028123982 .642          L
    AREA OF SED= 435905 .526          SQ.M
    RN=                   0 .062          1/DAY
    ENERGY GRADIENT=  0 .000004455    FT/FT
    OXSED=                0 .298          GMS/SQ.M/DAY
    DOSAT=                8 .498          MG/L/DAY
    SEDR=                 0 .062          GMS/SQ.M/DAY
    REAERATION COEF.= 0 .00109        1/DAY
    BD=                   0 .064          MG/L/DAY


    DISTANCE      BOD         NOD          DO DE FICICIT

    MILES         MG/L        MG/L         MG/ L

    19.092       0.891       0.686        -0. 231
    19.181       0.869       0.681        -0. 119
    19.269       0.847       0.675        -0. 007
    19.358       0.826       0.669         0. 103
    19.446       0.805       0.663         0. 213
    19.535       0.785       0.658         0. 322
    19.623       0.766       0.652         0. 430
    19.712       0.747       0.647         0. 538
    19.800       0.728       0.641         0. 645
    19.889       0.710       0.636         0. 751
 CORE USAGE       OBJECT CODE=   11808 BYTES,ARRA Y AREA=    2320 BYTES,TO TAL AREA AVAILABLE=   34 912  BY

 COMPILE TIME=     8.16 S EC,EXECUTION TIME=     7 .03 SEC,  WATFIV - VERSI ON 1 LEVEL 2 AUGUST  197 0
```

TABLE 4.18 SIMULATION RESULTS - REACH NO. 13

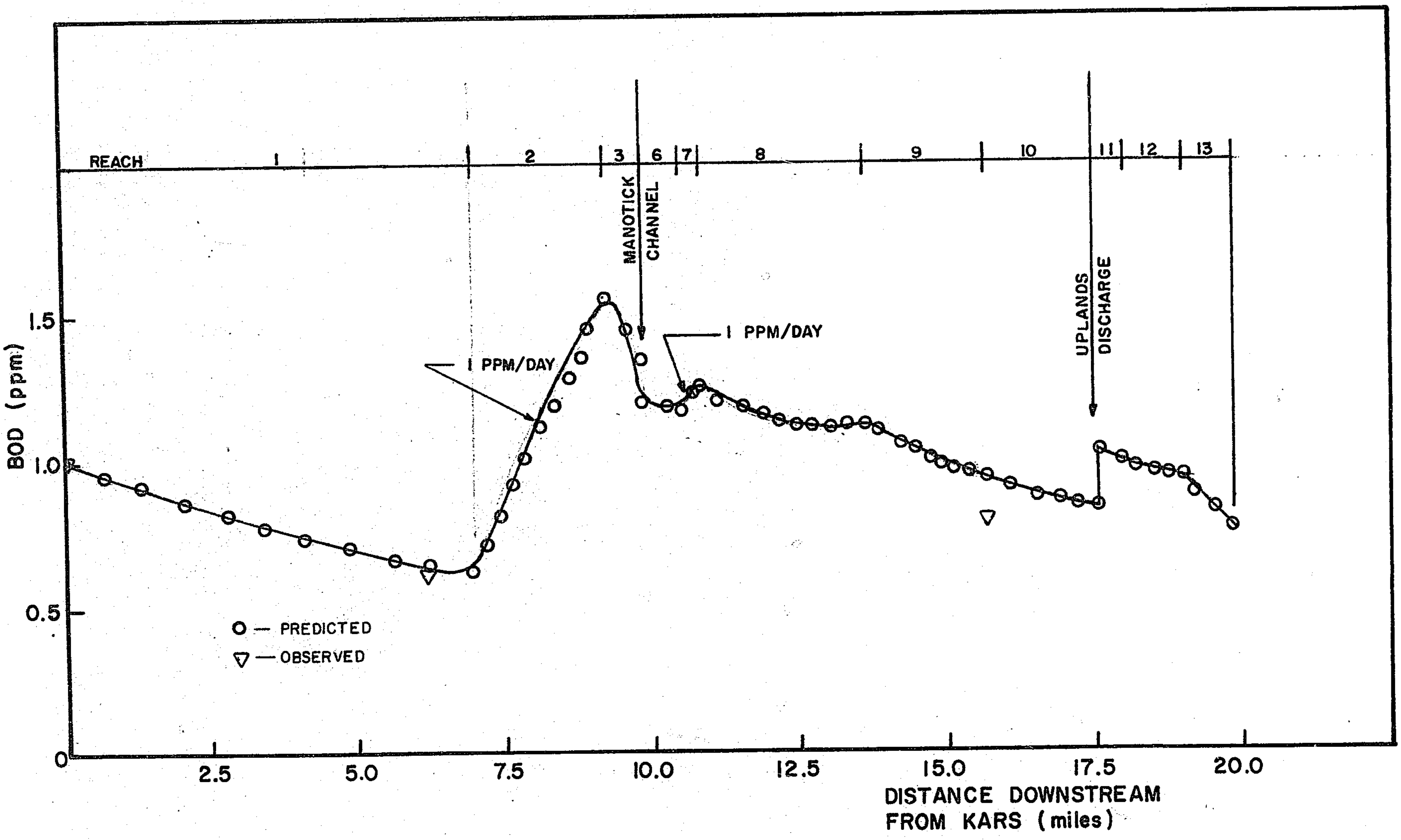

FIGURE 4.1 — BOD PROFILE

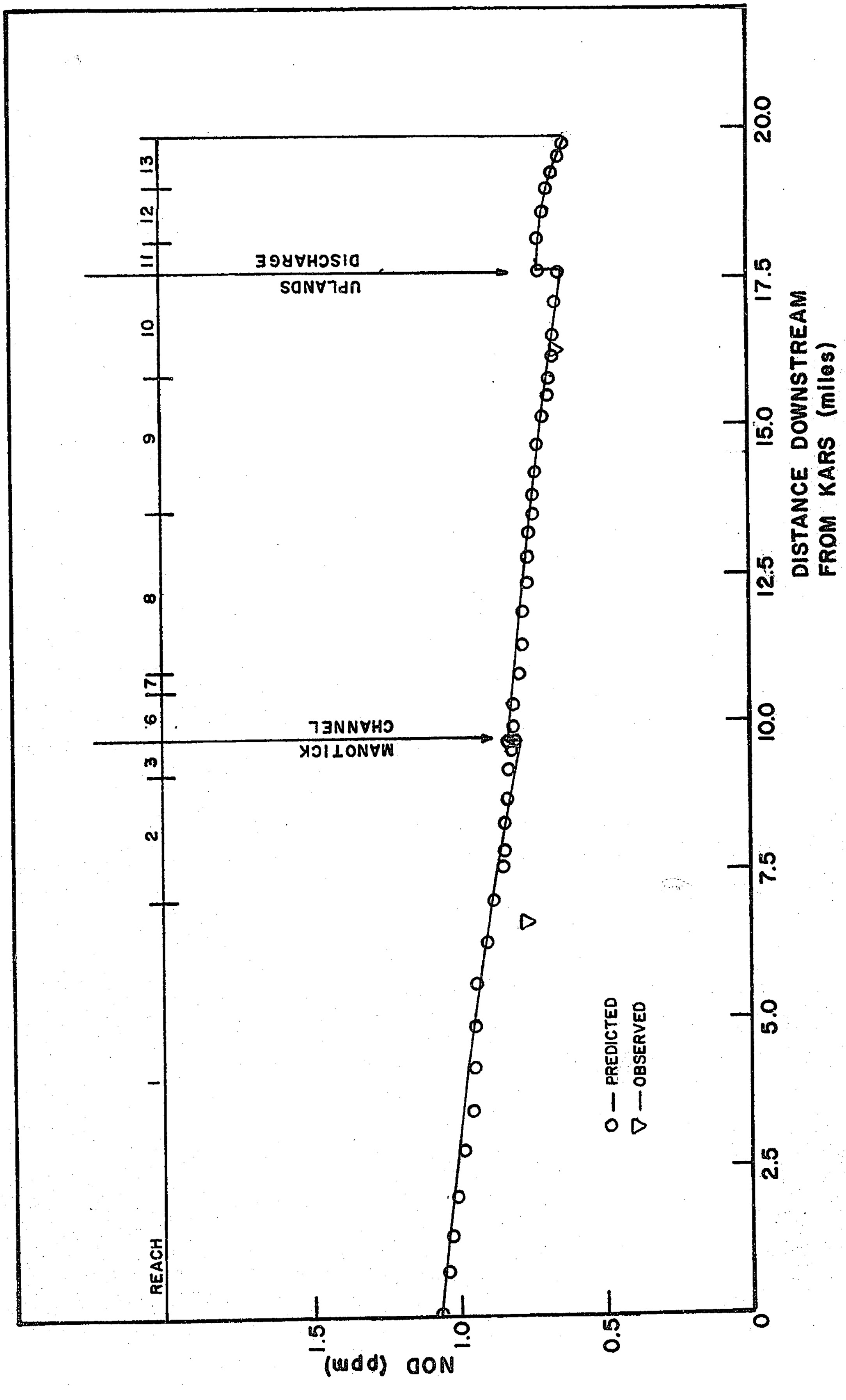

FIGURE 4.2 — NOD PROFILE

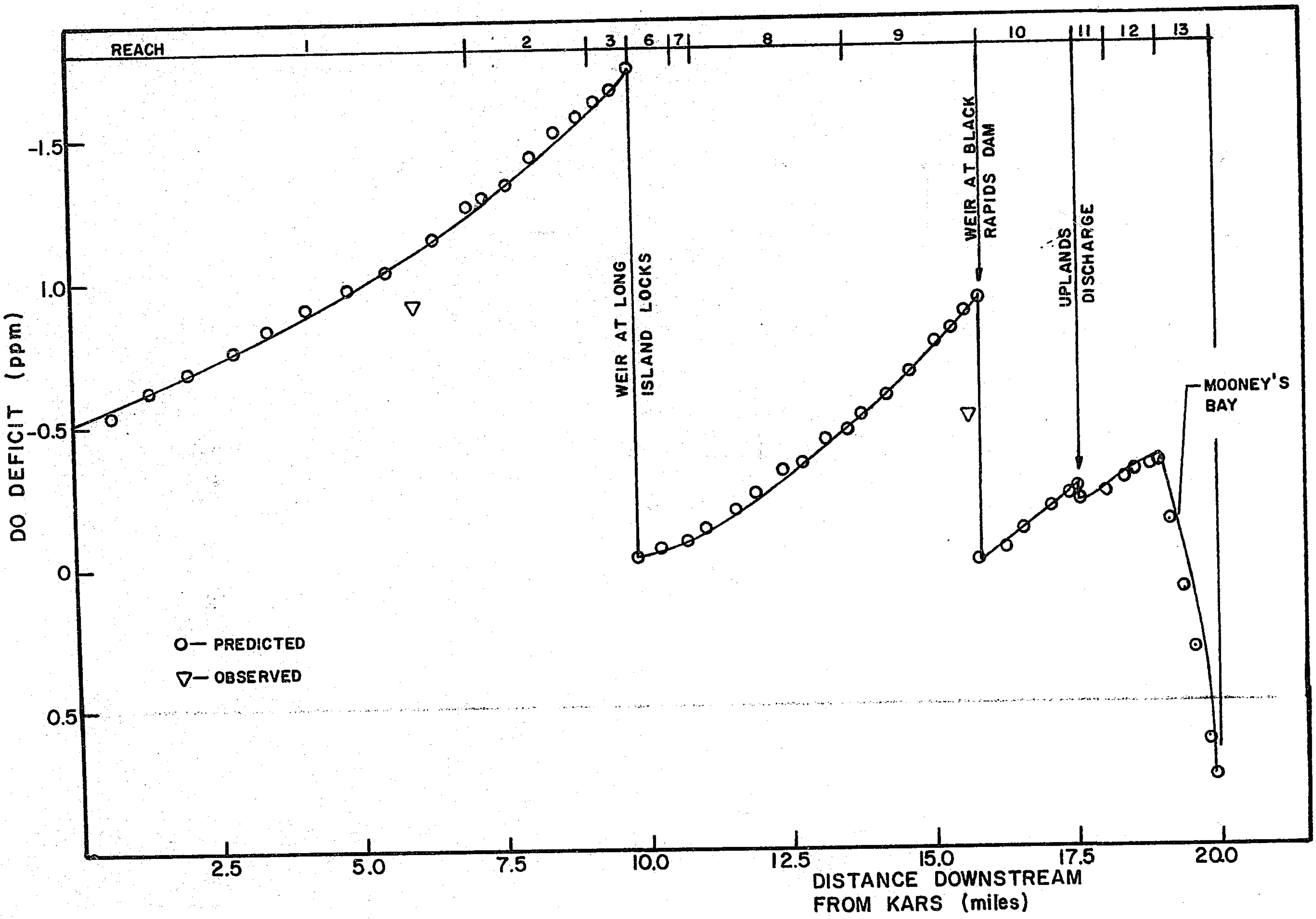

FIGURE 4.3 — DO DEFICIT PROFILE

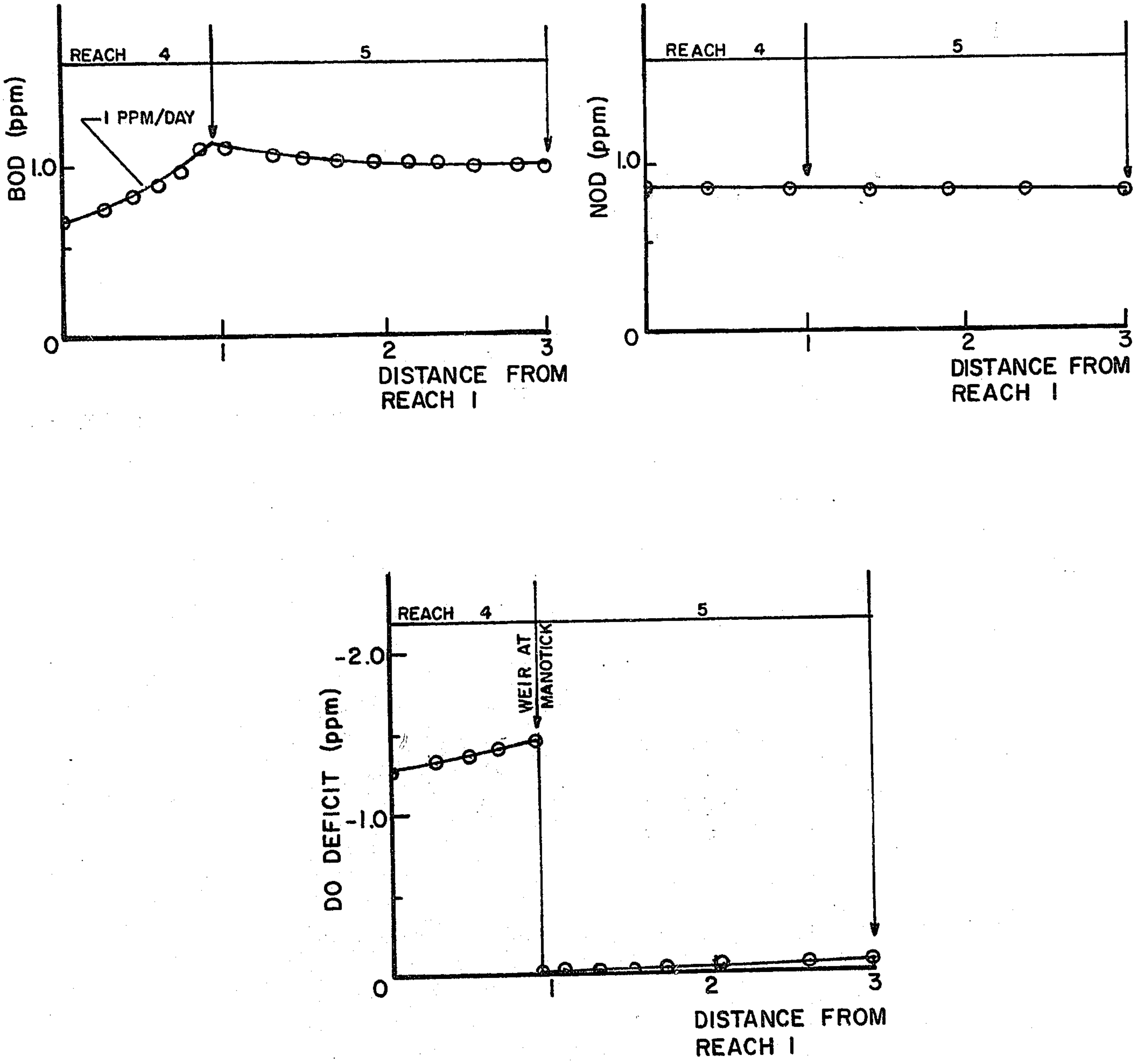

FIGURE 4.4 — BOD, NOD, & DO DEFICIT PROFILES IN THE MANOTICK CHANNEL

## 4.3 Simulation Results

To solve equations 4.1 to 4.3 a computer programme was written in WATFIV Fortran. The effects of all stream constants on the BOD, NOD, and DO deficit were computed and equations 4.1 to 4.3 were solved for each reach. Ten values of BOD, NOD, and DO deficit were obtained for each section. The upstream boundary conditions of reach one were taken from OWRC data (83).

The resulting downstream values at the junction of reaches one and two, computed by the BOD, NOD, and DO deficit equations, were taken as the upstream boundary conditions of reach two. The three equations were solved similarly for all thirteen reaches.

The Manotick Channel was divided into two reaches separated by a free-falling weir. In the model, reaches 4 and 5 represent the Manotick Channel which joins the main stream at the upper boundary of reach 6 below the weir on the Long Island impoundment.

The programme predictions for the various reaches under the conditions listed in Table 4.1 to 4.3 are presented in Tables 4.4 to 4.18. With these values the BOD, NOD, and DO deficit profiles over the 19.9 mile stream length were plotted in Figures 4.1 to 4.4. Figure 4.4 contains the BOD, NOD, and DO deficit profiles of the Manotick Channel.

There are only the two locations downstream from Kars where OWRC data (82) is available to compare with the predicted results. The concentrations of BOD, NOD, and DO deficit on the profile curves at these locations are, however, close to the observed values. It is emphasized that the gross average daily photosynthetic production, $G.P_{AV}$, was reduced from 2.46 to 1.75 ppm/day for all the reaches except Mooney's Bay. The value of 2.46 was found to give extremely high negative oxygen deficits. Therefore, the estimate that the average photosynthetic production throughout the stream above Mooney's Bay was too high. Possibily the conditions in the area below the Long Island locks, where the experiments were conducted to obtain the oxygen production value of 2.46 ppm/day, were extremely optimal for algal productivity. The estimate of 1.75 ppm/day is perhaps closer to the average photosynthetic rate throughout the entire stream.

To obtain a better correlation between the observed BOD concentration and that predicted at Black Rapids, the addition of oxidizable material by local runoff and ground water accrual in the areas around Manotick and Long Island (reaches 2, 4, and 7) was assumed to be 1.0 ppm/day. In these areas, there is a rather heavy concentration of houses and summer cottages which use septic tanks and it is probable that they also contribute a relatively substantial waste load to the river.

As a result of the above assumptions, the model to some extent reflects, primarily, existing conditions and its predicative ability is somewhat curtailed. However, in describing these conditions the model shows that

1. photosynethesis is almost the total source of oxygen in creating supersaturated dissolved oxygen levels during periods of optimum algal conditions. Similar observations were made from studies on rivers somewhat similar to the Rideau by O'Connor and Di Toro (55).
2. Oxygen is lost to the atmosphere during conditions of supersaturation. However, the loss of oxygen is very small and less than .008 ppm/day throughout the river. The weirs act as a sink liberating supersaturated dissolved oxygen and leaving the water saturated immediately below the weirs. This can be seen in Figures 4.3 and 4.4 at the location of the weirs at Long Island, Black Rapids and in the Manotick Channel.
3. Bottom sediments contribute but a very small organic load (0.028 ppm/day maximum in reach 1) and exert little oxygen demand. In reaches 1, and 9 to 12, the DO curve in Figure 4.3 show little effect of any oxygen demand due to the sediments.

There are two areas in which much more information is needed to improve the model. One is the determination of location and quantity of sources of organic loading. The OWRC (83) reports no sanitary sewers or industrial effluents discharging into the river along the reach and the addition of BOD along the river must therefore be by ground water accrual and storm surface runoff. The nature of this type of organic discharge is a function of land use in the immediate area of the river and the soil type. The only method of determining the quantity is through trial and error fitting of the BOD and NOD curves.

Photosynthetic production is another difficult quantity to obtain because of its dependence on other variables and its diurnal nature. As previously stated, if high concentrations of pelagial algae exclude rooted plants, light and dark bottles can measure the total production. If the seasonal variation is obtained, these values may be used for other years provided there is not an abrupt change in nutrients, since algal production follows a pattern of peak production in early and late summer with a lower period in between.

Where rooted plants cannot be neglected, only trial and error curve fitting or _in situ_ measurement with transparent chambers in shallow sections is possible to obtain photosynthetic values. However, the former method is possible only when all the other factors affecting DO response in a stream have been accurately evaluated. The ultimate method to obtain the photosynthetic DO contribution is to model primary production itself; but, this type of simulation is even more complex than modelling dissolved oxygen. Di Toro _et al_ (12) have devoted considerable effort in developing an experimental dynamic model of phytoplankton populations which could be applicable to more in-depth river models.

Organic pollution as such, appears to be of secondary importance in the Rideau. The river appears highly eutrophic and consequently, nutrient pollution is perhaps the major concern. Nutrients from phosphate and nitrogen compounds from agricultural or domestic sources increase plant production causing severe diurnal DO fluctuations and heavy demands of the DO resources of the river through plant decomposition at the end of the summer.

# CHAPTER 5

# CONCLUSIONS AND RECOMMENDATIONS

The water quality response of a natural stream was investigated through the development of a model to simulate the effects of the stream constants on the water quality parameters of BOD, NOD and DO in the river. From field and laboratory experiments and the literature review, several general conclusions and recommendations can be made which bear application to any stream or river, and in particular the Ottawa.

## 5.1 Conclusions

A general methodology has been outlined for developing a mathematical water quality model for a natural stream. This methodology may be given as follows:

a) Collect all existing information on the water quality of the stream to be modelled.

b) Select the water quality parameter whose concentration is such that it threatens the existing nature or ecology of the stream, e.g. salt water intrusion in an estuary, BOD, NOD, and DO.

c) Define the objectives of the water quality model, e.g. whether diurnal fluctuations of DO or simply the average daily DO concentrations are required.

d) Collect all existing information on the factors which affect water quality response.

e) Divide the river initially into reaches of similar hydraulic characteristics or where a major tributary or waste input enters the stream. Generally, reaches with uniform hydraulic conditions have uniform biochemical characteristics.

f) Select typical sections of the river where the extreme conditions may be found, e.g. rapid flowing sections and very sluggish reaches. In particular, dispersion studies should be undertaken where dispersion is believed to be greatest in the stream, to determine whether it is significant and whether a more detailed study is required throughout the entire river. In addition, if it is not possible to carry out a complete and intensive study to gather data to evaluate the stream constants in all the reaches, a rough correlation can be made to estimate their magnitude with values from the typical reaches.

g) Select an existing mathematical expression or develop one if none exists which describe actual conditions in the stream as indicated from the field data.

h) Solve the mathematical expression by the procedure that will give results within the objectives of the model and evaluate the model with existing data. Based on this evaluation, the model may be refined by mathematical changes or by re-evaluating certain critical stream constants.

A mathematical expression was formulated and the stream constants of a 19.9 mile stretch of the Rideau River were determined either by _in situ_ or laboratory experiments or from literature sources. The constants were used in the mathematical expression to simulate the BOD, NOD, and DO deficit in the river. The simulated results are as shown in Figures 4.1 to 4.4 and were compared to available existing observations.

From experiments performed on the river sediments, it was concluded that experiments on disturbed samples cannot adequately describe _in situ_ conditions. The dye studies showed that in areas where the stream channel contained large zones of stagnant water, the mean stress velocity is much larger than the total discharge velocity, i.e. Q/A, and to use the latter, serious errors would result in predicting the location of a pollutant as it is transported downstream. In limnetic streams, such as the Rideau, studies of algal oxygen production indicate that atmospheric reaeration may be a much smaller source of dissolved oxygen than algae and during darkness, algal respiration may be a greater sink of dissolved oxygen than the oxidation of organic material.

## 5.2 Recommendations

From the field and laboratory experiments and results from the water quality model of the Rideau River, the following recommendations are made:

1. An in situ respirometer similar to that developed by O'Connell (53) should be used to measure sediment effects. To measure benthic algal production, two respirometers could be employed, one with an opaque and the other with a transparent closed semi-cylinder chamber.
2. Dye studies should be performed to determine the mean stress velocity since it has been shown that it can differ greatly from the discharge velocity. The mean stream velocity must be measured accurately because it not only represents convection, but the calculation of the reaeration and deoxygenation rate constants are also dependent upon it.
3. In eutrophic streams such as the Rideau, more emphasis should be placed on nutrient pollution rather than the classical organic forms of pollution.
4. With regard to areas of future research, studies should be made on the effect of turbulence caused by weirs, to determine if the organic oxidation rate is significantly increased. Since the organic oxidation rate is a function of stream velocity,

this relationship could be studied in the laboratory using a circular flume similar to that used by Isaacs and Gaudy (39) in their reaeration studies.

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# APPENDIX A

# SEDIMENT EVALUATION RESULTS

| Reach | Physical Appearance of Sediment Samples | Dry Solids as % of Wet Weight | Volatile Solids as % of Dry Solids | $BOD_5$ gm/kgm of Volatile Solids | T.O.N.* as % of Volatile Solids | $NH_3$ as % of Volatile Solids |
|---|---|---|---|---|---|---|
| 1 | No. 16-S: silt with organic material; greyish brown colour | 21.42 | 17.15 | 25.2 | 3.38 | 0.085 |
| | No. 15-S: medium fine sand with silt and organic material, greyish black colour | 57.10 | 3.29 | 27.4 | 2.88 | 0.045 |
| | No. 14-S: silt with organic material, greyish brown colour | 21.67 | 16.96 | 24.3 | 3.18 | 0.034 |
| | No. 13-S: fine sand with silt and organic material, greyish black colour | 36.04 | 7.71 | $>38.1$ | 2.99 | 0.053 |

*Total Organic Nitrogen.

TABLE A-1 DESCRIPTION AND COMPOSITION OF SEDIMENT SAMPLES

| Reach | Physical Appearance of Sediment Samples | Dry Solids as % of Wet Weight | Volatile Solids as % of Dry Solids | BOD5 gm/kgm of Volatile Solids | T.O.N.* as % of Volatile Solids | NH3 as % of Volatile Solids |
|---|---|---|---|---|---|---|
| 1 | No. 12-S: silt with organic material, greyish brown colour | 22.27 | 21.42 | 16.7 | 2.49 | 0.051 |
|  | No. 11-S: silt with organic material, greyish brown colour | 54.64 | 4.19 | 29.8 | 2.36 | 0.14 |
|  | No. 10-S: silty sand with heavy concentration of organic material | 16.98 | 18.87 | >25.8 | 4.20 | 0.0007 |
|  | No. 9-S: silty sand | 60.29 | 2.35 | 44.6 | 3.96 | 0.0003 |
|  | No. 8-S: silty sand | 49.38 | 2.97 | 51.5 | 4.13 | 0.0003 |
| 2 | No sample: rocky, coarse bottom | - | - | - | - | - |

*Total Organic Nitrogen.

TABLE A-2 DESCRIPTION AND COMPOSITION OF SEDIMENT SAMPLES

| Reach | Physical Appearance of Sediment Samples | Dry Solids as % of Wet Weight | Volatile Solids as % of Dry Solids | BOD5 gm/kgm of Volatile Solids | T.O.N.* as % of Volatile Solids | NH3 as % of Volatile Solids |
|---|---|---|---|---|---|---|
| 3 | No. 7-S: silt, dark grey colour | 20.75 | 13.91 | 51.3 | 4.11 | - |
| 4 | No sample: rocky, coarse bottom | - | - | - | - | - |
| 5 | No sample: rocky, coarse bottom | - | - | - | - | - |
| 6 | No sample: rocky, coarse bottom | - | - | - | - | - |
| 7 | No sample: rocky, coarse bottom | - | - | - | - | - |

*Total Organic Nitrogen.

TABLE A-3 DESCRIPTION AND COMPOSITION OF SEDIMENT SAMPLES

| Reach | Physical Appearance of Sediment Samples | Dry Solids as % of Wet Weight | Volatile Solids as % of Dry Solids | $BOD_5$ gm/kgm of Volatile Solids | T.O.N.* as % of Volatile Solids | $NH_3$ as % of Volatile Solids |
|---|---|---|---|---|---|---|
| 8 | No. 6-S: fine sand, most of reach is rocky, coarse bottom | 79.4 | 1.67 | 28.0 | - | - |
| 9 | No. 5-S: fine sand | 52.7 | 5.98 | 20.2 | - | - |
| 10 | No. 4-S: medium sand | 82.26 | 0.62 | 13.3 | 1.95 | - |
| 11 | No sample: coarse sand | - | - | - | - | - |
| 12 | No. 3-S: sand, many molluscs | 83.14 | 0.87 | 72.6 | - | - |
| 13 | No. 2-S: fine sand, dark brown colour, many molluscs | 80.14 | 0.76 | 39.9 | 3.35 | - |
|  | No. 1-S: fine, sandy silt, very dark, with many molluscs | 67.01 | 2.35 | 119.0 | 4.26 | - |

*Total Organic Nitrogen.

TABLE A-4 DESCRIPTION AND COMPOSITION OF SEDIMENT SAMPLES

CYLINDER NO. 1
SURFACE AREA OF SEDIMENT: 60.907 $\mathrm{cm^2}$
DEPTH OF SEDIMENT: 5.08 cm

| Day | $\Delta t$ Days | $C_i$[1]-$C_e$[2] mg/1 | Vol.[3] (1) | V(Ci-Ce) = $O_c$ $\mathrm{mg/m^2}$ | $O_c$ $\mathrm{mg/m^2}$ | $L_b$[4] ppm | $L_b$ $\mathrm{mg/m^2}$ | $L_b$ $\mathrm{mg/m^2}$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.03 | .55 | 2.850 | 257 | 257 | 2 | 1404 | 1404 |
| 1 | .97 | .55 | 1.810 | 163 | 420 | 3 | 594 | 1998 |
| 2 | 2.03 | .95 | 3.395 | 529 | 949 | 2 | 1115 | 3113 |
| 4 | 1.97 | 1.05 | 3.190 | 550 | 1499 | 2 | 1047 | 4160 |
| 6 | 2.03 | 1.0 | 3.24 | 532 | 2031 | 2 | 1011 | 5171 |
| 8 | 1.97 | 1.3 | 3.070 | 655 | 2686 | 1.9 | 252 | 5423 |
| 10 | 2.03 | 1.1 | 3.38 | 610 | 3296 | 0.5 | 277 | 5700 |
| 12 | 1.97 | 1.1 | 3.210 | 580 | 3876 | 0.5 | 105 | 5805 |
| 14 | 2.03 | 1.1 | 4.525 | 819 | 4696 | 0.2 | 149 | 5954 |
| 16 | 1.97 | 1.3 | 3.930 | 839 | 5535 | 0.2 | 129 | 6083 |
| 18 | | | | | | | | |

[1] Ci - DO of influent.

[2] Ce - DO of effluent.

[3] Vol. - Volume of supernatant flow.

[4] $L_b$ - BOD diffused from sediment.

TABLE A-5 SEDIMENT EVALUATION RESULTS

CYLINDER NO. 2
SURFACE AREA OF SEDIMENT: 60.907 cm$^2$
DEPTH OF SEDIMENT: 5.08 cm

| Day | $\Delta$t Days | Ci$^1$-Ce$^2$ mg/1 | Vol.$^3$ (1) | V(Ci-Ce) = $O_c$ mg/m$^2$ | $O_c$ mg/m$^2$ | $L_b{}^4$ ppm | $L_b$ mg/m$^2$ | $L_b$ mg/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.03 | .45 | 2.725 | 201 | 201 | 1 | 447 | 447 |
| 1 | .97 | .30 | 1.765 | 87 | 288 | 1 | 290 | 737 |
| 2 | 2.03 | .70 | 3.390 | 390 | 678 | 1 | 556 | 1293 |
| 4 | 1.97 | .90 | 3.330 | 492 | 1170 | 1 | 547 | 1840 |
| 6 | 2.03 | .85 | 3.370 | 470 | 1640 | 0.4 | 221 | 2061 |
| 8 | 1.97 | 1.1 | 3.250 | 587 | 2227 | 0.3 | 160 | 2221 |
| 10 | 2.03 | 1.05 | 3.500 | 603 | 2830 | 0.4 | 230 | 2451 |
| 12 | 1.97 | 1.00 | 3.250 | 534 | 3364 | 0.3 | 160 | 2611 |
| 14 | 2.03 | .85 | 4.080 | 569 | 3933 | 0.1 | 67 | 2678 |
| 16 | 1.97 | .75 | 2.560 | 315 | 4248 | | | |
| 18 | | | | | | | | |

[1] Ci - DO of influent.

[2] Ce - DO of effluent.

[3] Vol. - Volume of supernatant flow.

[4] Lb - BOD diffused from sediment.

TABLE A-6 SEDIMENT EVALUATION RESULTS

CYLINDER NO. 3
SURFACE AREA OF SEDIMENT: 60.907 cm$^2$
DEPTH OF SEDIMENT: 5.08 cm

| Day | $\Delta$t Days | Ci[1]-Ce[2] mg/1 | Vol.[3] (1) | V(Ci-Ce) = $O_c$ mg/m$^2$ | Oc mg/m$^2$ | Lb[4] ppm | $L_b$ mg/m$^2$ | $L_b$ mg/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.03 | .40 | 1.9 | 125 | 125 | 1 | 312 | 312 |
| 1 | .97 | .40 | 1.63 | 107 | 232 | 1 | 268 | 580 |
| 2 | 2.03 | .70 | 3.06 | 352 | 584 | 1 | 502 | 1082 |
| 4 | 1.97 | .85 | 3.01 | 420 | 1004 | 1 | 494 | 1576 |
| 6 | 2.03 | .90 | 3.20 | 473 | 1477 | 0.9 | 473 | 2049 |
| 8 | 1.97 | .80 | 3.07 | 403 | 1880 | 0.3 | 151 | 2200 |
| 10 | 2.03 | .95 | 3.20 | 499 | 2379 | 0.3 | 158 | 2358 |
| 12 | 1.97 | .8 | 3.145 | 413 | 2792 | 0.3 | 155 | 2513 |
| 14 | 2.03 | .75 | 4.305 | 530 | 3322 | .03 | 212 | 2725 |
| 16 | 1.97 | .9 | 2.00 | 296 | 3618 | | | |
| 18 | | | | | | | | |

[1] Ci - DO of influent.

[2] Ce - DO of effluent.

[3] Vol. - Volume of supernatant flow.

[4] $L_b$ - BOD diffused from sediment.

TABLE A-7 SEDIMENT EVALUATION RESULTS

CYLINDER NO. 4
SURFACE AREA OF SEDIMENT: 60.907 cm$^2$
DEPTH OF SEDIMENT: 5.08 cm

| Day | $\Delta$t Days | Ci$^1$-Ce$^2$ mg/l | Vol.$^3$ (l) | V(Ci-Ce) = $O_{c_2}$ mg/m$^2$ | $O_{c_2}$ mg/m$^2$ | $L_b$$^4$ ppm | $L_b$ mg/m$^2$ | $L_{b_2}$ mg/m$^2$ |
|---|---|---|---|---|---|---|---|---|
| 0 | 1.03 | .5 | 2.29 | 188 | 188 | 4 | 1504 | 1504 |
| 1 | .97 | .55 | 1.79 | 162 | 350 | 3 | 882 | 2386 |
| 2 | 2.03 | .85 | 3.49 | 487 | 837 | 4 | 2292 | 4678 |
| 4 | 1.97 | 1.40 | 3.41 | 784 | 1621 | 4 | 2239 | 6917 |
| 6 | 2.03 | 1.05 | 3.40 | 586 | 2207 | 2.2 | 1228 | 8145 |
| 8 | 1.97 | 1.15 | 3.20 | 604 | 2811 | 0.5 | 263 | 8408 |
| 10 | 2.03 | 1.15 | 3.40 | 642 | 3453 | 0.4 | 223 | 8631 |
| 12 | 1.97 | 1.30 | 3.335 | 712 | 4165 | 0.5 | 274 | 8905 |
| 14 | 2.03 | 1.20 | 4.07 | 802 | 4967 | 0.5 | 334 | 9239 |
| 16 | 1.97 | .90 | 3.680 | 544 | 5511 | | | |
| 18 | | | | | | | | |

[1] Ci - DO of influent.

[2] Ce - DO of effluent.

[3] Vol. - Volume of supernatant flow.

[4] Lb - BOD diffused from sediment.

TABLE A-8 SEDIMENT EVALUATION RESULTS

# APPENDIX B

## COMPUTER PROGRAMME AND RESULTS FOR DISPERSION AND MEAN STREAM VELOCITY

## STUDY NO. 1 - NEAR BLACK RAPIDS DAM

## MONITORING POINT NO. 1

| Time Minutes | Concentration mg/1 | Time Minutes | Concentration mg/1 |
|---|---|---|---|
| 2.500 | 0.0700 | 75.0000 | 18.6500 |
| 5.0000 | 1.8100 | 77.5000 | 15.9800 |
| 7.5000 | 5.9800 | 80.0000 | 13.6200 |
| 10.0000 | 10.9800 | 82.5000 | 11.8400 |
| 12.5000 | 9.4700 | 85.0000 | 10.9500 |
| 15.0000 | 10.9500 | 87.5000 | 10.0600 |
| 17.5000 | 10.9500 | 90.0000 | 8.8800 |
| 20.0000 | 12.1300 | 92.5000 | 8.8800 |
| 22.5000 | 17.1700 | 95.0000 | 8.8800 |
| 25.0000 | 24.5700 | 97.5000 | 8.5800 |
| 27.5000 | 26.6400 | 100.0000 | 8.2900 |
| 30.0000 | 23.6800 | 102.5000 | 8.2900 |
| 32.5000 | 23.9800 | 105.0000 | 7.7000 |
| 35.0000 | 29.6000 | 107.5000 | 7.4000 |
| 37.5000 | 35.5200 | 110.0000 | 7.1000 |
| 40.0000 | 40.8500 | 112.5000 | 6.8100 |
| 42.5000 | 46.7700 | 115.0000 | 6.5100 |
| 45.0000 | 52.6900 | 117.5000 | 6.2200 |
| 47.5000 | 55.0700 | 120.0000 | 5.9200 |
| 50.0000 | 53.2800 | 122.5000 | 5.6200 |
| 52.5000 | 42.9200 | 125.0000 | 5.3300 |
| 55.0000 | 38.4800 | 127.5000 | 4.7400 |
| 57.5000 | 40.2600 | 130.0000 | 4.1400 |
| 60.0000 | 45.2900 | 132.5000 | 3.5500 |
| 62.5000 | 42.0300 | 135.0000 | 2.6600 |
| 65.0000 | 32.5600 | 137.5000 | 2.0700 |
| 67.5000 | 26.9400 | 140.0000 | 1.1800 |
| 70.0000 | 23.6800 | 142.5000 | 0.8800 |
| 72.5000 | 21.3100 | 145.0000 | 0.5900 |
|  |  | 147.5000 | 0.3000 |

Mean Time of Passage = 56.7977
Variance = 722.5760
Third Moment = 244282.3335
Skewness Coefficient = 4300.9202

TABLE B-1 TIME CONCENTRATION OBSERVATIONS AND COMPUTER RESULTS FROM MONITORING POINT NO. 1 - STUDY NO. 1

## STUDY NO. 1 - NEAR BLACK RAPIDS DAM

## MONITORING POINT NO. 2

| Time Minutes | Concentration mg/l | Time Minutes | Concentration mg/l |
|---|---|---|---|
| 345.0000 | 0.4900 | 480.0000 | 6.9500 |
| 350.0000 | 1.9500 | 485.0000 | 6.9500 |
| 355.0000 | 4.2400 | 490.0000 | 6.9500 |
| 360.0000 | 6.8100 | 495.0000 | 6.9500 |
| 365.0000 | 7.0900 | 500.0000 | 6.8100 |
| 370.0000 | 6.3900 | 505.0000 | 6.7400 |
| 375.0000 | 6.2600 | 510.0000 | 6.3900 |
| 380.0000 | 5.8400 | 515.0000 | 6.3900 |
| 385.0000 | 5.4900 | 520.0000 | 6.3200 |
| 390.0000 | 5.1400 | 525.0000 | 6.1200 |
| 395.0000 | 4.9300 | 530.0000 | 5.9800 |
| 400.0000 | 4.7900 | 535.0000 | 5.7000 |
| 405.0000 | 4.4500 | 540.0000 | 5.2800 |
| 410.0000 | 4.3100 | 545.0000 | 4.8700 |
| 415.0000 | 4.3800 | 550.0000 | 5.1400 |
| 420.0000 | 5.2800 | 555.0000 | 4.1000 |
| 425.0000 | 4.0200 | 560.0000 | 3.4800 |
| 430.0000 | 8.0600 | 565.0000 | 3.4800 |
| 435.0000 | 7.9200 | 570.0000 | 3.8900 |
| 440.0000 | 8.0600 | 575.0000 | 4.1700 |
| 445.0000 | 7.9200 | 580.0000 | 4.3100 |
| 450.0000 | 7.7100 | 585.0000 | 3.8900 |
| 455.0000 | 7.4400 | 590.0000 | 3.1300 |
| 460.0000 | 7.0200 | 595.0000 | 2.2200 |
| 465.0000 | 6.8100 | 600.0000 | 1.1100 |
| 470.0000 | 6.7400 | 605.0000 | 0.1400 |
| 475.0000 | 6.8800 | | |

Mean Time of Passage = 467.1849
Variance = 4353.4945
Third Moment = 197946490.7645
Skewness Coefficient = 423700.5452

TABLE B-2 TIME CONCENTRATION OBSERVATIONS AND COMPUTER RESULTS FROM MONITORING POINT NO. 2 - STUDY NO. 1

STUDY NO. 2 - NEAR KARS

MONITORING POINT NO. 3

| Time Minutes | Concentration mg/1 |
|---|---|
| 2.5000 | 0.4800 |
| 5.0000 | 2.3500 |
| 7.5000 | 5.0300 |
| 10.0000 | 10.1100 |
| 12.5000 | 17.8700 |
| 15.0000 | 26.7000 |
| 17.5000 | 32.5800 |
| 20.0000 | 32.0500 |
| 22.5000 | 13.0500 |
| 25.0000 | 5.0300 |
| 27.5000 | 4.2300 |
| 30.0000 | 5.3000 |
| 32.5000 | 6.9000 |
| 35.0000 | 7.4400 |
| 37.5000 | 7.4400 |
| 40.0000 | 6.9000 |
| 42.5000 | 5.8300 |
| 45.0000 | 4.2300 |
| 47.5000 | 3.4200 |
| 50.0000 | 2.6200 |
| 52.5000 | 2.0900 |
| 55.0000 | 1.8200 |
| 57.5000 | 1.8200 |

Mean Time of Passage = 23.2218
Variance = 138.9254
Third Moment = 17059.1037
Skewness Coefficient = 734.6164

TABLE B-3 TIME CONCENTRATION OBSERVATIONS AND COMPUTER RESULTS FROM MONITORING POINT NO. 3 - STUDY NO. 2

## STUDY NO. 2 - NEAR KARS

## MONITORING POINT NO. 4

| Time Minutes | Concentration mg/l |
|---|---|
| 175.0000 | 0.4600 |
| 180.0000 | 1.0300 |
| 185.0000 | 1.4600 |
| 190.0000 | 2.0300 |
| 195.0000 | 2.6000 |
| 200.0000 | 2.6000 |
| 205.0000 | 2.6500 |
| 210.0000 | 2.8800 |
| 215.0000 | 3.0300 |
| 220.0000 | 3.0700 |
| 225.0000 | 3.0300 |
| 230.0000 | 3.0700 |
| 235.0000 | 2.8400 |
| 240.0000 | 2.7400 |
| 245.0000 | 2.7400 |
| 250.0000 | 2.6900 |
| 255.0000 | 2.6500 |
| 260.0000 | 2.6000 |
| 265.0000 | 2.6000 |
| 270.0000 | 2.6500 |
| 275.0000 | 2.7400 |
| 280.0000 | 2.9300 |
| 285.0000 | 2.8800 |
| 290.0000 | 2.8400 |
| 295.0000 | 2.8400 |
| 300.0000 | 2.6900 |
| 305.0000 | 2.5500 |
| 310.0000 | 2.4600 |
| 315.0000 | 2.3100 |
| 320.0000 | 2.1200 |
| 325.0000 | 2.2700 |
| 330.0000 | 2.3100 |
| 335.0000 | 2.4100 |
| 340.0000 | 2.5500 |
| 345.0000 | 2.6500 |
| 350.0000 | 2.3600 |
| 355.0000 | 2.1200 |
| 360.0000 | 1.9300 |
| 365.0000 | 1.8800 |
| 370.0000 | 1.8800 |
| 375.0000 | 2.1700 |
| 380.0000 | 2.3600 |
| 385.0000 | 2.4600 |
| 390.0000 | 2.5000 |
| 395.0000 | 2.2700 |
| 400.0000 | 1.6900 |
| 405.0000 | 1.1700 |
| 410.0000 | 0.6900 |
| 415.0000 | 0.4600 |

Mean Time of Passage = 289.2002
Variance = 4108.8855
Third Moment = 45103031.3383
Skewness Coefficient = 155957.7905

TABLE B-4 TIME CONCENTRATION OBSERVATIONS AND COMPUTER RESULTS FROM MONITORING POINT NO. 4 - STUDY NO. 2

Mean Stream Velocity = 2.8244 mi./day Study No. 1
Dispersion Coefficient = 0.025 sq. mi./day
Mean Stream Velocity = 1.7089 mi./day Study No. 2
Dispersion Coefficient = 0.015 sq. mi./day

```
$JOB  $W681180       HJB CURRAN                              WATFIV JOB CARD
C     ****************************************************************
C
C
C     DISPERSION & MEAN VELOCITY DETERMINATIONS
C     RIDEAU RIVER TRACER STUDY
C
C
C     DEFINITION OF TERMS
C
C     N=NUMBER OF VALUES TAKEN FROM THE TIME CONCENTRATION CURVE
C     OF EACH MONITORING POINT
C     C=CONCENTRATION OF TRACER AT TIME 'T'
C     P1=MEAN OF TIME CONCENTRATION CURVE OR FIRST MOMENT
C     P2=VARIANCE OF TIME CONCENTRATION CURVE OR SECOND MOMENT
C     P3=THIRD MOMENT OF THE TIME CONCENTRATION CURVE
C     SC=SKEWNESS COEFFICIENT
C     AVEL1=MEAN STREAM VELOCITY NEAR BLACK RAIDS  MI/DAY
C     AVEL2=MEAN STREAM VELOCITY NEAR KARS
C     DL1=DISPERSION COEFFICIENT NEAR BLACK RAPIDS  SQ.MI./DAY
C     DL2=DISPERSION COEFFICIENT NEAR KARS
C     X1=DISTANCE BETWEEN MONITORING POINTS 1 AND 2
C     X2=DISTANCE BETWEEN MONITORING POINTS 3 AND 4
C
C     ****************************************************************
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION C(100),T(100)
      WRITE(3,101)
  101 FORMAT('1',20X,'STUDY NEAR BLACK RAPIDS DAM'///)
      N=59
      READ(1,11)(C(I),I=1,N)
      READ(1,11)(T(I),I=1,N)
   11 FORMAT(10F8.2)
      CALL VARI(C,T,P1,P2,P3,SC,N)
      WRITE(3,105)
  105 FORMAT(20X,'MONITORING POINT NO. 1'//)
      WRITE(3,21)
   21 FORMAT(15X,'TIME',12X,'CONCENTRATION')
      WRITE(3,25)
   25 FORMAT(14X,'MINUTES',14X,'MG/L'/)
      WRITE(3,31)(T(I),C(I),I=1,N)
   31 FORMAT(2F20.4)
      WRITE(3,111)P1
      WRITE(3,112)P2
      WRITE(3,113)P3
```

```
      WRITE(3,114)SC
  111 FORMAT(///15X,'MEAN TIME OF PASSAGE=',F13.4)
  112 FORMAT(15X,'VARIANCE=',F23.4)
  113 FORMAT(15X,'THIRD MOMENT=',F20.4)
  114 FORMAT(15X,'SKEWNESS COEFFICIENT=',F12.4////)
      P11=P1
      P12=P2
      N=53
      WRITE(3,201)
  201 FORMAT(20X,'MONITORING POINT NO. 2'//)
      READ(1,11)(C(I),I=1,N)
      READ(1,11)(T(I),I=1,N)
      CALL VARI(C,T,P1,P2,P3,SC,N)
      WRITE(3,21)
      WRITE(3,25)
      WRITE(3,31)(T(I),C(I),I=1,N)
      WRITE(3,111)P1
      WRITE(3,112)P2
      WRITE(3,113)P3
      WRITE(3,114)SC
      P21=P1
      P22=P2
      N=23
      READ(1,11)(C(I),I=1,N)
      READ(1,11)(T(I),I=1,N)
      CALL VARI(C,T,P1,P2,P3,SC,N)
      WRITE(3,102)
  102 FORMAT('1',20X,'STUDY NEAR KARS',/)
      WRITE(3,301)
  301 FORMAT(20X,'MONITORING POINT NO. 3'//)
      WRITE(3,21)
      WRITE(3,25)
      WRITE(3,31)(T(I),C(I),I=1,N)
      WRITE(3,111)P1
      WRITE(3,112)P2
      WRITE(3,113)P3
      WRITE(3,114)SC
      PP11=P1
      PP12=P2
      N=49
      READ(1,11)(C(I),I=1,N)
      READ(1,11)(T(I),I=1,N)
      CALL VARI(C,T,P1,P2,P3,SC,N)
      WRITE(3,401)
  401 FORMAT(20X,'MONITORING POINT NO. 4'//)
      WRITE(3,21)
```

```
      WRITE(3,25)
      WRITE(3,31)(T(I),C(I),I=1,N)
      WRITE(3,111)P1
      WRITE(3,112)P2
      WRITE(3,113)P3
      WRITE(3,114)SC
      PP21=P1
      PP22=P2
C
C
C     ****************************************************************
C
C
      READ(1,41)X1,X2
   41 FORMAT(2F10.4)
      AVEL1=X1/(P21-P11)
      AVEL2=X2/(PP21-PP11)
      DL1=.5*AVEL1*AVEL1*(P22-P12)/(P21-P11)
      DL2=.5*AVEL2*AVEL2*(PP22-PP12)/(PP21-PP11)
      DL1=DL1*24*60/(5280*5280)
      DL2=DL2*24*60/(5280*5280)
      AVEL1=AVEL1*24*60/5280
      AVEL2=AVEL2*24*60/5280
      WRITE(3,51)AVEL1
      WRITE(3,501)DL1
      WRITE(3,901)AVEL2
      WRITE(3,601)DL2
   51 FORMAT(///10X'MEAN STREAM VELOCITY=',F6.4,'  MI/DAY','   STUDY NO.
     *1')
  901 FORMAT(10X'MEAN STREAM VELOCITY=',F6.4,'  MI/DAY','   STUDY NO.2')
  501 FORMAT(10X'DISPERSION COEFFICIENT=',F8.3,'   SQ.MI./DAY')
  601 FORMAT(10X'DISPERSION COEFFICIENT=',F8.3,'   SQ.MI./DAY')
      RETURN
      END
C
C     ****************************************************************
C

      SUBROUTINE VARI(C,T,P1,P2,P3,SC,N)
C
C     CALCULATION OF MEAN,VARIANCE,AND SKEWNESS COEFFICIENT
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION T(100),C(100)
C
C     CALCULATE MEAN
```

```
      SUMC=0.
      SUMCT=0.
      DO 10 I=1,N
      SUMCT=C(I)*T(I)+SUMCT
   10 SUMC=SUMC+C(I)
      P1=SUMCT/SUMC
C
C     CALCULATE VARIANCE
      SUMVAR=0.
      DO 20 I=1,N
   20 SUMVAR=SUMVAR+T(I)*T(I)*C(I)
      P2=SUMVAR/SUMC-P1*P1
C
C     CALCULATE SKEWNESS COEFFICIENT
      SKEW=0.
      DO 30 I=1,N
   30 SKEW=(SKEW+T(I)*T(I)*T(I)*C(I))/SUMC
      P3=SKEW-3.*P1*P2+2.*P1**3.
      SC=P3/P1
      RETURN
      END

 $ENTRY
```

# APPENDIX C

## BOD RESULTS

## CALCULATION OF Kr - BY METHOD OF MOMENTS(52)

DOWNSTREAM STATION
(See Figure 3.1 for Map Location)

| t Days | BOD (y) ppm | ty |
|---|---|---|
| 1 | 0.49 | .49 |
| 2 | 0.94 | 1.88 |
| 3 | 1.19 | 3.57 |
| 4 | 1.39 | 5.56 |
| 5 | 1.69 | 8.45 |
|  | $\Sigma y = 5.70$ | $\Sigma ty = 19.95$ |

TABLE C-1 RIVER BOD RESULTS

From Graphs prepared by Moore, Thomas, and Snow:(52)

$$k_{10} = .106 \text{ per day}$$

and

$$\frac{\Sigma y}{L} = 2.44$$

Hence

$$L_{dn} = 2.34 \text{ ppm}$$

UPSTREAM STATION
(See Figure 3.1 for Map Location)

| t<br>Days | BOD (y)<br>ppm | ty |
|---|---|---|
| 1 | 0.65 | 0.65 |
| 2 | 0.90 | 1.80 |
| 3 | 1.40 | 4.20 |
| 4 | 1.70 | 6.80 |
| 5 | 2.05 | 10.25 |
|  | $\Sigma y = 6.70$ | $\Sigma ty = 23.70$ |

TABLE C-2 RIVER BOD RESULTS

From Graphs prepared by Moore, Thomas, and Snow:(52)

$$k_{10} = .08 \text{ per day}$$

and

$$\frac{\Sigma y}{L} = 2.00$$

Hence

$$L_{up} = \frac{6.70}{2.00} = 3.35 \text{ ppm}$$

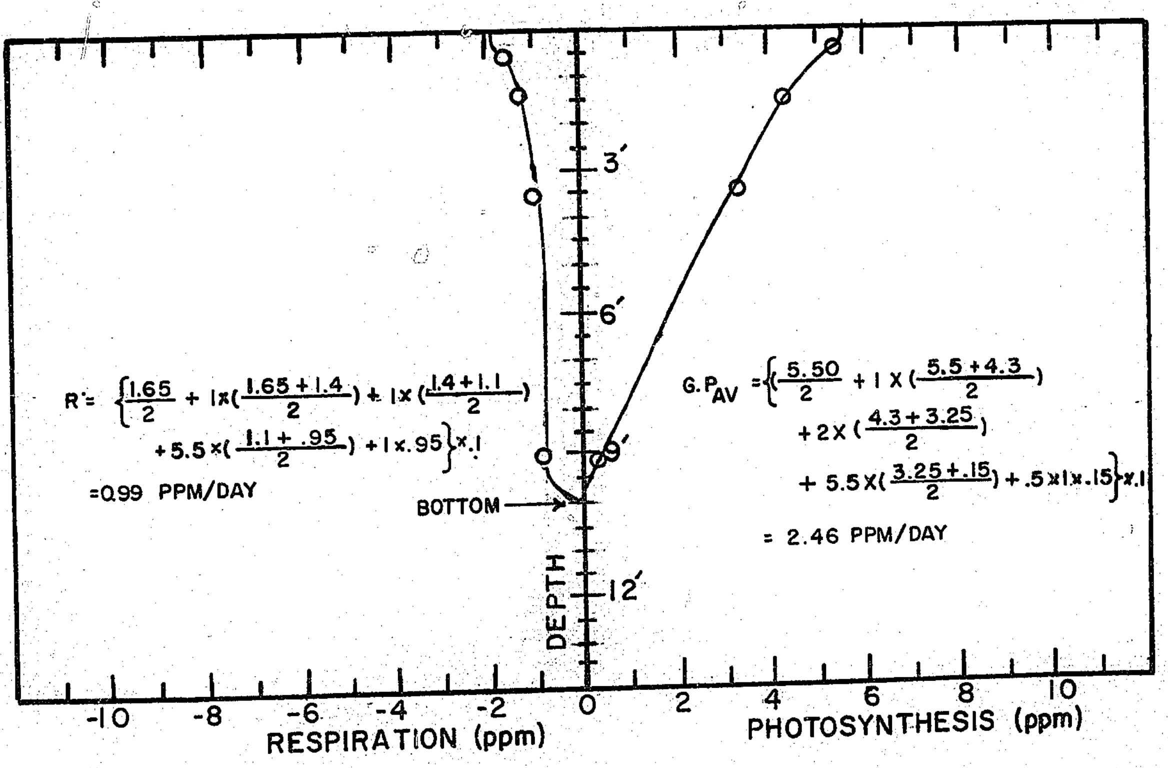
# APPENDIX D

# PHOTOSYNTHESIS AND RESPIRATION RESULTS

LOCATION: Below Long Island Locks (2-PR)
SEECHI DISC READING: 2 Metres
DEPTH OF CHANNEL: 10 Feet

| Depth ft. | Initial DO ppm | Light Bottle DO ppm | Dark Bottle DO ppm | Resp. ppm | Gross Photo. ppm |
|---|---|---|---|---|---|
| .5 | 9.05 | 12.9 | 7.4 | 1.65 | 5.50 |
| 1.5 | 8.5 | 11.4 | 7.1 | 1.4 | 4.3 |
| 3.5 | 7.4 | 9.55 | 6.3 | 1.1 | 3.25 |
| 9.0 | 7.2 | 6.4 | 6.25 | .95 | .15 |

TABLE D-1 LIGHT AND DARK BOTTLE TEST RESULTS



$$R = \left\{\frac{1.65}{2} + 1\times\left(\frac{1.65+1.4}{2}\right) + 1\times\left(\frac{1.4+1.1}{2}\right) + 5.5\times\left(\frac{1.1+.95}{2}\right) + 1\times.95\right\}\times.1$$

$$= 0.99 \text{ PPM/DAY}$$

$$G.P_{AV} = \left\{\left(\frac{5.50}{2}\right) + 1\times\left(\frac{5.5+4.3}{2}\right) + 2\times\left(\frac{4.3+3.25}{2}\right) + 5.5\times\left(\frac{3.25+.15}{2}\right) + .5\times1\times.15\right\}\times.1$$

$$= 2.46 \text{ PPM/DAY}$$

FIGURE D.1 — AVERAGE DAILY GROSS PHOTOSYNTHETIC PRODUCTION & RESPIRATION EVALUATION BELOW LONG ISLAND LOCKS

LOCATION: In Mooney's Bay (1-PR)
SEECHI DISC READING: 1.2 Metres
DEPTH OF CHANNEL: 24.5 Feet

| Depth ft. | Initial DO ppm | Light Bottle DO ppm | Dark Bottle DO ppm | Resp. ppm | Gross Photo. ppm |
|---|---|---|---|---|---|
| .5 | 10.1 | 10.70 | 8.15 | 1.95 | 2.55 |
| 1.5 | 10.2 | 10.55 | 8.85 | 1.35 | 1.70 |
| 3.5 | 10.25 | 9.9 | 9.0 | 1.25 | .90 |
| 12. | 6.95 | 6.45 | 6.40 | .55 | .05 |

TABLE D-2 LIGHT AND DARK BOTTLE TEST RESULTS

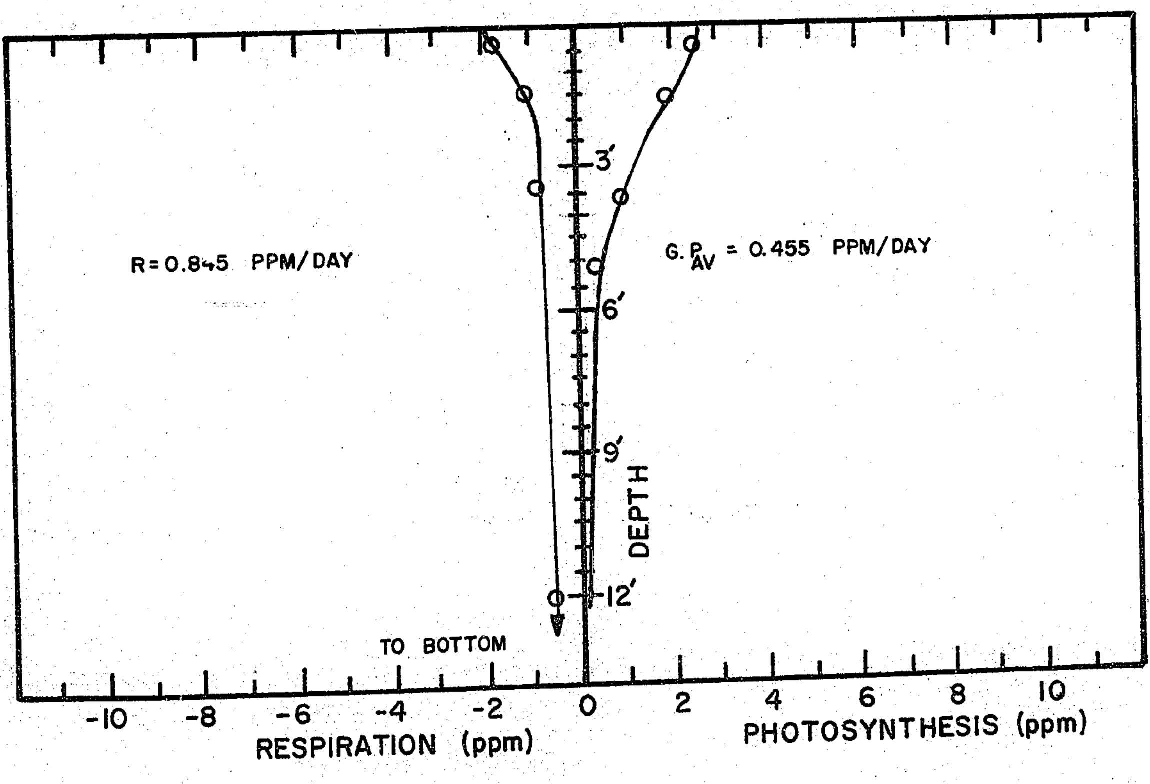


FIGURE D.2 —— AVERAGE DAILY GROSS PHOTOSYNTHETIC PRODUCTION & RESPIRATION EVALUATION FROM MOONEY'S BAY

LOCATION: Upstream from Kars (3-PR)
SEECHI DISC READING: 1.5 Metres
CHANNEL DEPTH: 26 Feet

| Depth ft. | Initial DO ppm | Light Bottle DO ppm | Dark Bottle DO ppm | Resp. ppm | Gross Photo. ppm |
|---|---|---|---|---|---|
| .5 | 7.44 | 8.7 | 6.8 | .64 | 1.9 |
| 1.5 | 7.40 | 8.25 | 7.15 | .25 | 1.1 |
| 3.5 | 7.37 | 7.55 | 6.8 | .57 | .75 |
| 6. | 7.35 | 6.95 | 6.75 | .60 | .60 |

TABLE D-3 LIGHT AND DARK BOTTLE TEST RESULTS

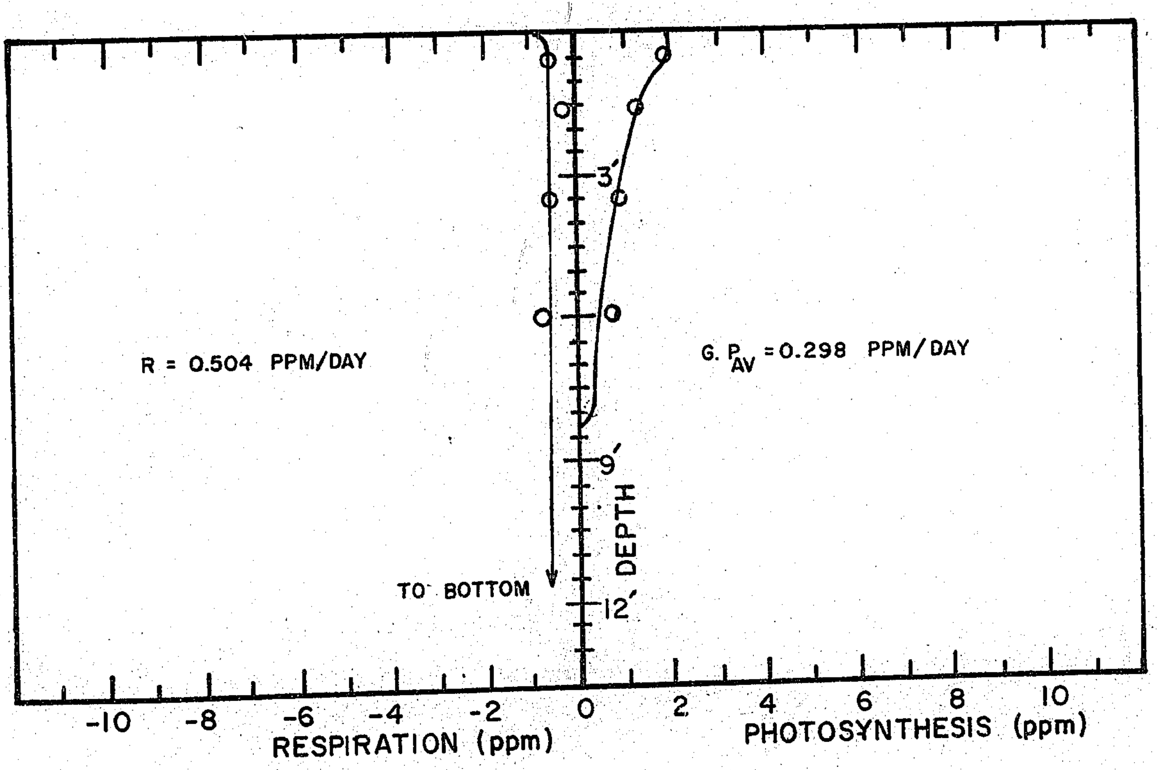


FIGURE D.3 —— AVERAGE DAILY GROSS PHOTOSYNTHETIC PRODUCTION & RESPIRATION EVALUATION UPSTREAM OF KARS

| | |
|---|---|
| LOCATION: | Downstream of Kemptville Creek (4-PR) |
| SEECHI DISC READING: | 2 Metres |
| DEPTH OF CHANNEL: | 8 Feet |

| Depth ft. | Initial DO ppm | Light Bottle DO ppm | Dark Bottle DO ppm | Resp. ppm | Gross Photo. ppm |
|---|---|---|---|---|---|
| .5 | 7.6 | 7.85 | 7.35 | .25 | .50 |
| 1.5 | 7.61 | 7.60 | 7.45 | .16 | .15 |
| 3.5 | 7.63 | 7.75 | 7.55 | .08 | .20 |
| 7. | 7.90 | 7.80 | 7.65 | .25 | .15 |

TABLE D-4 LIGHT AND DARK BOTTLE TEST RESULTS

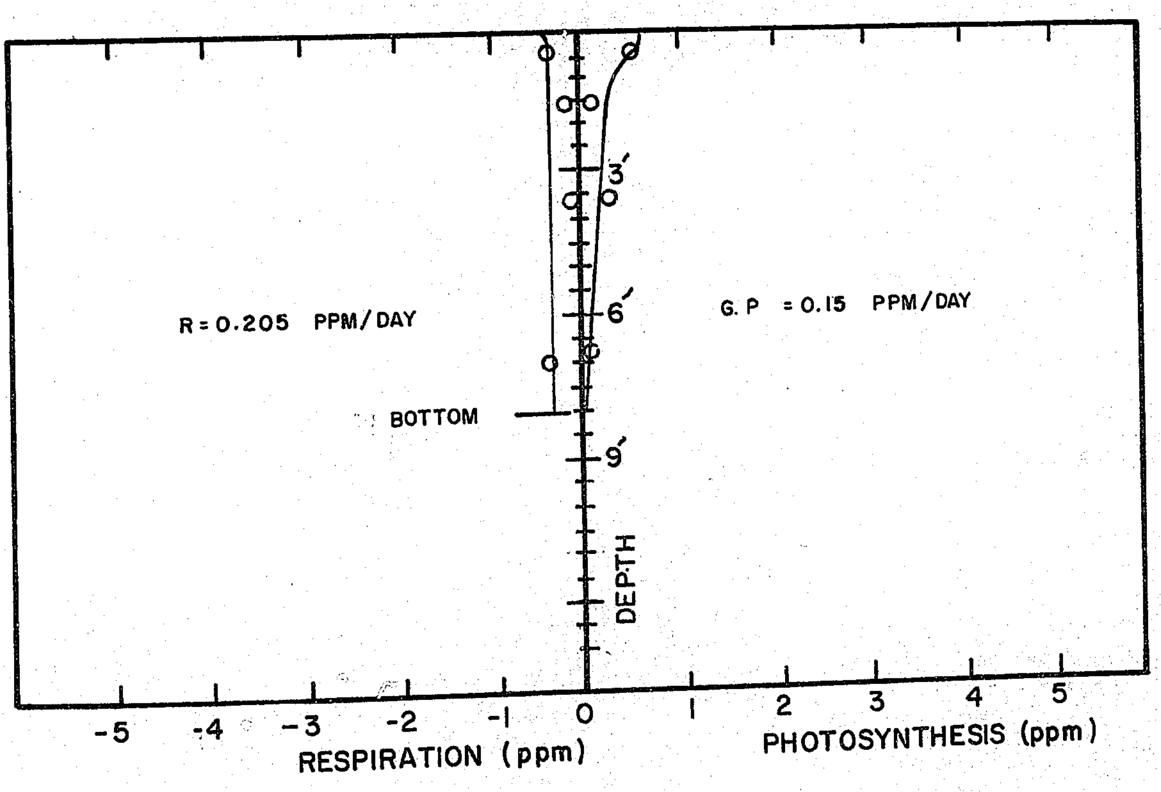


FIGURE D.4 — AVERAGE DAILY GROSS PHOTOSYNTHETIC PRODUCTION & RESPIRATION EVALUATION DOWNSTREAM OF KEMPTVILLE CREEK

# APPENDIX E

## COMPUTER PROGRAMME FOR THE DETERMINATION OF THE BOD, NOD, AND DO DEFICIT PROFILES IN THE RIDEAU RIVER

```
$JOB  $W681180       HJB CURRAN                      WATFIV JOB  CARD
C     ********* *********************** ************************ ********
C
C
C     CALCULATI ON OF THE BOD, NOD, DO D EFICIT PROFILES
C     OF THE RI DEAU RIVER BETWEEN KARS AND MOONEY'S BAY
C
C
C     ********* *********************** ************************ ********
C
C
C     DEFINITIO N OF TERMS
C
C     DOX=DISSO LVED OXYGEN DEFICIT MG/L
C     BOD=BIOCH EMICAL OXYGEN DEMAND MG/ L
C     BODN=NITR OGENOUS OXYGEN DEMAND  M G/L
C     DOSAT=DIS SOLVED OXYGEN SATURATION  CONCETRATION
C     VELOCITY COEFFICIENT TO ACCOUNT F OR DEAD ZONES IN THE RIV ER
C     THETA=TEM PERATURE COEFFICIENT FOR  REAIRATION
C     H=HEIGHT OF WEIRS
C     VEL=STREA M VELOCITY
C     A=CROSS S ECTION AREA
C     Q=STREAM FLOW  CFS
C     XX=SLOPE OF THE ENERGY GRADE LINE
C     RA=REAERA TION COEFFICIENT
C     OXSED=OXY GEN DEMAND OF THE SEDIME NTS
C     SEDR=BOD FROM SEDIMENTS
C     AG=ACCELE RATION OF GRAVITY    MIL ES/DAY
C     RC=MANNIN G'S COEFFICIENT OF ROUGH NESS
C     RESP=PLAN T RESPIRATION
C     FOTOM=OXY GEN PRODUCED BY PHOTOSYN THESIS
C     TEMP=STRE AM TEMPERATURE
C     RR=RIVER REACTION RATE COEFFICIEN T
C     RN=NITROG ENOUS REACTION RATE COEF FICIENT
C
      IMPLICIT REAL*8(A-H,O-Z)
      DIMENSION  Q(20),BOD(20),BODN(20), VC(20),DOX(20),TS(15,5), TT(15,5),
     0N(10),R(1 0),H(10),X(15)
      RR=.175*1 .047**3.
      AG=32.2*3 600.*24.*3600.*24./5280.
      RC=.03
      RESP=.99
      BOD(1)=1. 0
      FOTOM=1.7 5
      TEMP=23.
      BOD(1)=1. 0
```

```
      DOSAT=14. 652-.410222*TEMP+.007991 *TEMP**2.-.00007777*TEMP **3.
      DOX(1)=DO SAT-9.0
      BODN(1)=1 .07
      BODNA=0.
      RN=.00475 -.00184*TEMP+.000326*TEM P**2.-.000017*TEMP**3.+. 000000479
     0*TEMP**4.
      VC(2)=.22 6
      Q(2)=150.
      DO 60 I=3 ,4
      VC(I)=.24 8
   60 Q(I)=.61* 150.
      DO 70 I=5 ,6
      VC(I)=.24 8
   70 Q(I)=.39* 150.
      DO 80 I=7 ,15
      VC(I)=.24 8
   80 Q(I)=150.
      THETA=1.0 17
      DO 222 I= 1,3
      READ(1,22 3) H(I)
  223 FORMAT(F1 0,5)
  222 R(I)=1.+. 11*1.25*(1.+.046*TEMP)*H (I)
      R1=R(1)
      R2=R(2)
      R3=R(3)
      DIS=0.
      DO 100 J= 2,6
      K=J-1
C
C     ********* *********************** *********************** ********
C
C     CALCULATI ON OF THE REAERATION COE FFICIENT
C
C     ********* *********************** *********************** ********
C
      READ(1,10 )A
   10 FORMAT(F1 0.2)
      READ(1,20 )DEPTH
   20 FORMAT(F1 0.3)
      VEL=Q(J)/ (A*VC(J))*24.*3600/5280.
      RH=A/(A/D EPTH+2.*DEPTH)
      XX=VEL*RC /(1.49*RH**.667)
      SEG=XX*XX
      YY=AG*DEP TH
      XY=VEL/DS QRT(YY)
      YX=SEG/DE PTH*AG
```

```
      RA=.00012 5*(1.+DSQRT(XY))*DSQRT(Y X)
      RAT=RA*TH ETA**3.*2.3026
      RA=RAT
      READ(1,55 5)OXSED
  555 FORMAT(F1 0.3)
      READ(1,30 )DIST
   30 FORMAT(F1 0.5)
      DIST=DIST /10.
      READ(1,40 )SEDR
   40 FORMAT(F1 0.3)
      ASED=(A/D EPTH+2.*DEPTH)*DIST*5280 ./10.7638
      VOL=A*DIS T*5280.*28.316
      BODA=SEDR *ASED/VOL*1000.
      IF(J.EQ.3 ) BODA=1.+BODA
      IF(J.EQ.5 )BODA=1.+BODA
      CR=RR*DIS T/VEL
      CN=RN*DIS T/VEL
      CA=RAT*DI ST/VEL
      BD=OXSED* ASED/VOL*1000.
      X(1)=DIS
C
C     ********* *********************** *********************** ********
C
C     CALCULATE  BOD, NOD, DO DEFICIT
C
C     ********* *********************** *********************** ********
C
      DO 199 I= 2,11
      BOD(I)=BO D(I-1)*1./DEXP(CR)+(BODA /RR)*(1.-1./DEXP(CR))
      BODN(I)=B ODN(I-1)*1./DEXP(CN)+BOD NA/CR*(1.-1./DEXP(CN))
      CBOD=RR*B OD(I)/(RA-RR)
      CBON=RN*4 .57*BODN(I)/(RA-RN)
      AA=DOX(I- 1)*1./DEXP(CA)
      B=CBOD*(1 ./DEXP(CR)-1./DEXP(CA))
      C=CBON*(1 ./DEXP(CN)-1./DEXP(CA))
      D=BD/RA*( 1.-1./DEXP(CA))
      E=RESP/RA *(1.-1./DEXP(CA))
      G=FOTOM/R A*(1.-1./DEXP(CA))
      G1=BODA/R A*(1.-1./DEXP(CA))
      G2=BODA/( RA-RR)*(1./DEXP(CR)-1./D EXP(CA))
      DOX(I)=AA +B+C+D+E-G+G1-G2
      X(I)=DIST +X(I-1)
  199 CONTINUE
      VOL=VOL*1 0.
      ASED=ASED *10.
      WRITE(3,1 21)K
```

```
      WRITE(3,3 34)A
      WRITE(3,3 35)DEPTH
      WRITE(3,3 46)VEL
      WRITE(3,3 45)BODA
      WRITE(3,3 43)VOL
      WRITE(3,3 42)ASED
      WRITE(3,3 40)RN
      WRITE(3,3 39)SEG
      WRITE(3,3 37)OXSED
      WRITE(3,3 38)DOSAT
      WRITE(3,3 36)SEDR
      WRITE(3,3 41)RA
      WRITE(3,3 47)BD
      WRITE(3,1 22)
      WRITE(3,1 23)
      WRITE(3,1 24)(X(I),BOD(I),BODN(I), DOX(I),I=2,11)
  121 FORMAT('1 ',///33X,'          REACH  NO.',I5///)
  334 FORMAT(30 X,'AREA=',F18.3,8X,'SQFT ')
  335 FORMAT(30 X,'DEPTH=',F17.3,8X,'FT' )
  346 FORMAT(30 X,'VELOCITY=',F14.3,8X,' MI/DAY')
  342 FORMAT(30 X,'AREA OF SED='F11.3,8X ,'SQ.M')
  345 FORMAT(30 X,'BODA=',F18.3,8X,'MG/L /DAY')
  343 FORMAT(30 X,'VOLUME=',F16.3,8X,'L' )
  340 FORMAT(30 X,'RN=',F20.3,8X,'1/DAY' )
  339 FORMAT(30 X,'ENERGY GRADIENT=',F13 .9,2X,'FT/FT')
  337 FORMAT(30 X,'OXSED=',F17.3,8X,'GMS /SQ.M/DAY')
  338 FORMAT(30 X,'DOSAT=',F17.3,8X,'MG/ L/DAY')
  336 FORMAT(30 X,'SEDR=',F18.3,8X,'GMS/ SQ.M/DAY')
  341 FORMAT(30 X,'REAERATION COEF.=',F8 .5,6X'1/DAY')
  347 FORMAT(30 X,'BD=',F20.3,8X,'MG/L/D AY'////)
  122 FORMAT(24 X,'      DISTANCE','      BOD','        NOD','           D
     0O DEFICIC IT'/)
  123 FORMAT(22 X,'        MILES','         MG/L','       MG/L', '
     0   MG/L'/ )
  124 FORMAT(18 X,F17.3,F13.3,F12.3,F16. 3)
      DOX(1)=DO X(11)
      BOD(1)=BO D(11)
      BODN(1)=B ODN(11)
      DIS=X(11)
      IF(J-2) 2 71,272,271
  272 ADOX=DOX( 11)
      BODX=BOD( 11)
      BODNX=BOD N(11)
  271 IF(J-4) 7 76,777,776
  777 DOX(1)=AD OX
      BOD(1)=BO DX
```

```
      BODN(1)=B ODNX
      DIS=0.
      WDOX2=DOX (11)
      BOD4=BOD( 11)
      BODN4=BOD N(11)
      X4=X(11)
  776 IF(J-5) 1 00,700,100
  700 DOX(11)=R 1*DOX(11)
      IF(DOX(11 ).LT.0) DOX(1)=0.
      XDOX=DOX( 1)
      WRITE(3,3 33)XDOX
   31 FORMAT(// 28X,'   PARAMETERS AFTER  MIXING BELOW LONG ISLAN D DAM'//)
  100 CONTINUE
      WDOX2=WDO X2*R2
      IF(WDOX2. LT.0) WDOX2=0.
      WRITE(3,2 2)WDOX2
   22 FORMAT('1 ',///30X,'DO DEFICIT BEL OW WEIR AT LONG ISLAND=' ,F10.5)
      DOX(1)=.3 9*DOX(11)+.61*WDOX2
      BOD(1)=.3 9*BOD(11)+.61*BOD4
      BODN(1)=. 39*BODN(11)+.61*BODN4
      WRITE(3,3 1)
      WRITE(3,3 7)X4,BOD(1),BODN(1),DOX( 1)
   37 FORMAT(22 X,F13.3,F15.4,F13.3,F16. 3)
      X(1)=X4
      DOXU=DOSA T-2.
      BODNU=7.5
      QUP=1.125
      BODU=40.
  333 FORMAT(// /24X,'      DO DEFICIT B ELOW WEIR AT MANOTICK=', F10.5)
      DO 200 J= 7,14
      K=J-1
      IF(J-14) 444,557,444
  557 FOTOM=.45 5
      RESP=.845
  444 CONTINUE
C
C     ********* *********************** *********************** *********
C
C     CALCULATI ON OF THE REAERATION COE FFICIENT
C
C     ********* *********************** *********************** *********
C
      READ(1,10 )A
      READ(1,20 )DEPTH
      VEL=Q(J)/ (A*VC(J))*24.*3600/5280.
      RH=A/(A/D EPTH+2.*DEPTH)
```

```
      XX=VEL*RC /(1.49*RH**.667)
      SEG=XX*XX
      YY=AG*DEP TH
      XY=VEL/DS QRT(YY)
      YX=SEG/DE PTH*AG
      RA=.00012 5*(1.+DSQRT(XY))*DSQRT(Y X)
      RAT=RA*TH ETA**3.*2.3026
      RA=RAT
      READ(1,55 5)OXSED
      READ(1,30 )DIST
      DIST=DIST /10
      READ(1,40 )SEDR
      ASED=(A/D EPTH+2.*DEPTH)*DIST*5280 ./10.7638
      VOL=A*DIS T*5280.*28.316
      BODA=SEDR *ASED/VOL*1000.
      IF(J.EQ.8 ) BODA=1.+BODA
      CR=RR*DIS T/VEL
      CN=RN*DIS T/VEL
      CA=RAT*DI ST/VEL
      BD=OXSED* ASED/VOL*1000.
      DIS=0.
C
C     ********* ********************** ********************** *********
C
C     CALCULATE  BOD, NOD, DO DEFICIT
C
C     ********* ********************** ********************** *********
C
      DO 299 I= 2,11
      BOD(I)=BO D(I-1)*1./DEXP(CR)+(BODA /RR)*(1.-1./DEXP(CR))
      BODN(I)=B ODN(I-1)*1./DEXP(CN)+BOD NA/CR*(1.-1./DEXP(CN))
      CBOD=RR*B OD(I)/(RA-RR)
      CBON=RN*4 .57*BODN(I)/(RA-RN)
      AA=DOX(I- 1)*1./DEXP(CA)
      B=CBOD*(1 ./DEXP(CR)-1./DEXP(CA))
      C=CBON*(1 ./DEXP(CN)-1./DEXP(CA))
      D=BD/RA*( 1.-1./DEXP(CA))
      E=RESP/RA *(1.-1./DEXP(CA))
      G=FOTOM/R A*(1.-1./DEXP(CA))
      G1=BODA/R A*(1.-1./DEXP(CA))
      G2=BODA/( RA-RR)*(1./DEXP(CR)-1./D EXP(CA))
      DOX(I)=AA +B+C+D+E-G+G1-G2
      X(I)=DIST +X(I-1)
  299 CONTINUE
      VOL=VOL*1 0.
      ASED=ASED *10.
```

```
      WRITE(3,1 21)K
      WRITE(3,3 34)A
      WRITE(3,3 35)DEPTH
      WRITE(3,3 46)VEL
      WRITE(3,3 45)BODA
      WRITE(3,3 43)VOL
      WRITE(3,3 42)ASED
      WRITE(3,3 40)RN
      WRITE(3,3 39)SEG
      WRITE(3,3 37)OXSED
      WRITE(3,3 38)DOSAT
      WRITE(3,3 36)SEDR
      WRITE(3,3 41)RA
      WRITE(3,3 47)BD
      BOD(1)=BO D(11)
      BODN(1)=B ODN(11)
      DOX(1)=DO X(11)
      X(1)=X(11 )
      WRITE(3,1 22)
      WRITE(3,1 23)
      WRITE(3,1 24)(X(I),BOD(I),BODN(I), DOX(I),I=2,11)
      IF(J-10) 905,800,905
  800 DOX(11)=R 3*DOX(11)
      IF(DOX(11 ).LT.0) DOX(1)=0.
      WRITE(3,2 66)DOX(1)
  266 FORMAT(// /28X,'   DO DEFICIT BELO W WEIR AT BLACK RAPIDS=' ,F10.5)
  905 IF(J-11) 200,899,200
  899 BOD(1)=(B OD(11)*Q(J)+QUP*BODU)/(Q (J)+QUP)
      BODN(1)=( BODN(11)*Q(J)+QUP*BODNU) /(Q(J)+QUP)
      DOX(1)=(D OX(11)*Q(J)+QUP*DOXU)/(Q (J)+QUP)
      WRITE(3,4 9)
   49 FORMAT('1 ',///29X,'  PARAMETERS A T UPLANDS TREATMANT PLAN T:'//)
      WRITE(3,1 22)
      WRITE(3,1 23)
      WRITE(3,3 7)X(11),BOD(1),BODN(1),D OX(1)
  200 CONTINUE
      RETURN
      END

$ENTRY
```