

DEOXYGENATION RATES IN AN  
ICE-COVERED RIVER

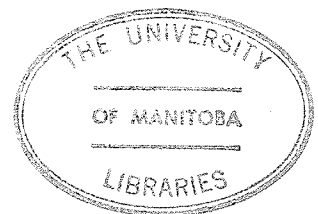
by  
Arnold H. Permut

A THESIS  
SUBMITTED TO THE FACULTY OF GRADUATE STUDIES  
IN PARTIAL FULFILMENT OF THE REQUIREMENTS FOR THE DEGREE  
OF MASTER OF SCIENCE

Department of Civil Engineering

Winnipeg, Manitoba

February, 1976



"DEOXYGENATION RATES IN AN  
ICE-COVERED RIVER"

by

Arnold H. Permut

A dissertation submitted to the Faculty of Graduate Studies of  
the University of Manitoba in partial fulfillment of the requirements  
of the degree of

MASTER OF SCIENCE

© 1976

Permission has been granted to the LIBRARY OF THE UNIVER-  
SITY OF MANITOBA to lend or sell copies of this dissertation, to  
the NATIONAL LIBRARY OF CANADA to microfilm this  
dissertation and to lend or sell copies of the film, and UNIVERSITY  
MICROFILMS to publish an abstract of this dissertation.

The author reserves other publication rights, and neither the  
dissertation nor extensive extracts from it may be printed or other-  
wise reproduced without the author's written permission.

Abstract

Deoxygenation rate constants were determined for a portion of the Red River in the South End of Winnipeg. Methodology problems were encountered and are discussed in the text. The effects of temperature and nitrification were studied and discussed herein.

It was found that little confidence could be placed in the values determined due to high standard deviations associated with these values. The reasons for these high standard deviations are also discussed in this thesis.

### Acknowledgement

I would like to take this opportunity to thank those people without whose help this thesis would not have been possible: my adviser Dr. A.B. Sparling and my thesis committee members Dr. D.D. Schulte and W.D. Carroll.

I would like to acknowledge the financial support of National Research Council grant 311-272-013.

Finally, I would like to thank my wife Susan for her patience and moral support while this thesis was being written.

TABLE OF CONTENTS

	Page	
CHAPTER 1	INTRODUCTION	1
	1.1. Statement of Problem	1
	1.2. Reason for Study	1
CHAPTER 2	PURPOSE AND SCOPE	4
	2.1. Study Objectives	4
	2.2. Extent of Investigation	
CHAPTER 3	LITERATURE REVIEW	7
	3.1. Introduction	7
	3.2. The Streeter-Phelps Equation and Stream Self-Purification Capacity	8
	3.2.1. The Streeter Phelps Equation	9
	3.2.2. The Application of Self-Purification Capacity	14
	3.3. The Determination of the Deoxygenation Rate Constant ( $k_1$ )	16
	3.3.1. The BOD Test	16
	3.3.2. The BOD Reaction	17
	3.3.3. The Determination of $k_1$	17
	3.3.4. Laboratory Versus Stream Conditions	19
	3.3.5. The Magnitude of $k_1$	21
	3.4. Temperature Effects on the Deoxygenation Rate	21
	3.4.1. The van't Hoff-Arrhenius Relationship	21
	3.4.2. The Temperature Coefficient	22
	3.5. Nitrification Effects	24
	3.5.1. The Nitrification Reaction	25
	3.5.2. Nitrification and the BOD Test	25
	3.5.3. Temperature Effects on Nitrification	26
	3.5.4. Nitrification in Streams	27
	3.5.5. Nitrification Inhibition in the BOD Test	28
	3.6. Microbiological Considerations in the BOD Test	29
	3.6.1. Substrate Concentration	29
	3.6.2. Temperature Acclimation	31
	3.6.3. Bacterial Populations	32
	3.6.4. First-Order Kinetics?	33

	Page
CHAPTER 3 Continued	
3.7. COD, TOC and TOD	37
3.7.1. COD	37
3.7.2. TOC and TOD	38
3.8. Validity of Results	39
CHAPTER 4 EXPERIMENTAL PROCEDURE	41
4.1. Winter Study Period	41
4.2. Summer Study Period	42
CHAPTER 5 DETERMINATION OF RESULTS	46
5.1. Determination of Deoxygenation Rates	46
5.1.1. Determination of Carbonaceous Rates by the Thomas Method	46
5.1.2. Determination of Nitrogenous Rates by the Thomas Method	49
5.1.3. Determination of Carbonaceous Rates by the Method of Moments Method	50
5.1.4. Determination of Nitrogenous Rates by the Method of Moments Method	52
5.1.5. Determination of Carbonaceous Rates by the Daily Difference Method	53
5.2. van't Hoff-Arrhenius Correlation	55
5.3. Statistics	55
5.3.1. Mean and Standard Deviation	55
5.3.2. Least Significant Difference	56
5.4. Chemical Oxygen Demand	58
CHAPTER 6 EXPERIMENTAL RESULTS	59
6.1. River Flow and Treatment Plant Effluent Parameters	59
6.2. Standard Plate Counts	59
6.3. Chemical Oxygen Demand	59
6.4. Deoxygenation Rate Constants	60
6.5. Statistical Results	61
6.5.1. Standard Deviation and Mean of $k_1$ and $L$	61
6.5.2. Least Significant Difference of Results	62
6.6. van't Hoff-Arrhenius Calculation Results	62

	Page	
CHAPTER 7	DISCUSSION OF EXPERIMENTAL RESULTS	83
7.1.	River Flow and Treatment Plant Effluent Parameters	83
7.1.1.	River Flow	83
7.1.2.	Effluent Volume	83
7.2.	Standard Plate Counts	84
7.2.1.	Temperature Affects	84
7.2.2.	Nitrification Inhibitor Effects	84
7.2.3.	Significance of Results	85
7.2.4.	SPC's and the BOD-Time Curve	85
7.3.	Chemical Oxygen Demand	86
7.4.	Deoxygenation Rate Constants	88
7.4.1.	Thomas Method vs. Methods of Moments Method	88
7.4.2.	Variation in Rate Constants	90
7.4.2.1.	Variations from Station to Station	90
7.4.2.2.	Variations with Temperature	92
7.4.2.3.	Variations in $k_c$ Values Due to the Nitrification Inhibitor	96
7.5.	Statistics	97
7.5.1.	Standard Deviation	97
7.5.2.	Least Significant Difference Comparison	98
7.5.2.1.	Least Significant Difference Between Thomas and Method of Moments Methods	98
7.5.2.2.	Comparison of Nitrification Inhibited and Uninhibited Values of $k_c$	99
7.5.2.3.	Comparison Between Carbonaceous Deoxygenation Rates at 3°C and at 20°C	100
CHAPTER 8	CONCLUSIONS	102
CHAPTER 9	FUTURE STUDY	105
9.1.1.	Computer Program to Calculate $(t/y)^{1/3}$ Values for the Thomas Method	107
9.1.2.	Computer Program to Calculate $k_{(CARB)}$ , $L_{(CARB)}$ , and BOD, to BOD <sub>10</sub> from Thomas Method Results	108

	Page
CHAPTER 9	
Continued	
9.1.3. Computer Program to Calculate $\Sigma y$ and $\Sigma y/\Sigma yt$ for Method of Moments Method	109
9.1.4. Computer Program to Calculate $L_C$ and Carbonaceous Values for $BOD_1$ to $BOD_{10}$ Respectively for Method of Moments Method	110
9.1.5. Computer Program to Calculate $\Sigma(y)$ and $\Sigma(y)/\Sigma(yt)$ for Nitrogenous Values for Method of Moments Method	111
REFERENCES	112
Abstract	i
Acknowledgements	ii



LIST OF FIGURES

FIGURE		Page
2-1	Location of sampling points.	5
3-1	The Dissolved-oxygen sag curve.	13
3-2	Generalized BOD reaction curve.	34
3-3	The BOD curve. (a) Normal curve for oxidation of organic matter. (b) The influence of nitrification.	36
4-1	Shoreline sampling apparatus.	43
5-1	BOD vs. time curve.	47
5-2	$(t/y)^{1/3}$ vs. time.	48
5-3	Time t (days).	51

LIST OF TABLES

TABLE		Page
1	River flow and treatment plant effluent parameters.	64
2	Standard Plate Counts (SPC's in no./ml.).	64
3	COD Values (mg/l).	67
4	Deoxygenation Rate Constants - Winter Testing.	68
5	Summer Testing, Station 1, Deoxygenation Rate Constants.	69
6	Summer Testing, Station 2, Deoxygenation Rate Constants.	70
7	Summer Testing, Station 3, Deoxygenation Rate Constants.	71
8	Summer Testing, Station 4, Deoxygenation Rate Constants	72
9	Winter Data, Standard Deviation (s), and Mean ( $\bar{x}$ ) of k and L. (L = mg/l).	73
10	Summer Data, Station 1, Standard Deviation (s), and Mean ( $\bar{x}$ ) of k and L.	74
11	Summer Data, Station 2, Standard Deviation (s), and Mean ( $\bar{x}$ ) of k and L.	75
12	Summer Data, Station 3, Standard Deviation (s), and Mean ( $\bar{x}$ ) of k and L.	76
13	Summer Data, Station 4, Standard Deviation and Mean ( $\bar{x}$ ) of k and L.	77
14	Winter Data, Comparison of Thomas Method and Method of Moments Method.	78
15	Summer Data, 20 <sup>o</sup> Uninhibited Thomas Method and Method of Moments Method Comparison	79

LIST OF TABLES Continued

TABLE		Page
16	Summer Data, Comparison of Inhibited and Uninhibited for $k_c$ at 20°C, Thomas Method Only.	80
17	Summer Data, k Rates at Different Temperatures, (Thomas Method Only).	81
18	Comparison of Calculated Rates at 3°C and 0°C by the van't Hoff-Arrhenius Relationship with Actual Results.	82

## CHAPTER I.

## INTRODUCTION

### 1.1. Statement of Problem

A water pollution control problem existing in western Canada is the depletion of oxygen in ice-covered rivers. This situation is a result of a lack of reaeration due to ice cover. Ice-covered rivers are characterized by low winter stream flows, and low water temperatures. These characteristics limit the allowable loading of a stream with oxygen demanding materials as may be found in the effluent of a wastewater treatment facility, and other effluents containing organic material.

A more complete understanding of a river's ability to accept an organic pollution load requires the foreknowledge of the deoxygenation rate constant of the river. This deoxygenation constant is required for calculating maximum oxygen depletions in a river so that anaerobic conditions can be avoided.

### 1.2. Reason for Study

A study on oxygen depletion in ice-covered rivers is necessary since little work has been done on this subject. The majority of studies undertaken on stream pollution have involved receiving waters, which are not ice-covered, and with water temperatures in excess of 5°C.

A thorough understanding of the effect of temperature on the deoxygenation rate constant must exist before rate constant data can be correctly applied to actual river conditions.

Temperature affects both the carbonaceous and nitrogenous portions of the oxygen demand curve. These two portions combined, comprise the Biochemical Oxygen Demand-time relationship. Wastewaters, such as domestic wastewater, exhibit both carbonaceous and nitrogenous oxygen demands. The discharge of such effluents in an ice-covered receiving stream necessitates that the effect of temperature on the oxygen demand curve be known in order to correctly predict and assess the impact of the wastewater on the stream's oxygen balance.

Numerous methods for the determination of deoxygenation rate constants are cited in the literature. A method suited to the data must be used, so that the rates determined reflect the actual values. The suitability of various methods of determining deoxygenation rates in ice-covered rivers is a subject which requires investigation. This applies to both carbonaceous and nitrogenous portions of the oxygen demand curve.

A subject of study which is basic to ice-covered river pollution assessment is the investigation of whether or not the standard 20°C five-day BOD test adequately represents the oxygen demand conditions that are occurring in the river. That is, are carbonaceous and nitrogenous demands

occurring in both situations? Another question which must be considered is the validity of the widely accepted temperature conversions. There has been little mention of these questions in the literature. This implies that a study of the validity of the BOD test for assessing pollution in an ice-covered river is a necessary undertaking.

Adequate knowledge and application of rate constant data is becoming increasingly important. In western Canada, the winter river conditions may be the limiting factor in wastewater treatment plant design. Increased public awareness of environmental issues has led to a large degree of intolerance towards river pollution. Knowledge in the area of deoxygenation rate constants in ice-covered rivers may lead to improved discharge restrictions and a minimization of environmental damage.

Another factor of increasing importance is a sagging economic situation. Expenditure for pollution control facilities is an economic burden to which "over-design" contributes. It may be possible for the application of rate constant data to help minimize costly "over-design" of treatment facilities.

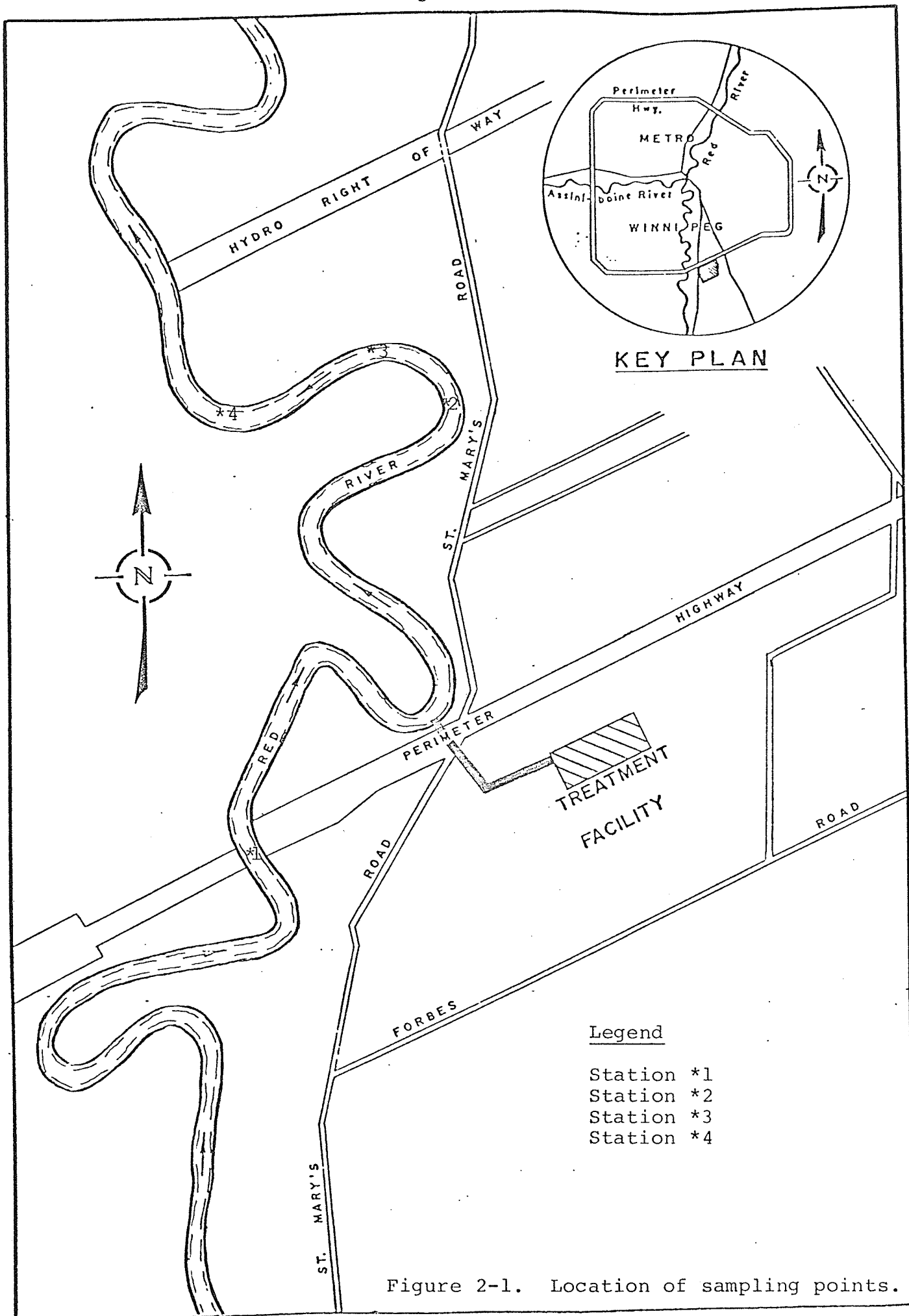
## CHAPTER II. PURPOSE AND SCOPE

### 2.1. Study Objectives

The main objectives of this investigation were to determine the deoxygenation rate constant in a portion of an ice-covered river, and to assess the factors affecting that determination. These factors include the effects of temperature and nitrification. The suitability of the BOD test for rate determinations were studied as well as the suitability of rate determination procedures applied to the resulting BOD data.

### 2.2. Extent of Investigation

The portion of river studied was the Red River in the South End of Winnipeg, Manitoba. The South End Treatment Plant outfall was used as an organic pollution point source. Four sampling points were used and were located as follows: one point upstream from the South End Treatment Plant outfall (at the South Perimeter Highway bridge); and three points located downstream from the outfall approximately  $\frac{1}{2}$  mile (0.8 km ) apart, the first point being approximately 3 miles (4.8 km ) from the outfall. The distance of approximately 3 miles was chosen to ensure adequate mixing in the river. The points from South to North were numbered 1 to 4 respectively. The location of the sampling points may be seen in figure 2.1.



Legend

- Station \*1
- Station \*2
- Station \*3
- Station \*4

Figure 2-1. Location of sampling points.



An oxygen sag curve for this portion of river was determined on October 25, 1974. This sag curve verified that the three downstream stations were all on the "downward" portion of the curve, that is, the critical oxygen deficit point was downstream from station 4.

The rate constants for the four stations were determined for samples collected from the ice-covered river on the following dates (all in 1975): February 14, 17, 18, 19, 20, 21 and 28th.

Another series of tests was conducted in order to study the effects of temperature and nitrification on the BOD data. In this series of tests, periodic bacterial counts were made to assess the effects of temperature and the nitrification inhibitor used. This series of tests was conducted on samples taken from open water at the four stations. The dates upon which samples were taken are as follows (all 1975):

July 11, 15, 17, 22, 24, 29, and 31. Samples were taken for stations 2 and 4 only on August 5th. This was due to the inaccessibility of stations 1 and 3 caused by a sudden drop in the river level (please see "Experimental Procedure" Chapter 4).

CHAPTER III                    LITERATURE REVIEW

3.1. Introduction

The ultimate application of a deoxygenation rate constant ( $k_1$ ) is as an aid to control river or stream pollution. Pollution in a broad sense is the befouling of the environment by man's activities, particularly by the disposal of a waste product (1)\*. Implicit in this, is the degree of befouling relative to the intended use of the water (1).

"Water pollution falls into two rather sharply defined classifications - namely (a) pathogenic organisms or toxic substances harmful and hazardous and (b) substances that are deleterious, offensive to sight, taste and smell, or detrimental to the usefulness of natural waters" (1).

The nature of man's activities dictate that pollution can never be eliminated. The degree of pollution in a stream depends on what people are willing to accept and pay for.

More specifically,  $k$  rates are used in the Streeter-Phelps equation (please see sec. 3.2.) to predict maximum levels of oxygen depletion in a stream, as well as the location of this deficit in relation to an organic pollution source.

The depletion of oxygen in a stream is generally caused by the presence of unstable organic matter from muni-

---

\* The numbers in parenthesis indicate references used in the text.

cipal and industrial sources (1). The dissolved oxygen in the river is consumed in the stabilization of this organic matter. This depletion of oxygen in a stream can in its extreme create fish kills due to asphyxiation and unsightly conditions due to an anaerobic state in the river.

The depletion of oxygen in ice-covered rivers is a problem in cold climates such as experienced in Western Canada. Problems specific to ice-covered rivers are lack of reaeration plus low winter stream flows. These factors severely limit the allowable loading of oxygen demanding materials, and may also aggravate such problems as taste and odor (2). The cold temperatures also have significant effects on biological activity.

The rate of oxygen depletion in an ice-covered river is a justifiable area of study due to the uniqueness of the problem. The Red River near Winnipeg is a significant reach of river to study since the loading on the river originates from a relatively large population of almost 600,000 persons. Knowing the deoxygenation ( $k_1$ ) rate of the Red River under ice cover can help rational standards to be set for discharges into the river.

### 3.2. The Streeter-Phelps Equation and Stream Self-Purification Capacity

The dissolved oxygen balance has been recognised for many years to be a relatively easily determined quantitative

measure capable of indicating the state of self-purification in a stream (3). Lueck et al report that Streeter and Phelps had referred to self-purification in streams as early as 1925 (3).

"The development of the 'oxygen sag' concept for mathematical formulation of the oxygen balance of a stream has been a most useful tool in gaining an understanding of stream conditions and in predicting the reaction of a stream to changes in the pollution load." (3)

The purification capacity of a stream may be expressed in units of biochemical oxygen demand (BOD) that can be satisfied in a specified period of time, for a given flow of a reach of stream, at a specified temperature or reaction rates (3). Implicit in mathematical models of self-purification are the presence of adequate dissolved oxygen (DO) and sufficient nutrients required for a balanced ecosystem in the stream.

### 3.2.1. The Streeter Phelps Equation

The dissolved oxygen sag curve as first proposed by Streeter and Phelps is widely discussed in the literature (1, 4, 5, 6, 7).

This model of stream self-purification describes the simultaneous effects of deoxygenation and reoxygenation or reaeration in a stream. The deoxygenation results from

BOD exertion in a stream (5). Reaeration occurs as a result of oxygen absorption from the atmosphere and from green plants such as algae during photosynthesis (5).

Metcalf and Eddy (7) caution that the Streeter-Phelps equation applies only "for channels of uniform cross section where effects of algae and sludge deposits are negligible".

The Streeter-Phelps equation is based on the generalization that: "the rate of the biochemical oxidation of organic matter,  $k_1$ , is proportional to the remaining concentration of unoxidized substance, measured in terms of oxidizibility." (4)

The equation describing the simultaneous action of deoxygenation and reaeration is:

$$\frac{dD}{dt} = k_1^1 L - k_2^1 D \quad (6)$$

where

D = dissolved oxygen deficit, mg/l

t = time of flow in days

L = concentration of organic matter in mg/l

$k_1^1$  = coefficient of deoxygenation,  $\text{day}^{-1}$

$k_2^1$  = coefficient of reaeration,  $\text{day}^{-1}$

A graphical interpretation of this equation may be seen in figure 3.1.

The concentration of organic matter L must be expressed in terms of the initial concentration  $L_0$  at the

point of waste discharge before integrating (please see fig. 3.1.).

$$L = L_o e^{-k_1^1 t} \quad (6)$$

where  $L_o$  = initial concentration of organic matter in the stream as mg/l BOD.

Substituting this value for L and integrating yields:

$$D = \frac{k_1^1 L_o}{k_2^1 - k_1^1} (e^{-k_1^1 t} - e^{-k_2^1 t}) + D_o e^{-k_2^1 t} \quad (3)$$

where  $D$  = oxygen deficit in time  $t$ , mg/l and  $D_o$  = initial oxygen deficit at the point of waste discharge, mg/l.

Generally, common logarithms are used. Since  $e^{-k^1 t} = 10^{-kt}$ , where  $k = 0.434 k^1$  (6), the equation then becomes:

$$D = \frac{k_1^1 L_o}{k_2^1 - k_1^1} (10^{-k_1^1 t} - 10^{-k_2^1 t}) + D_o (10^{-k_2^1 t})$$

The deoxygenation rate constant  $k_1$  is essentially a temperature function (please see sec. 3.4.) (6). The reaeration rate constant is also affected by temperature, but it is primarily a function of the turbulence of the stream.

The reaeration in an ice-covered river may be considered non existent (2) due to ice cover preventing atmospheric reaeration. The presence of ice and snow cover also prevents the penetration of sunlight into the stream which is necessary for photosynthesis to occur. This means

that virtually no reaeration will result due to photosynthetic activity.

The dissolved oxygen sag curve (please see figure 3.2) indicates the point of minimum DO. "This critical point is the place in the stream where the rate of change of the deficit is zero and the demand rate equals the reaeration rate" (6).

$$k_2^1 D_c = k_1^1 L = k_1^1 L_o e^{-k_1^1 t_c} \quad (6)$$

Solving for the critical time  $t_c$ :

$$t_c = \frac{1}{k_2^1 - k_1^1} \ln \left( \frac{k_2^1}{k_1^1} \left( 1 - D_o \frac{k_2^1 - k_1^1}{k_1^1 L_o} \right) \right) \quad (6)$$

These equations assume that  $k_1$  and  $k_2$  are constant and that only one source of pollution exists with the only oxygen demand being the BOD (6).

There are other processes which may be taking place in the stream and may affect the oxygen balance.

Processes which demand oxygen may include (4):

1. microbiological decomposition in the continuously flowing water;
2. slime growths on attached rocks, debris, and other surfaces over which the water flows;
3. benthic demand (primary organic bottom sludge);
4. dead algae (secondary organic bottom deposits);
5. temperature rise causing a decrease in the saturation level of oxygen and an increase in microbiological activity;
6. chemical discharges;
7. discharge of deoxygenated effluent;

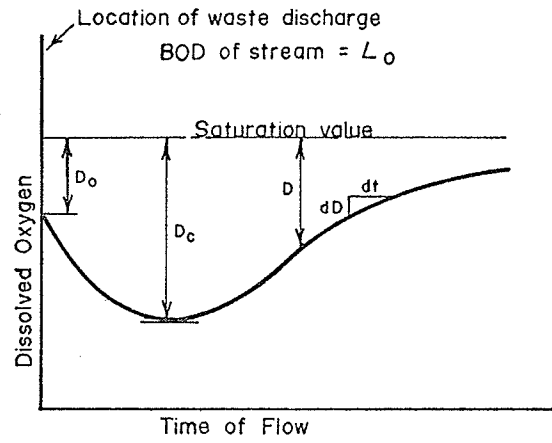


Figure 3-1. The dissolved-oxygen sag curve.



8. respiration needs of other aquatic organisms, such as fish;
9. organic contamination in branch streams;
10. salinity.

Processes which may contribute oxygen or reduce BOD include (4):

1. sedimentation or absorption of BOD;
2. reaeration due to turbulence;
3. photosynthesis;
4. temperature decreases causing a reduction in microbiological activity and an increase in oxygen saturation levels;
5. dilution from uncontaminated streams.

Dobbins (8) concluded that the effect of "longitudinal dispersion on the BOD and oxygen profiles is negligible in most fresh water streams." (8) Dobbins also concluded that "one of the most important requirements in stream pollution analysis is an accurate estimate of the rate of surface reaeration". This effect can be ignored when a river is frozen over.

### 3.2.2. The Application of Self-Purification Capacity

The dissolved oxygen level in a stream is critical to aquatic fauna. In order that fish, for example, may not

suffer from asphyxiation, a minimum level of DO is frequently set at 5.0 mg/l (1) by many regulatory agencies.

The waste assimilative capacity of a stream should be taken into account when determining the degree of treatment required, so that the stream DO may always meet quality objectives.

The self-purification capacity of a stream affords the basis for "evaluation of specific alternatives and combinations, such as water quality objectives and criteria, degree of waste-water treatment, low-flow augmentation, direction of urban-industrial growth, plant site location, land and water use planning, and zoning, multipurpose river development, and the effects of river developments and water uses." (1)

Anderson and Day (9) describe a systems analysis approach to water quality management using the DO sag curve. A reach of river upon which a number of waste treatment facilities are located was studied. An optimization problem was evolved using the DO sag model with an upper limit of oxygen deficit being imposed. Anderson and Day found that "the optimal level was attained when the total treatment cost for the entire region was minimized while maintaining DO standards in the river." (9) Another similar model, employing minimum allowable DO concentrations at every point in a river segment and maximum allowable BOD concentration at a specified downstream point has been proposed by Mediratta and Davidson (10).

Everyone does not agree with the use of optimization techniques where the discharge of BOD is maximized. Busch (11) has criticized such practices as being an abuse of natural water systems through intentional polluting. Busch says that the minimum assimilative capacity such as occurs under low-flow, summer temperature conditions are frequently not used as a basis for the system analysis. Busch's conclusion, which may be difficult to justify was: "Instead, engineers should repudiate the concept of intentional polluting and partial treatment and get on with the business of abating pollution by applying the same stringent quality control to waste treatment as they do to manufacturing operations." (11)

### 3.3. The Determination of the Deoxygenation Rate Constant ( $k_1$ )

#### 3.3.1. The BOD Test

The basis for determining deoxygenation rates is the BOD test. "Biochemical oxygen demand is usually defined as the amount of oxygen required by bacteria while stabilizing decomposable organic matter under aerobic conditions." (12)

The BOD test is widely used to determine the degree of pollution in a stream at any time. The test, as previously stated is also used to determine the purification capacity of streams (12).

The method of performing a BOD test may be found in Standard Methods for the Examination of Water and Wastewater (13).

Applications of the BOD test, such as in wastewater treatment may be found in Wastewater Engineering by Metcalf and Eddy, Inc. (7).

### 3.3.2. The BOD Reaction

The BOD reaction can be described as follows:

$$y = L (1 - 10^{-k_1 t}) \quad (7, 12)$$

where  $y$  = BOD at any time  $t$ , and  $L$  is the total or ultimate BOD. The value of  $k_1$ , or the deoxygenation constant must be determined by experiment.

The standard BOD test is run for 5 days at an incubation temperature of 20°C (13). Interferences in the test include temperature differences, and nitrification (please see sec. 3.4 and 3.5.).

### 3.3.3. The Determination of $k_1$

The value of  $k_1$  is required if the  $BOD_5$  (5-day BOD) is to be used to find the ultimate ( $BOD_L$ ) or the 20-day BOD (7). In order that  $k_1$  and  $L$  may be determined, a series of BOD measurements are made. From this data, several methods may be used to evaluate these constants. These methods in-