University of Alberta

A COMPARISON OF TWO AERATION SYSTEMS USED TO OVERWINTER FISH IN WINTERKILL LAKES

by

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Dedication

To my wife, Joy for her remarkable sacrifice and support

To the memory of Wesley L. Kinney, whose words of encouragement provided the motivation to go back to school

Abstract

The physical processes underlying successful aeration to prevent winterkill are not well understood. Several descriptive and quantitative measurements were performed in aerated lakes concerning lake stratification, water movement, energy use, polynya size, aeration efficiency, methane oxidation and oxygen depletion in aerated and unaerated lakes. The following hypotheses were tested: 1) Successful aeration induces large-scale (whole-lake) mixing as part of the aeration process; and 2) Surface aerators induce greater oxygen transfer than air diffusers due to creation of a greater surface area for air-water contact. During the ice covered period vertical and horizontal gradients of oxygen and temperature were compared between three lakes treated with point-release air injection, three with mechanical surface aerators and three lakes which served as unaerated controls.

All three unaerated lakes assumed typical inverse thermal stratification and dissolved oxygen (DO) fell to near zero mg L^{-1} throughout the entire water column by early January. Both types of aeration caused thermal destratification with the zone of influence of either technique reaching the most distant shorelines (up to 1100 m). Discrete near-field oxygenated cells were not identified using either technique. However, some decrease in oxygen was observed at distances greater than 350 m in surface aerated lakes and greater than 800 m in air injected lakes. Velocity measurements in the polynya and dye studies confirmed that air injection induced greater velocity and more rapid lake circulation than surface aeration. In addition, these measurements revealed a new conceptual model of near-field and whole-lake circulation patterns. The depth of oxygen and temperature uniformity was clearly set by the depth of the diffuser or by water depth below the surface aerator. Morphometric features such as small depressions or distinct basins separated from

the aerated basin by a shallow sill stratified and tended toward anoxia as winter progressed.

Polynya size was directly proportional to energy use at levels less than 0.15 kW ha^{-1}. polynya size was inversely proportional to energy at levels greater than 0.15 kW ha^{-1}. Warmest water and maximum polynya sizes were maintained with air flow of 0.011 m^3 $min^{-1} \cdot ha^{-1}$ [0.95 SCFM (standard cubic feet min^{-1}) $acre^{-1}$] or spray volume of 0.42 m^3 min^{-1} ha^{-1} [45 gpm (gallons min^{-1}) $acre^{-1}$] from surface aerators. Air-injection allowed greater decline in DO - even when much greater energy ha^{-1} was used. Off-gas samples indicated oxygen transfer from bubbles ranged from 0% efficiency using a coarse bubble (1.5 to 2.5 cm diameter) diffuser set at 1.25 m to 2.8% transfer efficiency using a medium bubble (3 to 5 mm diameter) diffuser set at 8 m deep. This provided a total transfer of approximately 5.5 kg O_2 day^{-1} 3.8 kW^{-1} when ambient lake DO was approximately 30% saturation. Conversely, DO in captured spray droplets increased by 40 to 65% (depending on ambient lake DO). This resulted in a total transfer of 23 to 36 kg O_2 day^{-1} 1.8 kW^{-1}. This resulted in surface aeration maintaining adequate DO using 30 to 70 % less energy.

Oxygen depletion rates varied substantially in relation to freeze up timing and periods of snow accumulation. Aeration startup enhanced oxygen depletion rates by up to 4-fold. Although methane accumulation varied among lakes it may profoundly affect the oxygen budget and aerator performance. Measurement of oxygen transfer and depletion rates allowed the calculation of empirical mass balance equations to describe the aeration process, the dynamic nature of oxygen depletion and the impediment that methane imposes on aeration success.

Preface

There are many types of commercially available and hand-constructed diffusers, air-lift pumps and mechanical surface aeration systems that are currently used in winter lake aeration projects. The research described in this thesis focused on a hand-constructed, coarse-bubble diffuser, a commercially available medium-bubble diffuser and two types of commercially available mechanical surface aerators.

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Table of Contents

Chapter **Page**

1. General introduction 1

2. Under-Ice water movements induced by mechanical surface aeration and air injection 11
   - Introduction 12
   - Materials and Methods 16
   - Results 24
   - Discussion 48
   - References 54

3. Optimizing artificial aeration for lake winterkill prevention 56
   - Introduction 57
   - Materials and Methods 58
   - Results 63
   - Discussion 69
   - References 74

4. Efficiency and effect on lake metabolism of air injection and surface mechanical aeration 76
   - Introduction 77
   - Materials and Methods 79
   - Results 89
   - Discussion 101
   - References 106

5. Elevated methane concentrations impede the success of artificial aeration........... 110
Introduction.......... 111
Methods and Materials 117
Results.......... 123
Discussion.......... 138
References 151

6. General conclusions.......... 158
References 167

Appendix A Relationship of snow depth, ice thickness, light penetration and chlorophyll *a* to dissolved oxygen.......... 169
Introduction.......... 170
Materials and Methods.......... 172
Results.......... 174
Discussion.......... 183
References 186

Appendix B. Convective circulation patterns in an unaerated lake and a destratified, post-aerated lake 190
Introduction 191
Methods and Materials 191
Results 193
Discussion 197
References 199

Appendix C. Additional methane profiles in aerated and control lakes (results and discussion) 200
Results and Discussion 201
References 205

List of Tables

Chapter **Page**

Chapter 2

Table 2-1. Specific density of freshwater at different temperatures 15

Table 2-2. Description of experimental lakes and initial study design for 1995-1996 winter.. 18

Table 2-3. Description of equipment and location within each of the aerated lakes used in the initial study design (winter, 1994-1995)........ 20

Chapter 3

Table 3.1 Number and type of aerators used to evaluate sizing and resultant effects on lake limnology 60

Table 3-2. Operation schedule at Moonshine and East Dollar Lakes during the 1995-1996 and 1996-1997 aeration seasons....................... 61

Table 3-3. Summary of aeration performance and their influence on aerated lakes.. 64

Chapter 4

Table 4-1. Aeration schedule at East dollar Lake during the 1995-1996 season... 81

Table 4.2. Operation schedule at Moonshine Lake during all three study years... 82

Table 4-3. Values for parameters used to compare aeration efficiency of air injection and surface sprayers in East Dollar Lake.................... 90

Table 4-4. Values for parameters used to compare aeration efficiency of air injection and surface sprayers in Moonshine Lake..................... 98

Chapter 5

Table 5-1. Dissolved oxygen and temperature for East Dollar Lake during the fall of 1996 125

Table 5-2 Estimates of the diffusion coefficient (K) and subsequent estimates of methane flux from the sediment surface.......... 132

Table 5-3. Summary of DO and CH_4 mass balance for East Dollar Lake resulting from aeration.......... 136

List of Figures

Chapter **Page**

Chapter 2

Fig. 2-1. (A) Near-field water currents generated by air injection (redrawn from Brown et al. 1989), and (B) Large- field water currents generated by air injection (redrawn from Baines 1961)........................ 13

Fig. 2-2. Bathymetry of the six aerated lakes 18

Fig. 2-3. The coarse-bubble diffuser, medium-bubble diffuser Air-O-Lator® mechanical surface aerator used in aeration experiments 27

Fig. 2-4. Typical mid-winter temperature and DO profiles for all the experimental lakes.. 21

Fig. 2-5. Representative isotherms in figure Eight Lake 23

Fig. 2-6. Oxygen isopleths for Figure Eight Lake during the 1994 to 1995 winter 28

Fig. 2-7. Isotherms for Moonshine Lake during the 1994 to 1995 aeration season 30

Fig. 2-8. Dissolved oxygen isopleths for Moonshine lake during the 1994 to 1995 aeration season.. 31

Fig. 2-9. Velocity measurements in the vicinity of the 2-hp and 1-hp aerators .. 33

Fig. 2-10. Near-field velocity of the radial jet generated by the coarse bubble and medium bubble diffusers 34

Fig. 2-11. Profiles of detectable water movement from (a) the 1-hp surface aerator, (B) the 2-hp aerator, (C) the cross-pipe coarse bubble diffuser and (D) the medium bubble diffuser.................. 35

Fig. 2-12. Dye movement in East Dollar Lake 37

Fig. 2-13. Dye movement in East dollar Lake during air injection 39

Fig. 2-14. Dye tracings in East Dollar Lake, February 4, 1997.......... 40

Fig. 2-15. Dye movement and oxygen isopleths in Moonshine Lake during air injection 42

Fig. 2-16. Dye tracings and oxygen isopleths in Moonshine Lake during Surface aeration.......... 43

Fig. 2-17. Near-field dye movements and isotherms in Moonshine Lake.......... 44

Fig. 2-18. Tracings of dye injected at 3.5 m in Moonshine Lake.......... 47

Fig. 2-19. Dye movement and isotherms in Figure Eight Lake at the startup of air injection 47

Fig. 2-20 Schematic models of near-field and whole-lake circulation 53

Chapter 3

Fig. 3-1. Relationship between energy use and average temperature at 1 m during January and February for both air injected and surface aerated lakes.......... 65

Fig. 3-2. Relationship between energy use and average polynya area during January and February for air injection and surface aeration..... 66

Chapter 4

Fig. 4-1. Response of oxygen depletion rate to the onset of circulation in East Dollar Lake.......... 92

Fig. 4-2. The relationship between surface transfer coefficient (K_L) and the polynya surface area for East Dollar Lake........................ 94

Fig. 4-3. Relationship between ambient lake DO in or near the polynya and the absorption of oxygen by spray droplets.................................... 96

Fig. 4-4. Response in oxygen depletion rate following the onset of aeration in Moonshine Lake during the 1995-96 season................. 100

.Chapter 5

Fig. 5-1. Temperature, DO and CH4 profiles measured in East Dollar Lake during the 1996-1997 winter.. 125

Fig. 5-2. Total mass of methane and DO in East Dollar Lake during the 1996-97 aeration season... 127

Fig. 5-3. Profiles of temperature, DO and methane in the aerated (A and C) and middle basin (B and D) of Figure Eight Lake............... 132

Fig. 5-4 Methane concentrations and oxidations rates in lake Kasumigaura, Japan illustrating hysteresis in relation to temperature and sampling time.. 144

Appendix A

Fig. A-1. Snow depth, ice thickness and light penetration in Moonshine Lake... 175

Fig. A-2. Snow depth, ice thickness and light penetration in East Dollar Lake... 177

Fig. A-3. Snow depth, ice thickness and light penetration in Figure eight Lake... 177

Fig. A-4. Snow depth, ice thickness and light penetration in Swan Lake 181

Fig. A-5. Snow depth, ice thickness and light penetration in West Dollar Lake 182

Appendix B

Fig. B-1. Dye movement in non-aerated West Dollar Lake 194

Fig. B-2. Dye dispersal following injection at the geographical center of East Dollar Lake 195

Fig. B-3. Dye tracings in East Dollar Lake initiated 3 weeks after cessation of aeration 196

Appendix C

Fig. C-1. Methane, temperature and DO profiles of two aerated lakes lakes and two unaerated control lakes 203

List of Symbols and Nomenclature

c .... Ambient concentration in the lake.

c_s ....Concentration at equilibrium with the atmosphere.

dM_{DO}/dt.............Change in total mass of lake dissolved oxygen over time dt

$(dM/dt)_b$ ....Addition of dissolved oxygen from rising bubbles.

$(dM/dt)_d$ ....Amount of dissolved oxygen absorbed by spray droplets over time.

$(dM/dt)_p$.............Amount of dissolved oxygen passing through the polynya surface over time.

$(dM/dt)_r$.............Amount of lake DO consumed by respiration.

D ....Diffusion coefficient in units of area · time^{-1}.

F_s ....Flux of a gas across a defined surface area of water.

K_La.....................Overall reaeration coefficient, where K_L is the liquid-air transfer coefficient in distance · time^{-1} and a is an abbreviation for the ratio area/volume.

k_2.........................Same as for Kla.

$MR_{O/N}$ ....Molecular ratio of oxygen to nitrogen.

OTE ....The percentage of oxygen gained by droplets or lost by bubbles.

Off gas ....Gas or bubbles released by a diffuser and captured at the surface.

Polynya............The area of open water in an ice-covered lake that is created and maintained by the aeration process.

Chapter 1

General Introduction

General Introduction

Winterkill is common in shallow, eutrophic north-temperate and boreal lakes. This has been a continuing problem for fisheries managers who are expected to provide and maintain sportfishing opportunities for anglers (Schneberger 1970, Ashley et al. 1992). Artificial aeration has become a standard practice to reduce oxygen depletion rates and sustain fish populations throughout winter (Ashley et al. 1992, Fast 1994).

There are several factors involved in winter oxygen depletion. With the advent of ice formation exchange of oxygen with the atmosphere ceases. Light penetration is reduced or effectively obstructed, depending on type of ice formation and depth and condition of snow cover. Consequently, photosynthetic oxygen production is greatly reduced and restricted to surface layers or may become nil (Greenbank 1945, Wetzel 1985). As during summer, respiration and chemical oxidation increase with depth as various organic materials settle out of the photic zone. Because of the relatively short settling distance and time in shallow lakes the majority of decomposition occurs on or within sediments (Greenbank 1945, Hutchinson 1957, Barica and Mathias 1979, Mathias and Barica 1980, Charlton 1980). Hence, the dominant factors conspiring to cause high rates of oxygen depletion are: shallowness (hence, poor oxygen storage capacity) (Greenbank 1945, Hutchinson 1957), high productivity (Hutchinson 1957, Barica 1974, Charlton 1980) and long periods of snow cover (Greenbank 1945, Barica and Mathias 1979, Mathias and Barica 1980). The prominent features in the time-course of winter oxygen depletion in natural lakes are: 1) more rapid depletion in early winter, after the first substantial snowfall following freeze-up (Jackson and Lasenby 1982, Babin and Prepas 1985, Prowse and Stephenson 1986); 2) Oxygen depletion is greater near the sediment than near the ice-water interface (Mortimer 1941, 1942, Welch et al. 1976, Mathias and Barica 1980, Jackson and Lasenby 1982); and 3) The oxygen depletion rate remains linear or slightly decreases throughout winter until ambient oxygen concentrations fall below approximately 3 mgL^{-1} (Welch et al. 1976, Barica and Mathias 1979, Mathias and Barica 1980, Babin and Prepas 1985). Below 3 mgL^{-1} the oxygen depletion rate varies with DO concentration.

However, artificial circulation of water over the sediment surface may alter the characteristics of oxygen depletion. Experimental circulation of water over core samples reduced the threshold of oxygen limitation from 3 to approximately 1 mgL^{-1} (Belanger 1981, Campbell and Rigler 1986). This is likely related to its influence on the boundary layer between the water and sediment surface. Boudreau and Guinasso (1982) and Jorgensen and Revsbech (1985) used microelectrodes to characterize the diffusive boundary layer overlying sediments. They found that the boundary layer varied from several cm in deep calm environments to less than 1 mm in shallow turbulent environments. This reduction in boundary layer effects would enhance oxygen consumption in organic sediments and should provide increased opportunity for reduced substances to enter the water column if the adjacent water layer is near anoxia (Hargrave 1969). Indeed, enhanced oxygen consumption has often been reported at the onset of lake aeration (i.e. Lackey and Holmes 1972, Smith et al. 1975).

These observations suggest that aeration induces large-scale convective currents throughout the treated lake. This has also been suggested by Baines (1961), although careful description of circulation patterns have never been performed. In addition, the velocity of flow across the sediment surface should dictate the degree of boundary layer reduction and subsequent enhanced oxygen depletion rate, particularly at the onset of aeration. This principle probably contributes to the sizing difficulty often experienced for individual lakes.

In addition, because eutrophic lakes often experience benthic and even hypolimnetic anoxia during summer and winter stratification, substantial amounts of oxygen-demanding methane may also be generated (Rudd and Hamilton 1975). Although this methane is usually oxidized or vented to the atmosphere during fall overturn, considerable methane may remain trapped under ice if fall mixing is incomplete, or is shortened due to an unusually early freeze. In such cases methane oxidation may be a dominant source of oxygen consumption and hasten depletion rates (Rudd and Hamilton 1978). Aeration induced circulation may diminish the diffusive boundary layer and expedite the oxidation of methane and other reduced substances. However, this relationship has not been studied.

The most common method of aeration continues to be air injection into point release diffusers. The diffusers are typically suspended 0.25 to 0.50 m above the sediment surface to entrain the deeper and hence warmer water in the lake and transport it to the surface. Impingement of this water on the ice melts the ice and maintains an open water area (polynya), the size of which depends upon air temperature, water temperature and water velocity (Rogers et al. 1996).

Surface aerators are used less common (perhaps 20 percent of lake aeration projects) than air injection. The support floats are also anchored over the deeper portion of the lake and the aerators are often fitted with a draught tube to insure entrainment of deeper waters.

The polynya surface is believed to be the greatest source of transfer of oxygen to the lake (Fast 1994). Additional oxygen is absorbed from rising bubbles (air injection) and from spray droplets (surface aeration) although these sources of oxygen are believed to be minor compared to oxygen uptake across the polynya surface (Nielson 1974, Smith et al. 1975, Ashley 1987). However, the actual contribution from bubbles or spray droplets has never been directly measured.

There is also some evidence that surface aerators effectively prevent winterkill at lower capital and operating costs (Pederson 1982, Ashley 1987). Such differences could result from greater energy efficiency simply by maintaining a sufficiently large polynya to provide adequate atmospheric oxygen transfer. However, this apparent greater efficiency could also be the result of greater oxygen transfer into spray droplets than is absorbed from diffuser bubbles.

Another important variable may be that different velocities of circulating currents are induced by the different aeration systems and particularly across the sediment surface. Air injection may cause higher velocities near the sediment because the diffusers are generally situated immediately above the sediment surface. However, this possibility has not been carefully evaluated either.

Aeration efficiency, circulation patterns and the principles involved in proper sizing have never been thoroughly investigated. In addition, an understanding of the relationship between methane oxidation and other components of oxygen depletion and the aeration process would help to improve the design and efficiency of lake aeration equipment.

Objectives

The objectives included: 1) develop a basic description of dissolved oxygen and temperature distribution in aerated lakes; 2) determine circulation patterns and velocity resulting from aeration; and 3) quantify the important variables involved in successful aeration including sources and rates of oxygen depletion and the factors involved in re-aeration, including oxygen transfer through the polynya, from diffuser bubbles and into spray droplets. Specifically, Chapter 2 compares the vertical and horizontal gradients in temperature and dissolved oxygen in lakes treated with air injection, surface mechanical aeration and unaerated control lakes. It also details velocity and flow patterns generated by the two aeration methods and compares these patterns with existing conceptual models of aeration-induced circulation. Chapter 3 investigates variables associated with energy use, resultant lake temperature and polynya size, timing of aeration startup and concludes with proper sizing recommendations. Chapter 4 is a culmination of earlier experiments and observations and presents a quantitative comparison of aeration efficiency through development of a mass balance model. Chapter 5 utilizes the mass balance models developed in Chapter 4 to determine rates of methane production and the impact of methane oxidation on the effectiveness of shallow and whole-lake circulation. Results are discussed in relation to aeration sizing, timing of startup and distance circulating water travels under ice.

Literature Cited

Ashley, K.I. 1987. Artificial circulation in British Columbia: Review and evaluation. B.C. Fisheries Branch Technical Circular No. 78. 34 p.

Ashley, K.I., K. Tsumura and B.M. Chan. 1992. Fisheries management of winterkill lakes in southern interior British Columbia. pp. 287-297. In: Roberts, R.D. and M.L. Bothwell (eds). Aquatic Ecosystems in semi-arid regions: Implications for resource management. Environment Canada N.H.R.I. Symposium Series 7.

Babin, J. and E.E. Prepas. 1985. Modeling winter oxygen depletion rates in ice-covered temperate zone lakes in Canada. Can. J. Fish Aquat. Sci. 42:239-249.

Baines, W.D. 1961. The principles of operation of bubbling systems. In: Proc. symp. on air bubbling. pp. 12-22. Technical Memo. No. 70. Canadian National Research Council. Ottawa.

Barica, J. 1974. Extreme fluctuations in water quality of eutrophic fish kill lakes: Effect of sediment mixing. Water Res. 8:881-888.

Belanger, T.V. 1981. Benthic oxygen demand in Lake Apopka, Florida. Water Res. 15: 267-274.

Barica, J. and J.A. Mathias. 1979. Oxygen depletion and winterkill in small prairie lakes under extended ice cover. J. Fish. Res. Board Can. 36:980-986.

Boudreau, B.P. and N.L. Guinasso. 1982. The influence of a diffusive sublayer on accretion, dissolution, and diagenesis at the sea floor. P. 115-145. In: K.A. Fanning and F.T. Manheim (eds.) The dynamic environment of the ocean floor. Lexington.

Campbell, P.J. and F.H. Rigler. 1986. Effect of ambient oxygen concentration on measurement of sediment oxygen consumption. Can. J. Fish. Aquat. Sci. 43:1340-1349.

Charlton, M.N. 1980. Hypolimnion oxygen consumption in lakes: discussion of productivity and morphometry effects. Can. J. Fish. Aquat. Sci. 37:1531-1539.

Fast, A.W. 1994. Winterkill prevention in lakes and ponds using artificial aeration. Rev. in Fish. Sci. 2:23-77.

Greenbank, J. 1945. Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. Ecol. Mon. 15(04):343-392.

Hargrave, B.T. 1969. Similarity of oxygen uptake by benthic communities. Limnol. Oceanogr. 14: 801-805.

Hutchinson, G.E. 1957. A treatise on limnology. I Geography, physics and chemistry. John Wiley and Sons, Inc. New York. 1015 p.

Jackson, M.B. and D.C. Lasenby. 1982. A method for predicting winter oxygen profiles in ice-covered Ontario lakes. Can. J. Fish. Aquat. Sci. 39:1267-1272.

Jørgensen, B.B. and N.P. Revsbech. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol. Oceanogr. 30(1):111-122.

Lackey, R.T. and D. W. Holmes. 1972. Evaluation of two methods of aeration to prevent winterkill. Prog. Fish Cult. 34: 175-178.

Mathias, J.A. and J. Barica. 1980. Factors controlling oxygen depletion in ice-covered lakes. Can J. Fish. Aquat. Sci. 37:185-192.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. I and II. J. Ecol. 280-329.

Mortimer, C.H. 1942. The exchange of dissolved substances between mud and water in lakes. III and IV. Summary and References. J. Ecol. 147-201.

Neilson, B.J. 1974. Reaeration dynamics of reservoir destratification. J. Am. Water Works Assoc. 66:617-620.

Pederson, D.W. 1982. Aeration and mixing systems in Minnesota lakes. Minnesota Department of Natural Resources, Division of Fish and Wildlife, Ecological Services Section. Special publication No. 133. 29 p.

Prowse, T.D. and R.L. Stephenson. 1986. The relationship between winter lake cover radiation receipts and the oxygen deficit in temperate lakes. Atmosphere-Ocean 24(4):386-403.

Rogers, C.K., G. A. Lawrence and P.F. Hamblin. 1996. Thermal impact of artificial circulation on an ice-covered mid-latitude lake. Can. J. Civil Eng. 23:1081-1091.

Rudd, J.W.M. and R.D. Hamilton. 1975. Factors controlling rates of methane oxidation and the distribution of the methane oxidizers in a small stratified lake. Arch. Hydrobiol. 75:522-538.

Rudd, J.W.M. and R.D. Hamilton. 1978. Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism. Limnol. Ocean. 23(2):337-348.

Schneberger, E. 1970. A symposium on the management of midwestern winterkill lakes. American Fisheries Society. North Central Division Special Publication. 75 p.

Smith, S.A., D.R. Knauer and T.L. Wirst. 1975. Aeration as a lake management technique. Wisc. Dept. Nat. Res. Tech. Bull. 87. 39 pp.

Welch, H.E., P.J. Dillon, and A. Sreedharan. 1976. Factors affecting winter respiration in Ontario lakes. J. Fish Res. Bd. Can. 33:1809-1813.

Wetzel, R.G. 1985. Limnology. W.B. Saunders Company. Toronto. 743 p.

Chapter 2

Under-ice Water Movements Induced by Mechanical Surface Aeration and Air Injection

Introduction

Current understanding of aeration-induced circulation patterns in lakes has primarily been derived by extrapolating small scale lab experiments to large natural lakes. (Kobus 1972, Lorenzen and Fast 1977, Torrest and Wen 1976). Results of these studies and others (Brown et al. 1989, Baines 1961) have lead to generalized models of entrainment and detrainment patterns (Fig. 2-1). The pattern of concentric circles of outgoing and return flow (Fig. 2-1B) implies that an aerated zone or cell is formed around the aeration device. This would suggest easy success in sizing aeration equipment, particularly in large lakes. Yet, sizing lake aeration equipment has continued to be one of the most difficult design problems, which suggests that aerated cells of a predictable size are not formed and flow patterns may be more complex. I tested the hypothesis that successful aeration induces large-scale (whole-lake) convective flow as part of the aeration process.

Laboratory work has produced a model which describes circulation induced by air injection. Under homogenous conditions the ascending plume widens at an angle of 12-15 degrees as it ascends (Fig. 2-1A). Detrainment at the surface is perpendicular to a linear diffuser line or radial to a point release diffuser. The outgoing surface jet thickens with distance at about a 10 degree angle (Lorenzen and Fast 1977) and has the greatest velocity just beneath the surface (Fig. 2-1A).

From tank studies, Torrest and Wen (1976) concluded that a circulating "cell" is created whose lateral extent is equal to 4 times the depth of the diffuser. These flow patterns remain a part of the central paradigm of winter lake aeration (e.g. Fast 1994).

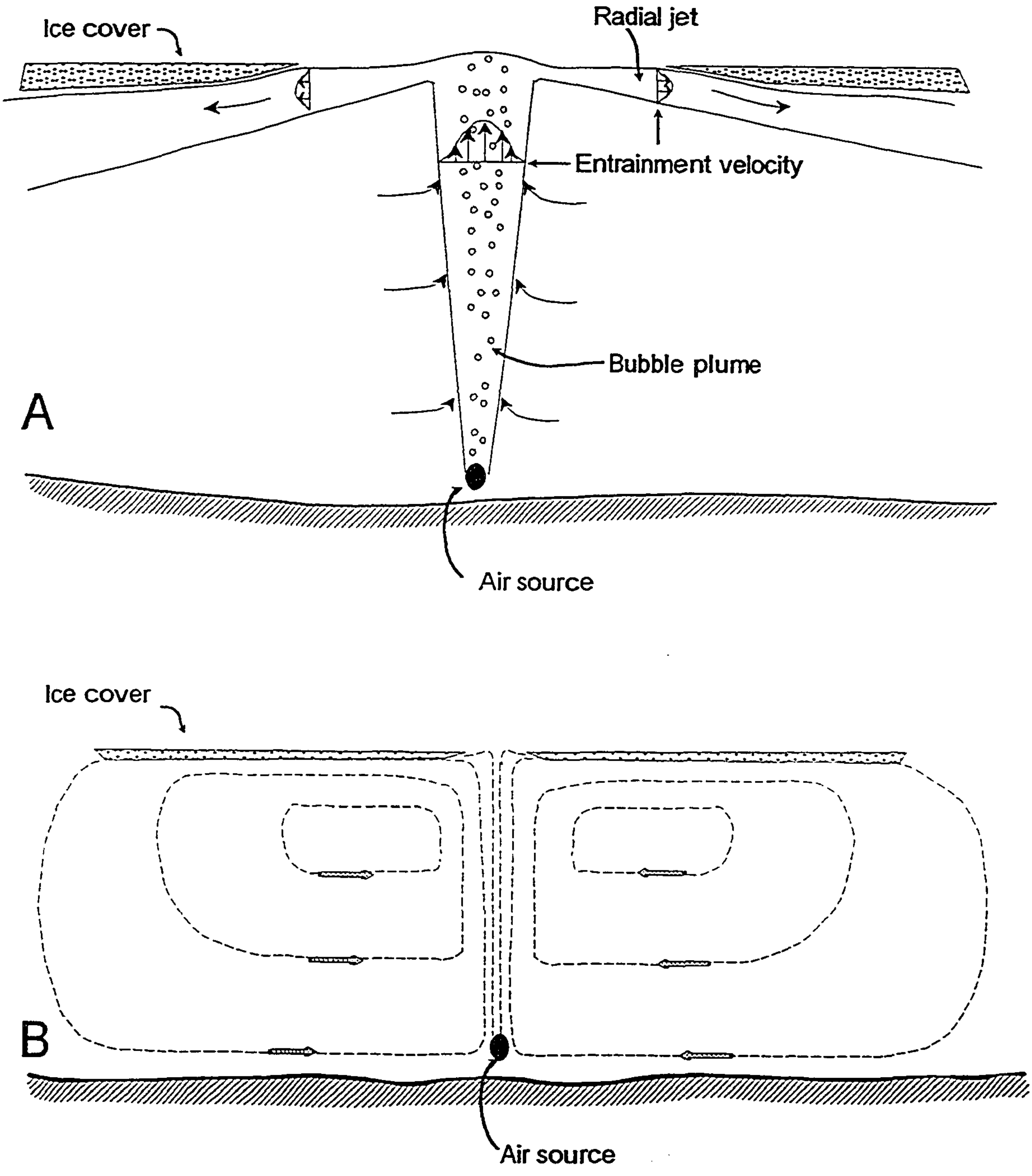

Figure 2-1. (A) Near-field water currents generated by air injection (redrawn from Brown et al. 1989). (B) Large-field water currents generated by air injection within a water body. (Redrawn from Baines 1961).

However, there is some evidence that raises questions about this model. Tubb (1966) injected Rhodamine B into Gravel Lake, North Dakota during winter aeration and measured dye movement at 1.5, 6 and 20 hours. The surface area of the lake was not reported, but the lake was approximately 5 m deep. Sampling was performed at approximately 1, 3 and 5 m and extended to include a distance of 274 m (300 yards). He judged that mixing would not extend beyond that point. Dye was found at all depths to a distance of 30 m after 1.5 hours and at all depths at the farthest location after six hours. A concurrent temperature profile near the diffuser indicated that the lake was nearly destratified with temperatures ranging from 0.5 °C at 1 m to 1.1 °C at 4 m and 2.2 °C at the bottom (5 m).

Although circulation patterns under ice have received little attention, this has not been the case for aeration during summer stratification. Where upwelling of the bubble plume is opposed by a vertical density gradient, such as at the beginning of aeration, there is a terminal height to which entrained water will rise before falling back to its level of neutral buoyancy (Schladow 1992). Because some mixing and temperature modification occurs in the plume itself, this detrained water falls only a short distance before reaching neutral buoyancy. The location of this internal detrainment depends on diffuser depth and the degree of density stratification. In addition, depending on depth and intensity of stratification, this process may be repeated several times before final detrainment at the surface (Schladow 1992). In Lake Nepean, Australia, the onset of destratification involved formation of a thin internal detrainment plume in the lower portion of the thermocline. At that point a horizontal jet was created which could be followed for several km (Schladow and Fisher 1996).

Winter stratification is much weaker than during summer and so winter mixing by air injection should be less complex. Water temperature ranges from 0 °C at the ice-water interface to approximately 4 °C at the sediment surface. The resultant density difference within this 4 degree range (0.14 g L^{-1}) is only a small percentage of those that occur at higher temperatures during summer, such as from 28 to 32 °C (1.20 g L^{-1}; Table 2-1). Hence, although it has never been described, aeration-induced entrainment likely continues throughout the entire water column with a single detrainment plume at the surface.

The work of Rogers et al. (1996) offers some support for this hypothesis. They aerated a small (4.75 ha), relatively deep (z_{max} = 16 m) lake in south-central British Columbia with a 1.8 kW (1-hp) surface aerator. Mean temperature was dramatically reduced and the water was vertically well mixed. The lake was nearly destratified to 13

Table 2-1. Specific density of freshwater at different temperatures.

Temperature (°C)	Density (g L^{-1})	Density difference (g L^{-1} 4° C^{-1})
0	998.82	0.14
4	998.96	0.05
8	998.91	0.39
12	998.52	0.54
16	997.98	0.72
20	997.26	0.89
24	996.37	1.05
28	995.32	1.20
32	994.12	

From: Hodgman, C.D., R.C. Weast, and S.M. Selby (Eds.). 1961. Handbook of Chemistry and Physics. pp. 2155-2156. The Chemical Rubber Co. Cleveland OH.

m (the apparent depth beneath the surface aerator) as water temperature ranged from 1.2 °C at 1 m to 1.6 °C m at 13 m and increased to 3.2 °C at 16 m. No attempt was made to actually describe entrainment or circulation patterns. However, the density stratification between 1.2 and 1.6 °C is negligible, suggesting that the entire lake volume was involved in the circulation process. Here, I measured near- and far-field flow patterns using a velocity meter and dye and compared these patterns to dissolved oxygen (DO) and temperature profiles to more fully describe the circulating patterns during winter aeration.

Materials and Methods

Study Lakes

Nine lakes were originally identified for this study; three were treated with air injection, three with surface aeration and three served as unaerated controls. Data from four lakes are reported here. These lakes provided representative data collected from the other study lakes as well as useful information describing the influence of unique morphologic characteristics and important variables such as aerator location within the lakes. These lakes, ranging from 4.9 to 38.6 ha, are located in the Peace River Region of Northwest Alberta were studied in the fall and winter of 1994 to 1997 (Fig. 2-2). The location and morphometry of these lakes are summarized in Table 2-2. These lakes are considered hypereutrophic (e.g. mean summer Chl a > 50 µg L^{-1}) and would experience frequent, if not annual winterkill without artificial aeration.

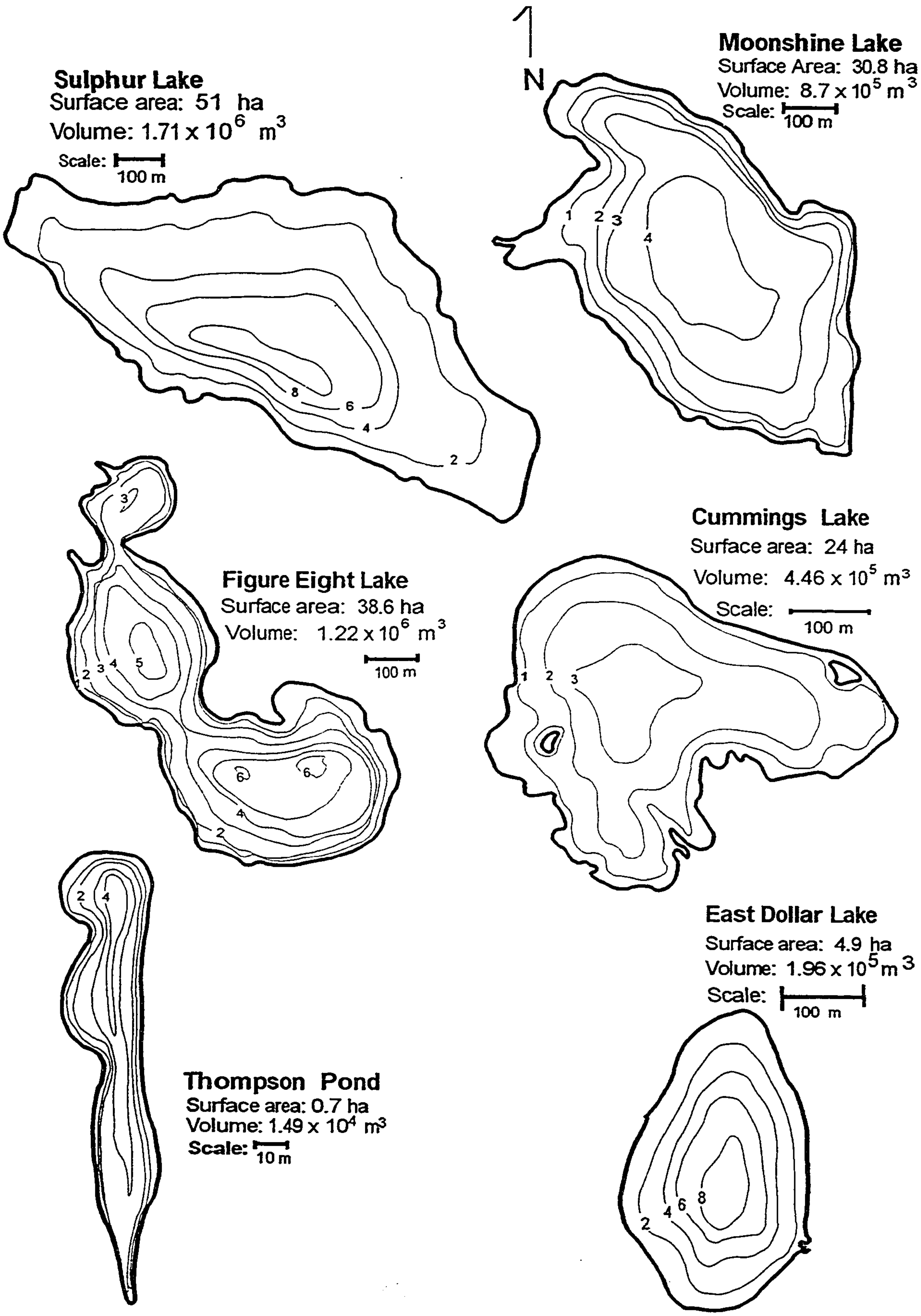

Fig. 2-2. Bathymetry of the six lakes that were aerated throughout this study.

Table 2-2. Description of experimental lakes and the initial study design for the 1994 - 1995 winter.

Lake	Location	Treatment	Max depth (m)	Mean depth (m)	Surf area (ha)	Volume (m^3)
Thompson	56°,14' N 117°,17' W	Surface aeration	4.3	2.1	0.7	0.15 x 10^5
Cummings	56°,06' N 118°,22' W	Surface aeration	4.0	2.0	24	4.86 x 10^5
Moonshine	55°53' N 119°,13' W	Surface aeration	4.2	2.6	30.8	8.75 x 10^5
East Dollar	55°,19' N 117°,12' W	Air injection	8.0	4.2	4.9	1.96 x 10^5
Figure Eight	56°,18' N 117°,54' W	Air injection	6.2	3.0	38.6	12.2 x 10^5
Sulphur	56°,42' N 118°,18' W	Air injection	8.1	3.4	51	17.3 x 10^5
West Dollar	55°,19' N 117°,12' W	Control	4.5	2.4	5	1.2 x 10^5
Saskatoon	55°,13' N 119°,05' W	Control	4.0	2.1	747	194.2 x 10^5
Swan	55°,04' N 117°,48' W	Control	5.6	3.2	140	44.8 x 10^5

Aeration Systems

Descriptions of the aeration systems are presented in Table 2-3. A schematic of the two types of diffusers and the surface aerators is presented in Fig. 2-3. Each of the two compressors in Figure Eight Lake delivered air 180 m from shore in reinforced rubber hose (50 mm ID). These air lines were approximately 100 m apart at the terminus. Each air line was fitted with a T coupler to split the flow to two 19 mm ID lines leading to two cross-pipe diffusers located approximately 30 m apart. These diffusers were set at approximately 300 mm above the bottom where z = 4.5 m. The deepest point in the lake (6.0 m) was

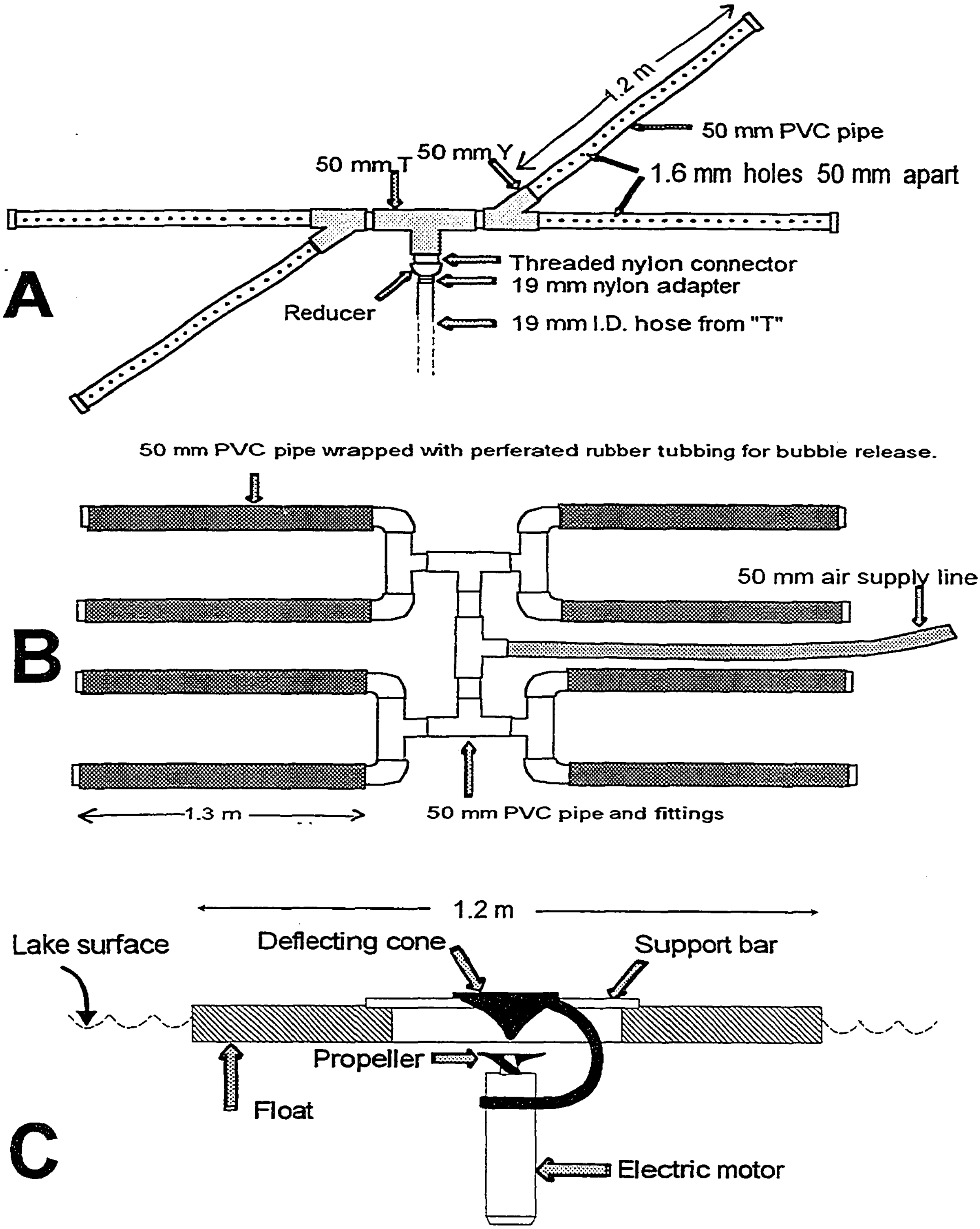

Figure 2-3. The coarse-bubble cross-pipe diffuser built by the Alberta Conservation Service (A), the medium-bubble commercially-built diffuser obtained from Envirodynamics, Columbia, MO (B), and the type of surface aerator used, obtained from Air-O-Lator, Kansas City, MO (C).

Table 2-3. Description of equipment and location within each of the aerated lakes used in the initial study design (winter of 1994-1995).

Lake	Description of aeration devices	Location of sprayers or diffusers
Thompson Pond	1.3 kW * (1/2-hp Air-O-lator® surface aerator)	Near spillway; overlying the deepest basin of 4.2 m
Moonshine	4.2 kW* (one 1-hp and one 2-hp Air-O-Lator surface aerators)	100 m from E. shoreline, 800 m from W. shoreline; overlying 1.25 m
Cummings	6.5 kW * (Two 2-hp and one 1-hp Air-O-lator surface aerators)	Near center of lake; overlying 3.25 m
East Dollar	3.75 kW (One 5 hp Gast rotary vane compressor). Aeration pod with one cross-pipe diffuser. Total air flow = approx. 0.38 $m^3 min^{-1}$ °	suspended 0.3 m above bottom near center of lake (8 m deep)
Figure Eight	9.32 kW (one 7.6-hp Sutorbilt blower with Baldor motor and one 4.9 hp Sutorbilt blower with direct drive motor) with four cross-pipe diffusers. Total air flow = approx. 0.91 $m^3 min^{-1}$ °.	180 m from E. shoreline, 900 m from the N.W. shoreline suspended 0.3 m above bottom in 4.5 m water
Sulphur	7.46 kW‡ (One 20-hp Lombardini diesel motor driving two 5 hp-blowers), with three cross-pipe diffusers. Total air flow = approx. 0.76 $m^3 min^{-1}$ °°	400 m from E. shoreline, 900 m from W. shoreline suspended 0.3 m above bottom in 4.5 m water

*Calculated from manufacturer's nameplate
‡Estimated equivalent kW
° Measured value
°°Manufacturer's estimate

approximately 100 m from the diffusers. The air injection system at Moonshine Lake delivered air through a 50 mm line which was similarly split to two diffusers situated approximately 30 m apart. The single diffuser used at East Dollar Lake was located approximately 90 m from shore in the center of the 8 m (z_{max}) basin.

Experimental Approach

I compared near-field and far-field circulation patterns where; 1) the aerator or diffuser was set at the deepest part of the lake; and 2) the aerators and diffusers were placed in shallower water at the approximate mean depth of the lake (Table 2-2).

During the initial study season of 1994-1995, both East Dollar and Figure Eight lakes were treated only with air injection. Surface aeration was intended for Moonshine Lake, however, initial electrical problems caused frequent tripping of the ground fault current interrupter (GFCI) shortly after the surface aerators were installed. This led to a string of operating arrangements that deviated from the simple surface aeration protocol but that are worth reporting. As a result of frequent GFCI tripping, the aerators operated intermittently, perhaps 10 - 20 % of the time, until December 6. Consequently, an air injection system that had been used in previous years was operated by provincial park personnel from December 1 - 5 in the mistaken belief that some aeration was necessary. In fact, an algal bloom was occurring in Moonshine Lake at that time, as there was no snow cover and DO values exceeded saturation (to a much greater extent than freeze-out would supply). On December 6, the surface aerators in Moonshine Lake were lowered to approximately 0.5 m below the surface to prevent the propellers from freezing during the frequent down periods. The aerators operated continuously in this fashion, maintaining a polynya, but without spray, until January 10, 1995. At that time, electrical modifications were made, after which the aerators were raised to the surface and operated problem-free for the remainder of the aeration season.

During the 1995-1996 season, East Dollar and Moonshine lakes were used for a side-by-side comparison of air injection and surface aeration. In East Dollar Lake the diffuser was set at 8 m and a 1-hp surface aerator was anchored about 20 m away, also over the 8 m depth. In Moonshine Lake the two diffusers were similarly set beside the two surface aerators and anchored in 1.5 m of water. This lake is much larger than East Dollar Lake, allowing horizontal tracing of water movement for approximately 800 m.

During the 1996 to 1997 winter, the comparison between surface aeration and air injection continued in East Dollar Lake with the aerator and diffuser set in shallow water with the goal of mixing only the top 4 m of the lake. The surface aerator was located nearer to shore and anchored over 4 m (z_{avg}) of water. The diffuser remained in the center, but was suspended at 4 m (for comparison with the shallow set of the surface aerator). In addition, I a new commercially available medium-bubble (4-5 mm diam.) diffuser obtained from Environmental Dynamics Inc., Columbia, MO (Fig. 3B). Later, this diffuser was lowered to 8 m to determine the efficiency of oxygen dissolution from bubbles (see Chapter 4) as well as velocity.

Near-field Measurements

A Gurley Pigmy current meter was used to determine velocity profiles for each aeration device. Vertical profiles were determined at 1 m intervals along a transect from the bubble plume or edge of the surface spray to the polynya edge. To determine the angle of the outgoing plume, velocity was measured at depth intervals of 0.3 m to a depth of 1.8 m or to where the velocity could no longer be detected. Recorded values were the mean obtained from approximately 15 seconds at each position and depth.

Whole-lake Circulation

The description of the outgoing plume was supplemented by applying dye at the surface at a point adjacent to the surface spray or the bubble plume. This allowed measurement of the thickness and velocity of the outgoing plume using both systems and in both lakes. Dye tracings were particularly useful at depths > 2 m and velocities < 2.5 cm sec^{-1}.

To evaluate the relationship between entrainment and detrainment, dye was injected in Moonshine Lake at 1, 2 and 3 m deep at a location 50 m from the surface aerator. This allowed tracking of the water leaving the aeration site as well as water being drawn to the aerator. Complications with equipment failure and thaw cycles (allowing water from melted snow to drain into injection and sampling holes), hindered observations when this experiment was repeated using diffusers and hence, these are not reported here.

The destratification process at the onset of aeration was also characterized. Several temperature and DO profiles were measured immediately following start up and, in Figure Eight Lake, these profiles were supplemented with the tracking of dye movement. This study included dye injection at a point 1.5 m deep and 10 m from the diffuser immediately prior to the onset of aeration.

Rhodamine WT (Ben Meadows Catalogue) was the chosen dye. Approximately 200 mL was used when dye was placed near the aerators and 100 mL was used when dye was injected under ice cover at Moonshine and Figure Eight lakes. Injection was accomplished by pouring dye through a 25 mm (ID) PVC pipe. The bottom of the pipe was fitted with a cap which was drilled in four directions to allow equal lateral dispersal. The dye was mixed with approximately 1 L of lake water prior to being poured into the PVC pipe. This was followed by 2 to 3 additional L of lake water to insure complete injection of the dye.

Samples were collected with a 1.2 L Kemmerer bottle and dye concentrations were measured using a Turner model 53A Fluourometer. Serial dilutions in tap water indicated that the detection limit was between 1 and 2 $\eta g\ L^{-1}$. Similar dilutions in lake water reduced sensitivity to approximately 5 $\eta g\ L^{-1}$. Dissolved oxygen was measured using Carpenter's (1965) modification of the Winkler method. Temperature was measured using a Barnandt Thermistor calibrated to 0.1 °C using a certified laboratory thermometer.

RESULTS

Temperature and DO Stratification

Typical winter (February) temperature and DO profiles are presented in Fig. 2-4. West Dollar Lake (control) exhibited typical inverse stratification resulting in temperatures ranging from 1.5 °C at 1 m to 4.7 °C near the bottom. The temperature greater than 4.0 °C near the bottom was associated with a 0 mg L^{-1} DO, low oxidation-reduction potential (circa -250 mV) and an increase in electrical conductivity (as measured using a Hydrolab Surveyor II).

Both types of aeration cooled lake waters and reduced the magnitude of vertical

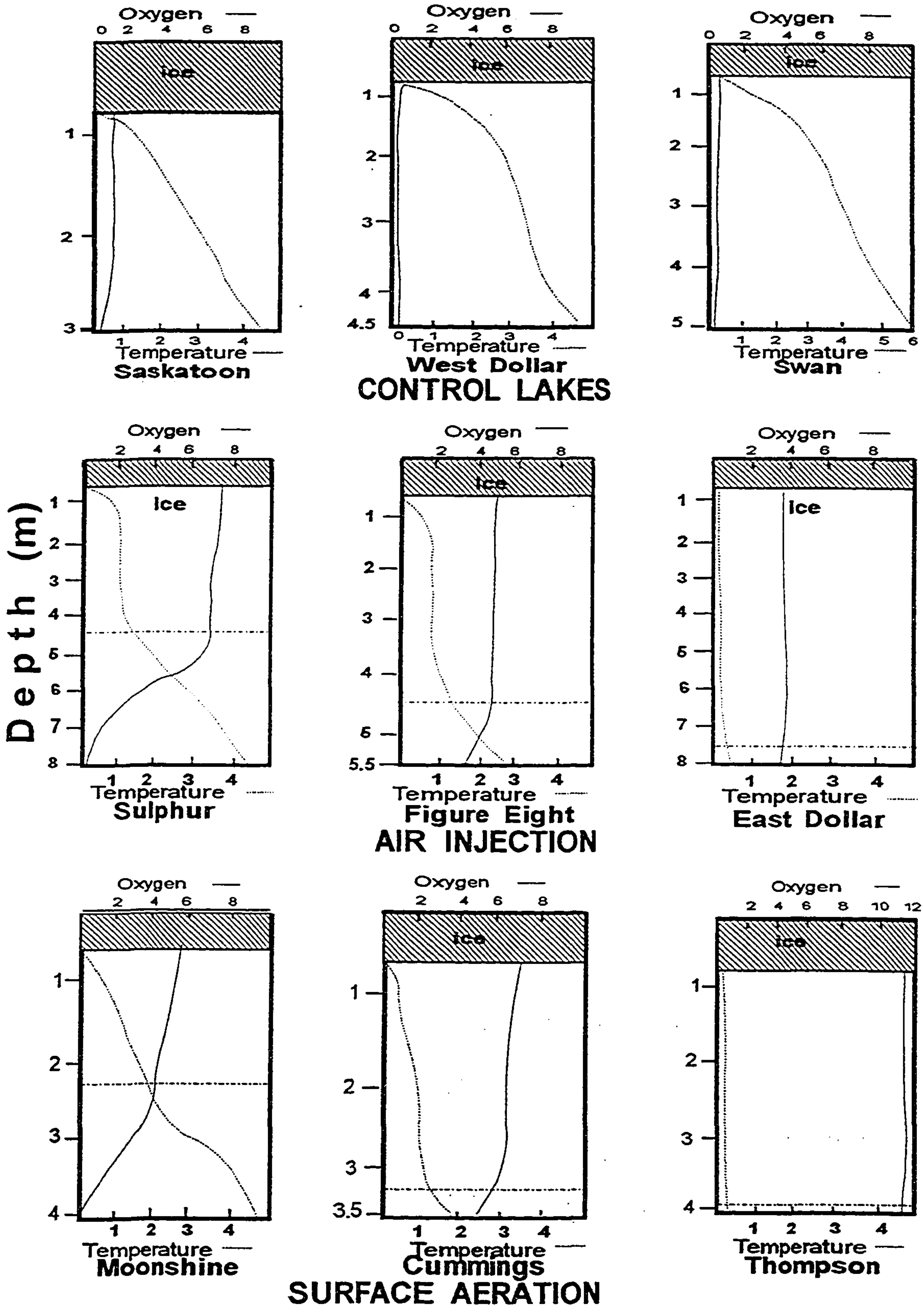

Figure 2-4. Typical midwinter temperature and DO profiles for all the experimental lakes. The dashed horizontal lines indicate the depth at which the diffuser was anchored or the total depth underlyng the surface aerators.

temperature and DO gradients under ice (Fig. 2-4). Water temperatures ranged from 0.1 to 0.8 °C at 1 m to between 0.6 and 2.8 °C at the bottom. The higher temperatures were observed in larger Figure Eight Lake. Both systems cooled and destratified the lakes to the exact depth at which the diffusers were located or the depth underlying the surface aerators (note the dashed lines in Fig. 2-4). The only variation from this characteristic occurred in Moonshine Lake where the surface aerators were placed over only 1.5 m of water. This resulted in more gradual changes in temperature and DO with depth.

Representative isopleths of DO and temperature were drawn for the two larger lakes, Figure Eight and Moonshine lakes, to illustrate the horizontal and vertical limits to the mixing process (Figs. 2-5 - 2-8). It should be noted that the bottom contours are exaggerated vertically due to the horizontal compression of the graphs. The air injection system for Figure Eight Lake was started October 20. The first basin was immediately cooled and destratified (Fig. 2-5). The second basin proceeded toward typical winter stratification.

DO isopleths indicate that the initial outgoing plume displaced or mixed water which was undergoing a post-freeze up algal bloom (DO had exceeded that which could be accounted for by freeze-out; Fig. 2-6). Subsequent profiles throughout the winter indicate that elevated DO levels were maintained for a distance of 700 to 800 m (Fig. 2-6). In addition, the shallow sill separating the first and second basins effectively precluded oxygenated water from reaching greater depths within the second basin (Fig. 2-6). The temperature profiles of Fig. 2-5 also illustrate this isolating effect. In addition, it should be noted that, unlike the DO profiles, thermal destratification continued across the entire

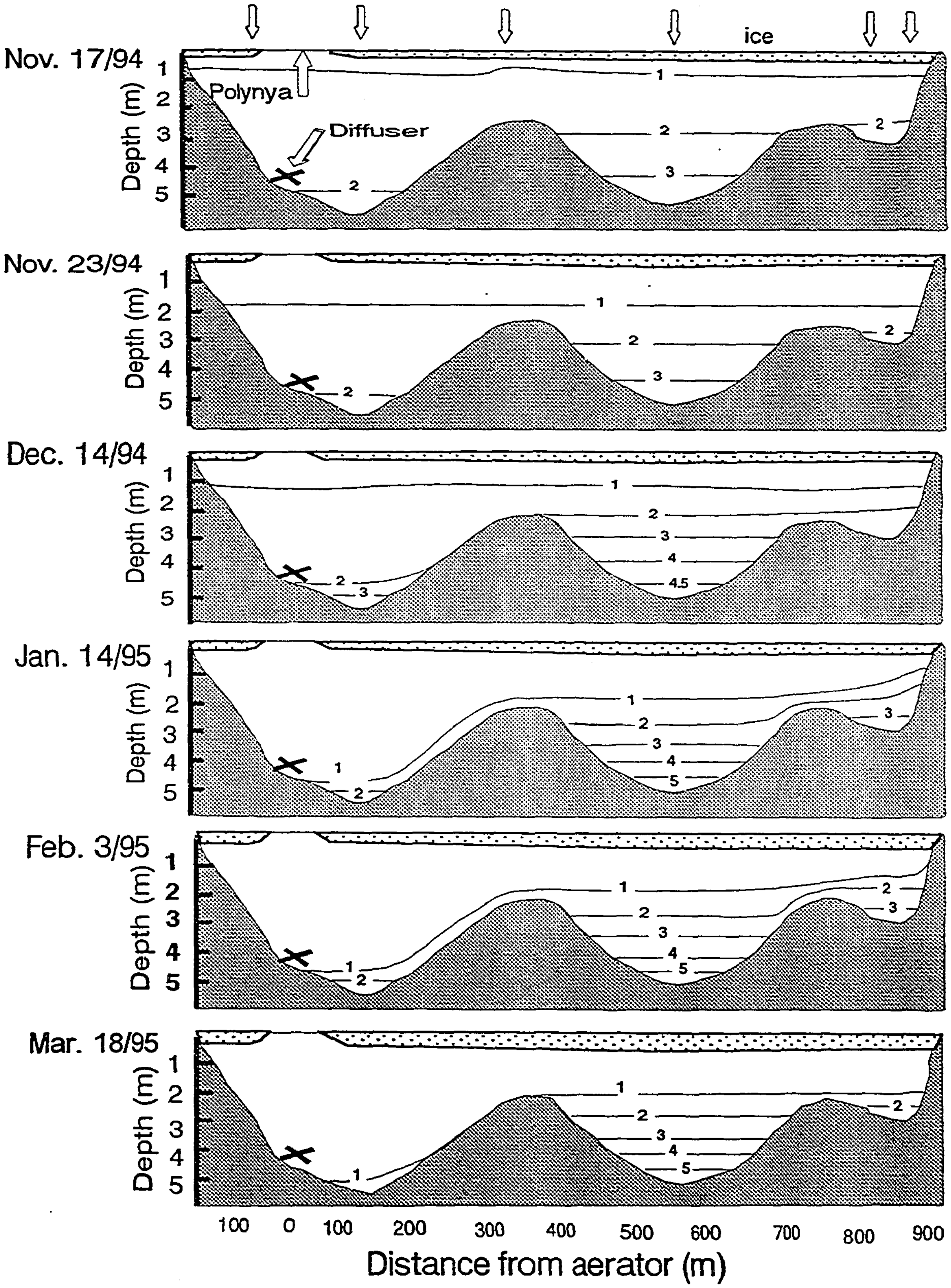

Figure 2-5. Representative isotherms in Figure Eight Lake showing zones of destratification and stratification. The crosses indicate the location of the point release diffusers. Arrows indicate station locations. Stippled area represents ice cover.

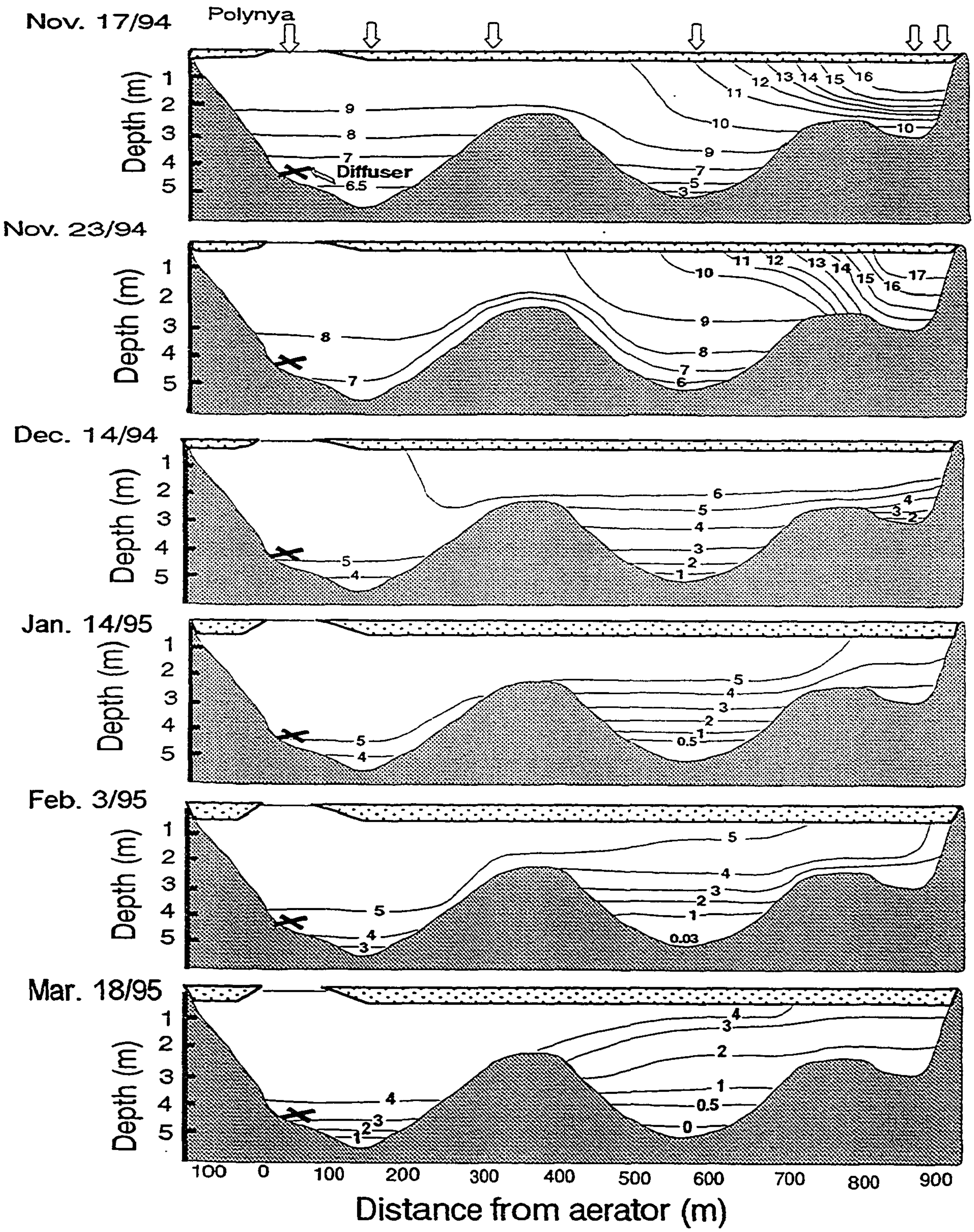

Figure 2-6. Oxygen isopleths for Figure Eight Lake during winter 1994-1995. Crosses indicate location of point release diffusers. Arrows indicate sampling locations. Stippled area represents ice cover.

distance of the lake, approximately 900 m.

In Moonshine Lake, the intermittent operation of the surface aerators at the beginning of the season did not disturb thermal stratification (Fig. 2-7), nor did it disturb the algal bloom that was occurring across most of the lake (Fig. 2-8). However, the short duration of air injection into the middle of the basin, from December 1-5, dramatically cooled and nearly destratified the lake (Fig. 2-7, second panel). Similarly, air injection upset the algal bloom throughout the lake (Fig. 2-8, top 2 panels). Notably, the greatest DO depletion occurred in the vicinity of the diffusers.

From December 6-January 10, the two surface aerators were suspended and operated at 0.5 m below the surface in order to prevent freezing in of the propellers following the frequent tripping of the ground fault current interrupter. However, during this time, the surface aerators ran nearly trouble-free. Yet, the lake restratified (Fig. 2-7, third panel) and although a polynya of about 12 m diameter formed around each aerator, the lake continued losing oxygen (Fig. 2-8 third panel).

The electrical problems were corrected on January 10 and normal operation of the aerators (creating a spray) resumed at that time. Although the lake retained near-natural temperature stratification throughout the remainder of winter (Fig. 2-7), DO values immediately began rising. Within 7 days a growing cell of 4 mg L^{-1} - plus water had traveled 650 m (Fig. 2-8, fourth panel). However, as with Figure Eight Lake, the range of elevated DO only reached 700 to 750 m while temperature uniformity reached the farthest shoreline (approx. 800 m; Figs. 2-7 and 2-8).

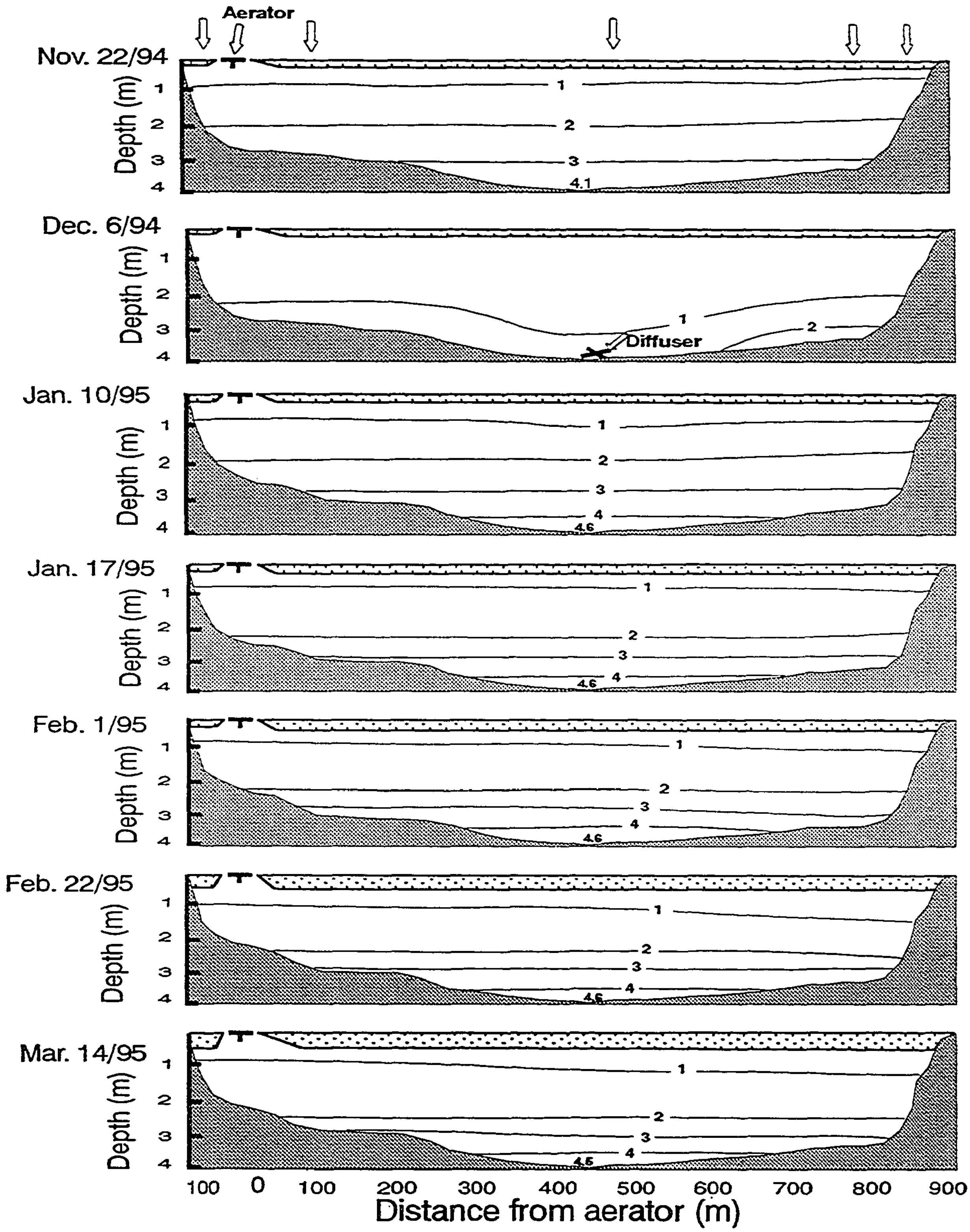

Figure 2-7. Isotherms for Moonshine Lake during the 1994 to 1995 aeration season. Sample locations are indicated by arrows above the top panel. The 'T' indicates the location of the surface aerators. The cross indicates the location of the diffusers which were operated December 1 to 6. Stippled area represents ice cover. Arrows indicate sampling locations.

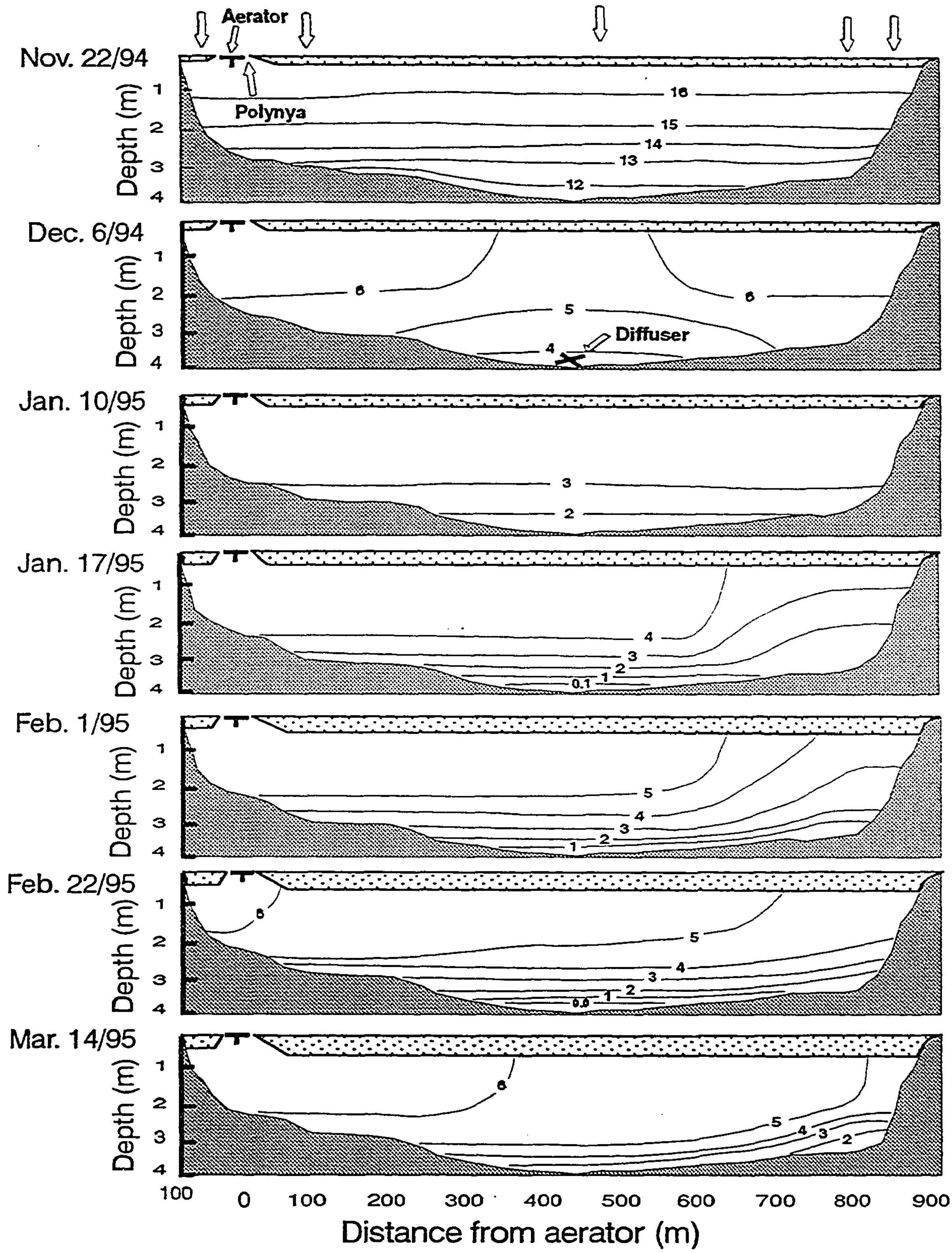

Figure 2-8. Oxygen isopleths for Moonshine Lake during the 1994 to 1995 aeration season. The locations of sampling stations are indicated by arrows above the top panel. The 'T' repesents the surface aerator in the polynya. The cross indicates the location of the diffusers which were operated December 1 to 6. Stippled area represents ice cover.

Near-field Velocity Measurements

Near-field water movements were measured mechanically using a Gurley Pigmy velocity meter and several dye injections. The various aeration devices generated different near-field velocities. Between the surface aerators, the 2-hp aerator generated twice the surface velocity of the 1-hp aerator (Fig. 2-9). Subsurface velocity at 0.3 and 0.6 m was also greater. Yet, the surface velocity decay was very similar between the two surface aerators. Velocity decay of the 1-hp aerator was slightly better fit to a power function rather than an exponential function that described the 2-hp aerator.

The coarse bubble diffuser generated a surface velocity somewhat greater than the 2-hp surface aerator (600 mm s^{-1} versus 550 mm sec^{-1}; Fig. 2-10), while the velocity generated by the medium bubble diffuser was substantially greater at 750 mm s^{-1} (Fig. 10). Despite these greater initial velocities for air injection, the velocity decay patterns were similar to those from surface aeration (Figs. 2-10 and 2-9). During both tests air flow was set at approximately 425 L min^{-1}.

Despite the similarity in surface flow patterns, subsurface velocities were quite variable. This prompted the development of Fig. 2-11. The shaded area reveals the zone of detectable velocity (>25 mm s^{-1}). Although the average angle of the thickening plume was approximately 15°, there were predictable and periodic variations from this angle. For both surface aerators the outgoing plume occurred at an initial angle of about 35° (Fig. 11A and B). However, this angle was actually reversed at distances between 2 and 4 m from the splash zone. Between 5 and 7 m, the 2 hp aerator displayed a second zone where the angle of the plume was again temporarily reversed (Fig.11B).

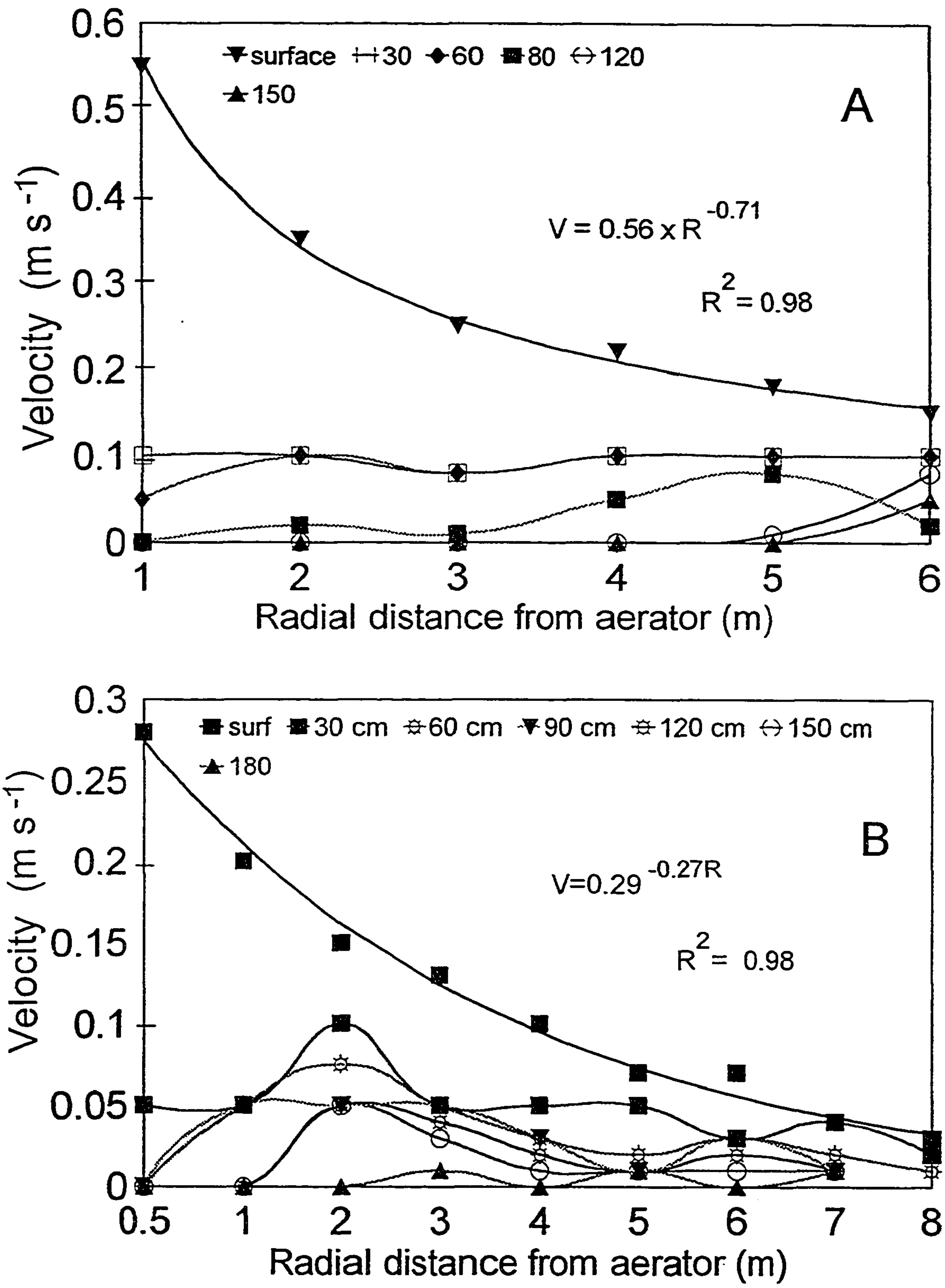

Figure 2-9. Velocity measurements in the vicinity of the 2 hp (A) and 1 hp (B) surface aerators. Velocity was measured using a Gurley pigmy current meter. Note the greater velocity of the 2 hp aerator and also the slightly different rate of velocity decay (i.e. the 1 hp was best fit to an exponential function while the 2 hp was best fit to a power function).

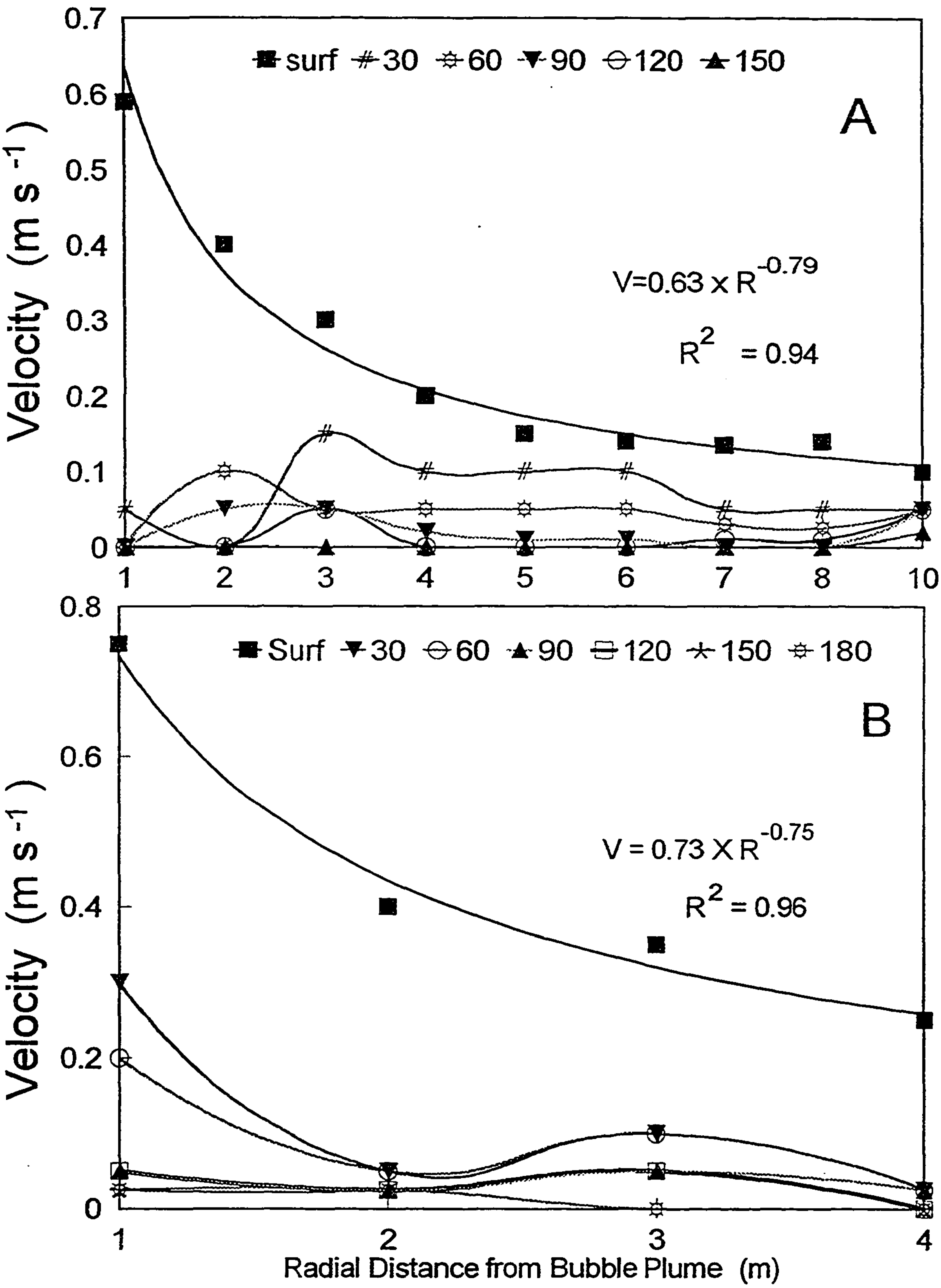

Figure 2-10. Near-field velocity of the radial jet generated by coarse-bubble (A) and medium-bubble (B) air injection.

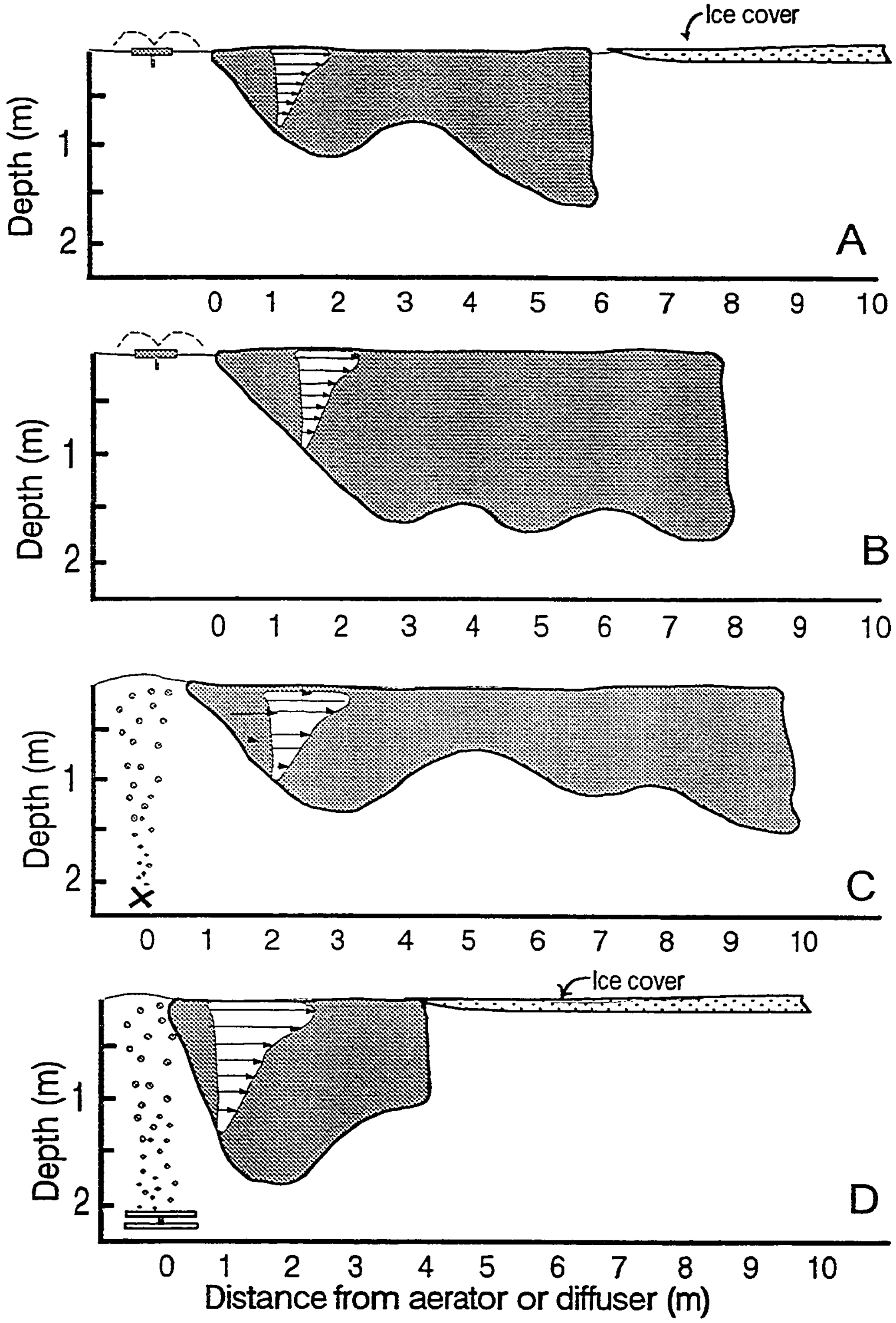

Figure 2-11. Profiles of detectible water movement from the 1-hp surface aerator (A), the 2-hp aerator (B), the cross-pipe coarse-bubble diffuser (C), and the medium-bubble diffuser (D). Except for panel D, shaded area represents the zone of detectable velocity (>25 mm s^{-1}). Determination of velocity profile beyond 5 m in (D) was impossible due to thin ice cover. The relative velocity is indicated by the length of the horizontal arrows.

The coarse bubble diffuser generated a velocity curve very similar to that of the 2-hp surface aerator (Figs. 2-11C and B). The major difference was that the zones of angle reversal were larger. The medium-bubble diffuser generated a velocity profile that was steeper than those of the surface aerators or the coarse-bubble diffuser. The initial angle of penetration was approximately 45°, reaching a depth of 1.8 m within the first 2 m. Again, the plume angle was temporarily reversed and in this case it occurred at a shorter distance to the bubble plume or splash zones than the other aerators. This very steep initial plume angle was followed by a large zone of angle reversal between 2 and 4 m from the bubble plume. Within this range, measurable velocity was reduced to the 1 m depth. Unfortunately, ice cover prevented additional velocity measurements beyond 4 m.

Subsequent observations of dye leaving the point of injection near the bubble plume and splash zones revealed that these discrete areas of reduced velocity and "shallowing" of the detrainment plume were associated with large and standing eddies generated by the various aeration devices.

Tracking Water Movements with Dye

East Dollar Lake

Aliquots of dye were poured onto the polynya surface during both surface aeration and air injection. During the first tests, the surface aerator and diffuser were anchored in 8 m deep water. Dye movement during surface aeration is illustrated in Fig. 2-12. Dye was found at the bottom, only 10 m from the surface aerator and sampling at 1 hr indicated that the dye had become re-entrained and dispersed in all directions from the aerator. Dye

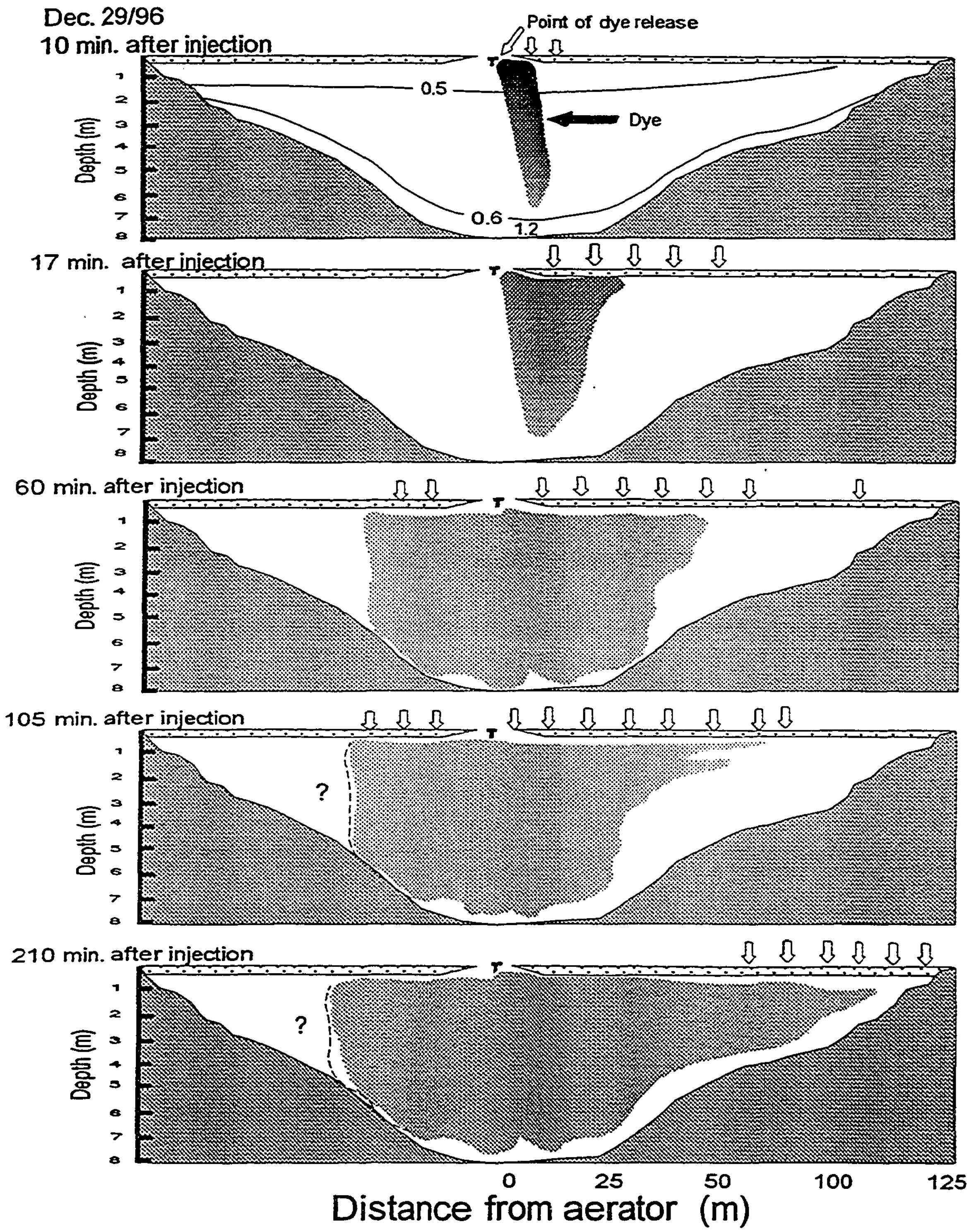

Figure 2-12. Dye movement in East Dollar Lake. Dye was poured onto the surface at 1 m from the spray of the surface aerator. The "T" in the polynya indicates the surface aerator. Shading of dye indicates relative concentration. The temperature profile is indicated in the top panel. Samples collected at 60 minutes indicated the dye had been re-entrained and dispersed in all directions. Arrows indicate sampling locations. Stippled area indicates ice cover.

had traveled approximately 100 m (nearly to the edge of the lake) after 3.5 hrs.

Dye movement during air injection was measured while operating the medium-bubble diffuser. Dye tracings were initially quite similar to that with surface aeration (Fig. 2-13). Dye was again found near the bottom at only 10 m from the diffuser and after 110 minutes a concentrated bolus of dye had become re-entrained and dispersed on the opposite side of the diffuser. Interestingly, horizontal dye movement was slower than for surface aeration, despite greater surface velocity generated by air injection.

Another dye injection was performed when the surface aerator was operated nearer to the shore and over 4 m of water (Fig. 2-14). Sharp temperature stratification was well established at depths greater than 5 m and the onset of this stratification marked the lower limit of dye penetration. As with other dye injections, immediate re-entrainment and subsequent radial dispersal occurred.

Following shallow water operation of the surface aerator, the medium bubble diffuser was operated at the 4 m depth. However, unlike the surface aerator, the diffuser was suspended at mid depth at the center of the lake. Unexpectedly, operation in this manner resulted in destratification of the entire water column and in just two days (data not shown). Hence dye studies were not conducted during this time.

Moonshine Lake

All dye injections in Moonshine Lake were performed while the aerators were located over only 1.5 m of water and approximately 100 m from the eastern shoreline. This allowed the lake to retain near-normal temperature stratification throughout the different

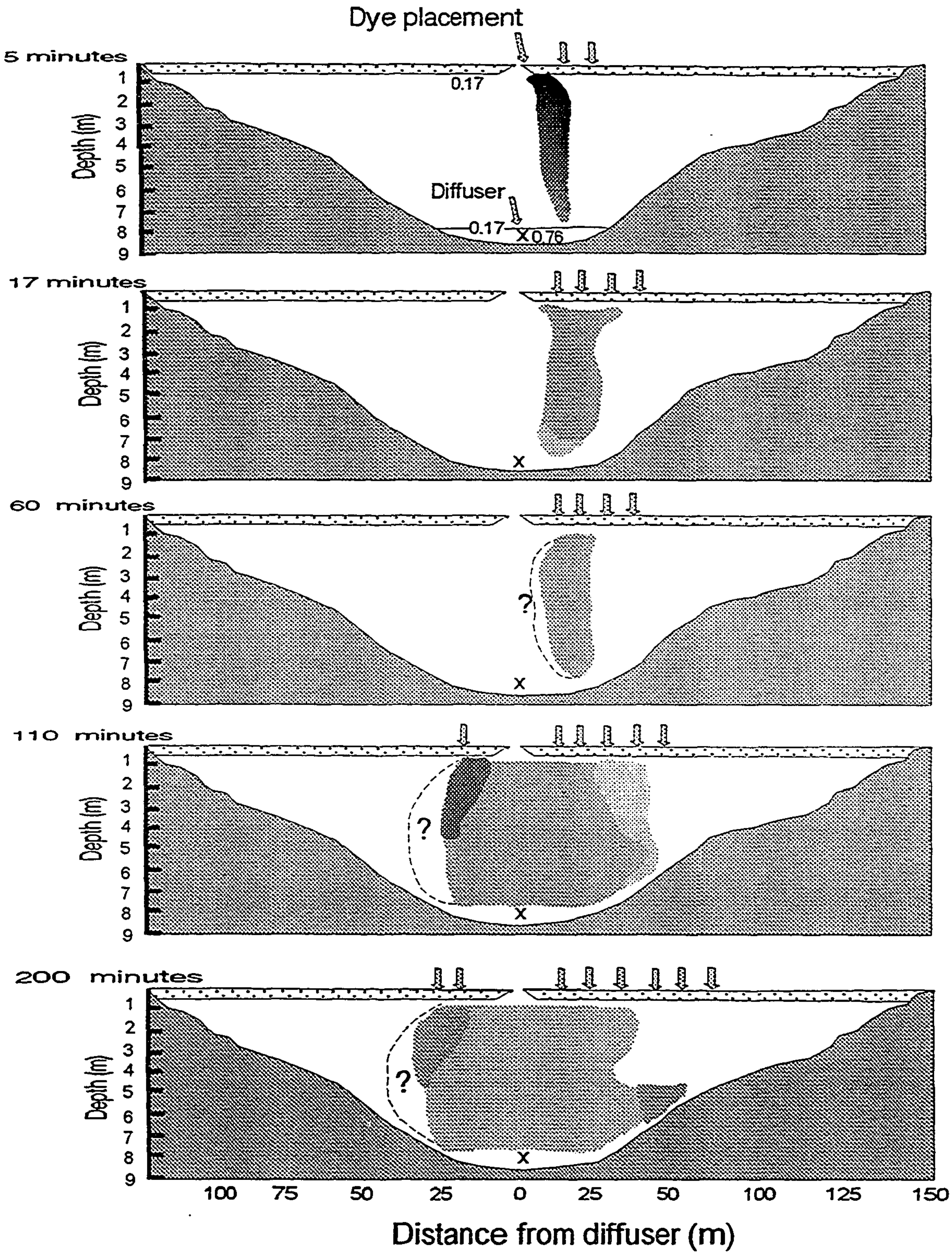

Figure 2-13. Dye movement in East Dollar Lake during air injection. Dye was poured onto the surface at approximately 1 m from the bubble plume. The X near the bottom indicates the locatin of the diffuser.The tempeature profile is indicated in the top panel. Sampling on both sites of the polynya indicate re-entrainment and dispersal in all directions. Arrows indicate sampling locations. Stippled area indicates ice cover.

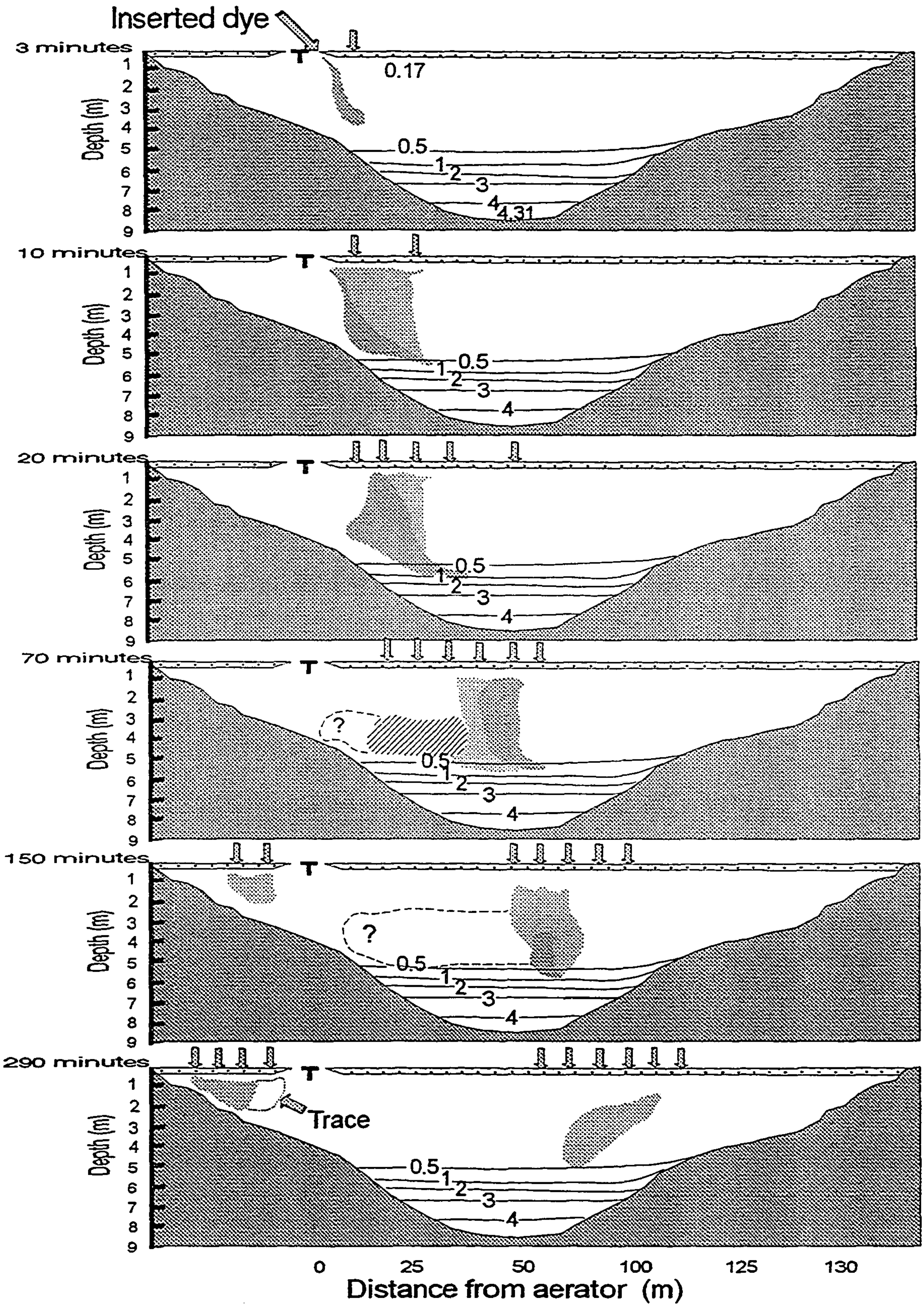

Figure 2-14. Dye tracings at East Dollar Lake February 4, 1997. Dye was administered immediately adjacent to the spray and tracked for 5 hours. Sample locations (arrows) were at 10 m intervals. Shading indicates relative dye concentrations.

experiments and throughout winter (see above). During the first 24 hours of aeration, dye traveled approximately 500 m and had reached the farthest shoreline (approximately 800 m) after 48 hours (Fig. 2-15). Vertical movement of the dye was limited to the top 2 m, even across the deepest part of the basin.

The detrainment plume from surface aeration traveled at approximately half of the velocity of that generated by air injection (Figs. 2-16 and 2-15). Dye traveled approximately 300 m during the first 24 hours and 500 m after 48 hrs. Interestingly, only one surface aerator had been operating prior to the dye injection with a resultant 5 mg L^{-1} oxygen isopleth stationary at 2 m in depth and a range of 400 m. Operation of the second surface aerator (initiated for better comparison with the two diffusers) extended the range of 5 mg L^{-1} to the same distance the dye had traveled after 48 hours.

Additional dye studies were performed at Moonshine Lake to more carefully define the characteristics of entrainment and detrainment. To accomplish this, dye was injected at 1, 2 and 2.75 m deep at a point 50 m from the aerator. Dye placed at or above 1.75 m was contained within the detrainment plume and traveled away from the aerator (Fig. 2-17). The dye injected at the 2 m depth formed a separate mass and was drawn to the aerator, although traces of this dye also continued to mix with shallower water (Fig. 2-17, second panel). This resulted in two separate masses of dye in the detrainment plume that were identified after 180 min. and again after 240 min. The dye injected at the bottom (2.75 m) remained at that location during the entire sampling period.

Another injection was made at the 3 m depth in the center of the lake to determine the stability of this apparent stagnant layer (Fig. 2-18). Dye generally spread very slowly in

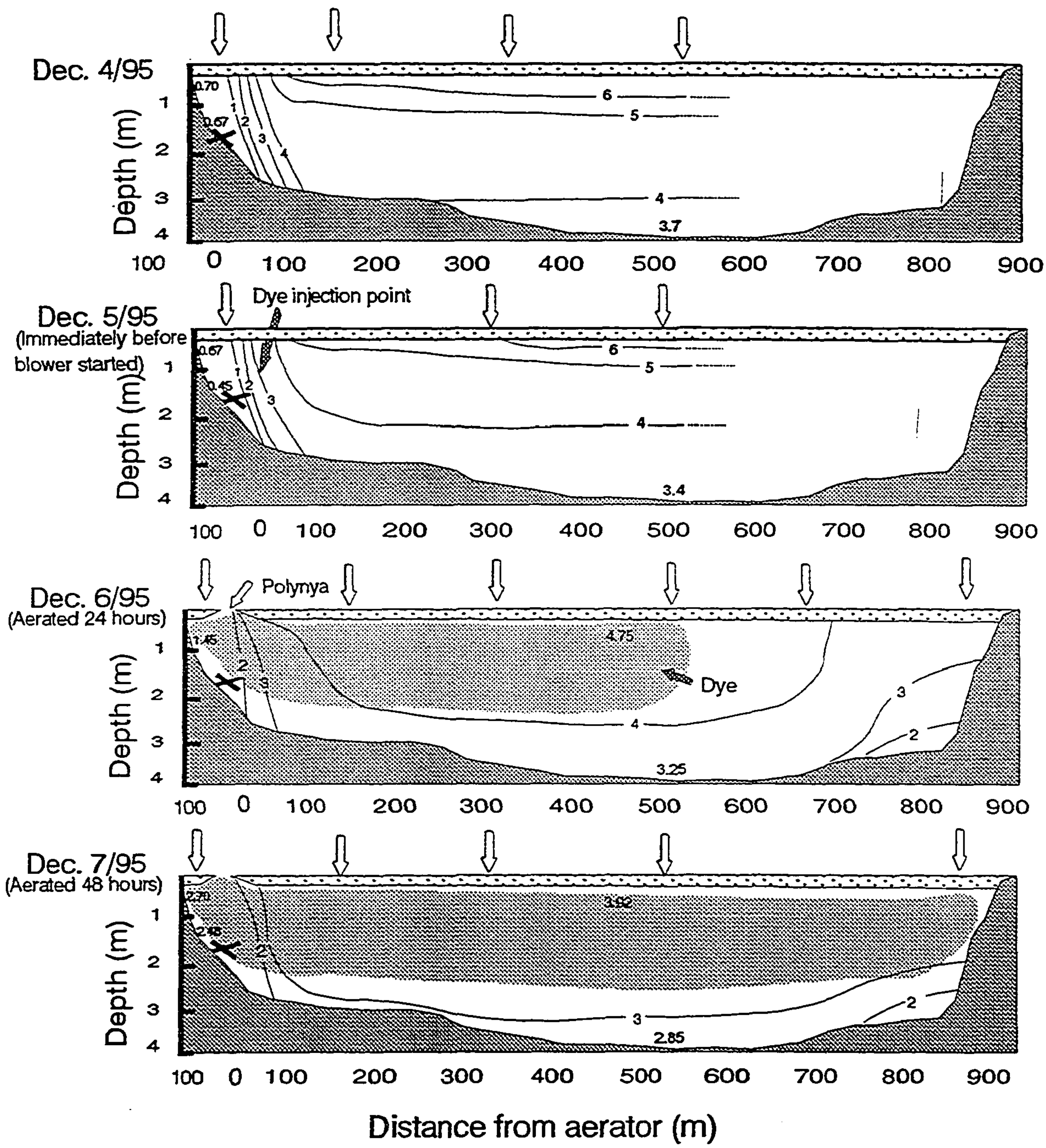

Figure 2-15. Dye movement and oxygen isopleths in Moonshine Lake during air injection. Dye was injected at 10 m from the diffuser and 1.5 m deep immediately prior to startup. Stippled area represents ice cover. Arrows indicate sampling sampling locations.

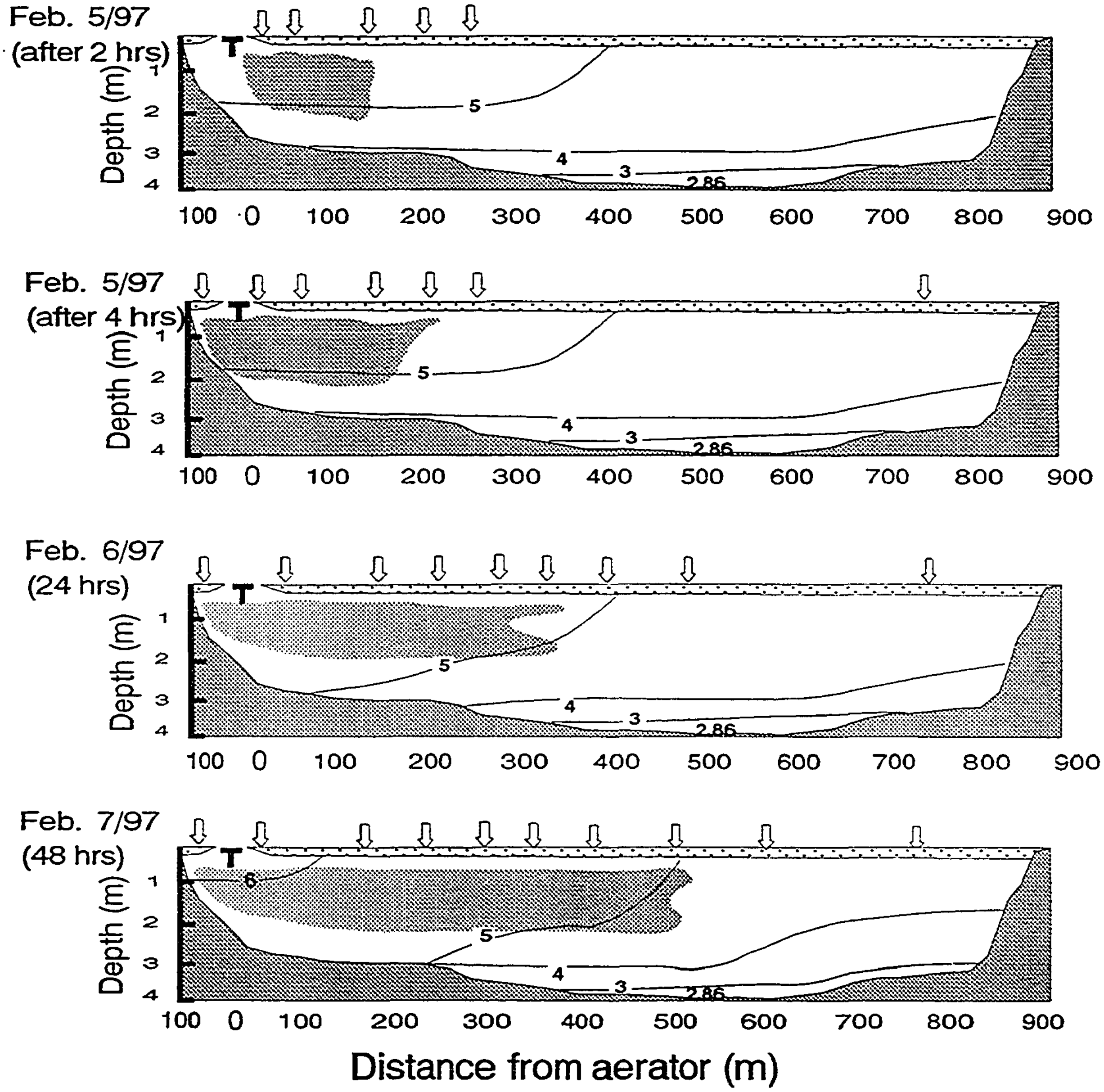

Figure 2-16. Dye and oxygen tracings performed in Moonshine Lake during surface aeration. Only one aerator was operating until February 4. Two aerators were operating from February 4 through 7. Stippled area represents ice cover. Arrows represent sampling locations.

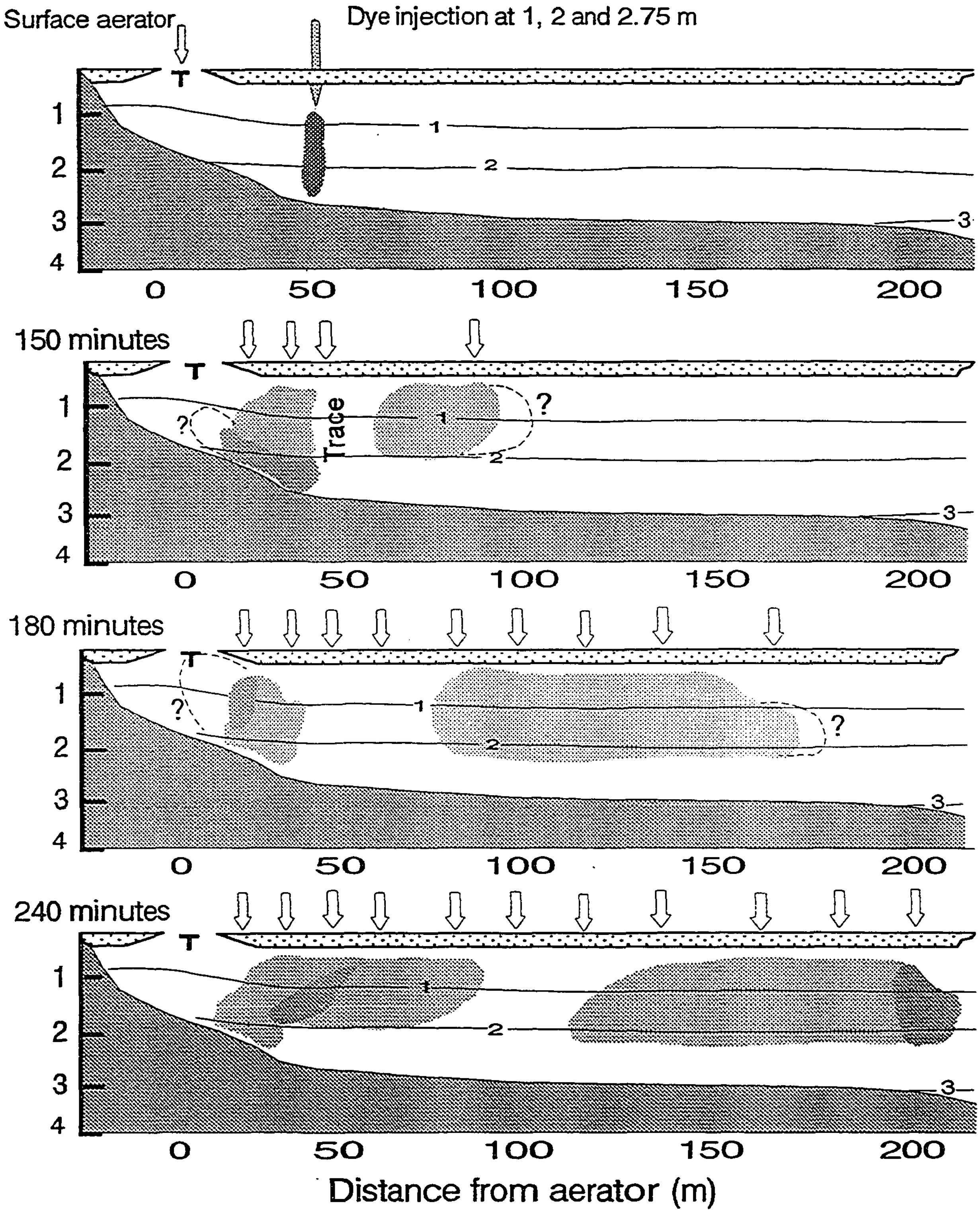

Figure 2-17. Near-field dye movement and isotherms in Moonshine Lake. Dye was injected at 1, 2 and 2.75 m deep at a point 50 m from the aerator. Dye injected at 2.75 m was drawn to the aerator and later appeared in a separate mass of detrained water. Different shading represents relative concentrations of dye. Arrows represent sampling location.

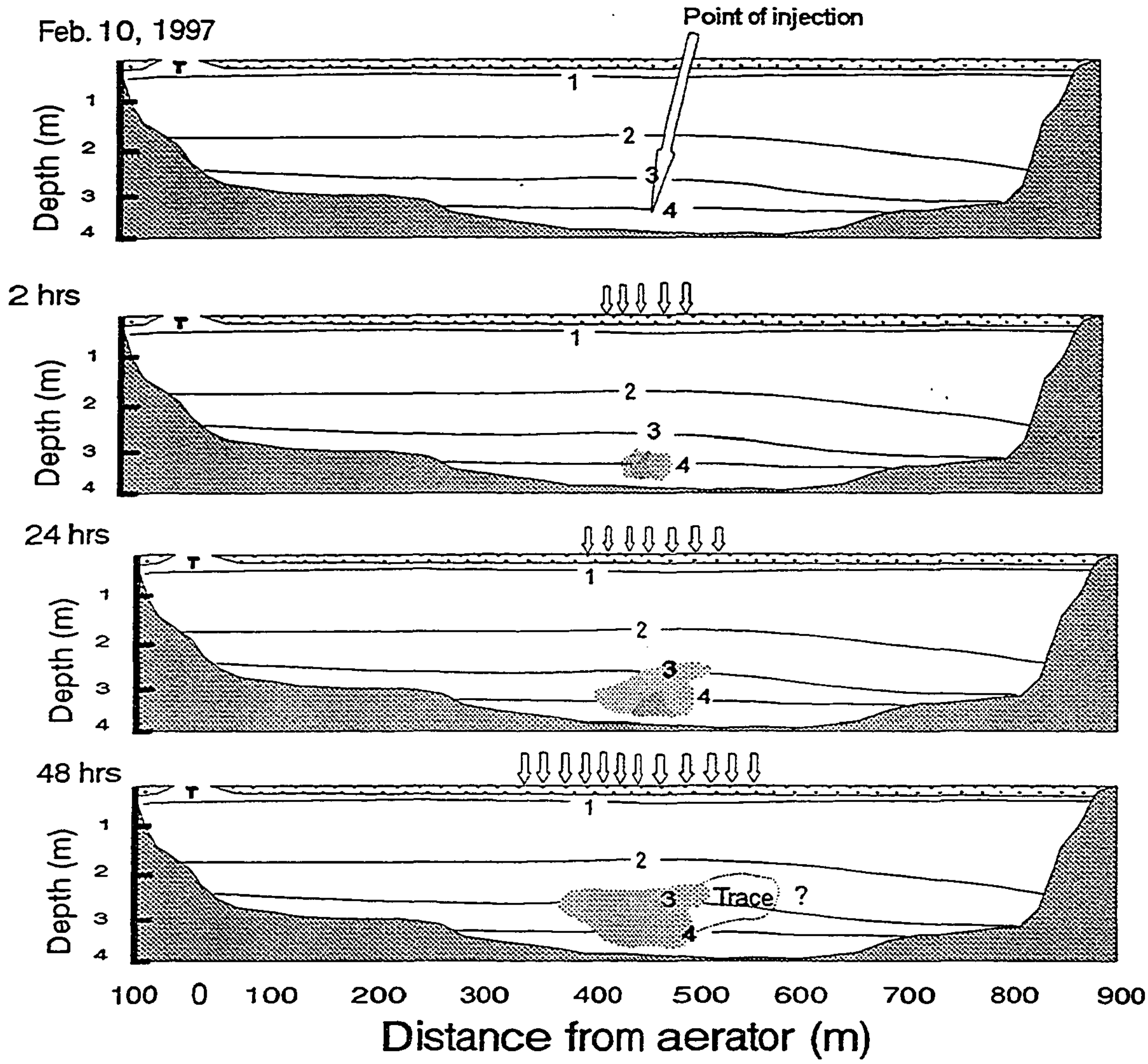

Figure 2-18. Tracing of dye injected at 3.5 m in Moonshine Lake. Most dye remained stationary in the lower strata (3 to 3.5 m). However, dye that entered the mixed layer (< 2.5 m) was either drawn to the aerator (2.5 m deep) or away from the aerator (2.5 to 2.0 m deep). Arrows indicate sample locations that were established 10 m apart. The question mark indicates that the horizontal extent of movement could not be determined from the sampling.

all directions. After 24 hours dye had dispersed approximately 25 m on both the north-south and east-west axes. However, after 48 hours dye that had diffused upward (to the approximate 2 m depth) appeared to enter the mixed layer. Dye movement became oriented primarily as return flow (entrainment) although there was also movement away from the aerator at somewhat shallower depths (Fig. 2-18). However, the rate of travel was still limited to 25 to 50 m per 24 hours.

Figure Eight Lake

Figure 2-19 illustrates dye movement and isotherms during the beginning minutes of air injection on November 21, 1995. Dye was injected at the 1.5 m depth at a distance of 10 m from one of the diffusers and just seconds before startup. Eight minutes after startup the dye was observed in the bubble plume rising through an observation hole drilled immediately above the diffuser (data not shown). After 12 minutes high concentrations of dye were measured at the same depth and location of the injection (Fig. 2-19, second panel). Subsequent sampling confirmed a narrow lens of dye disseminating at that approximate depth. Further, the distance the dye had traveled was accompanied by the onset of thermal destratification.

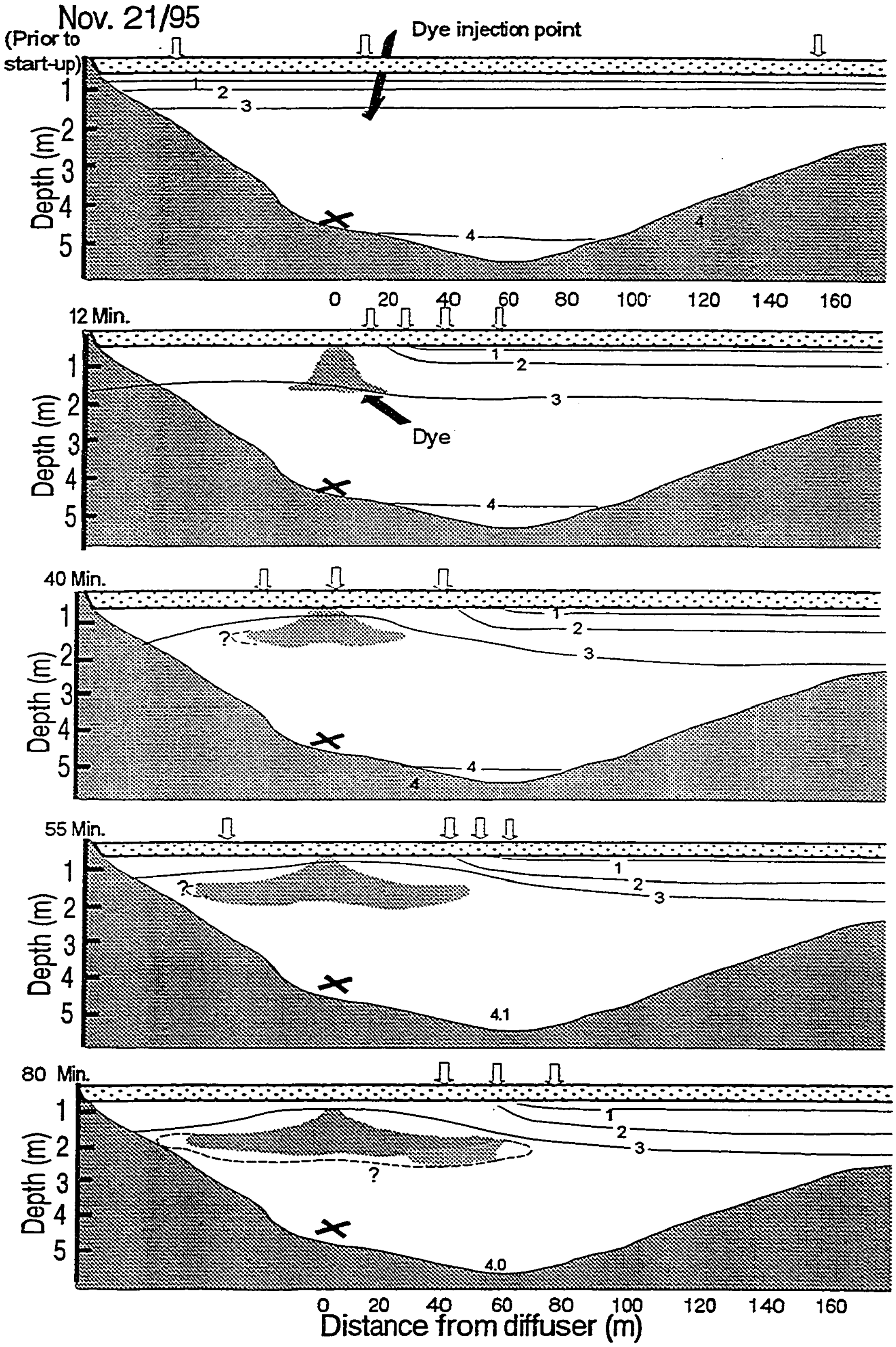

Figure 2-19. Dye movement and isotherms in Figure Eight Lake at the start-up of air injection. The "X" indicates the diffuser, arrows indicate sample locations, different shading represents relative dye concentrations and dashed line represents hypothetical location of dye.

DISCUSSION

Dimensions of the Mixed Layer

The key finding of this study is the definition of the mixed layer. Temperature profiles and dye studies indicate that discrete aerated cells are not formed. Rather, the outgoing plume and mixed layer continued to the most distant shorelines (900 m in Figure Eight Lake and 800 m in Moonshine Lake) within 48 hrs.

Unlike thermal destratification, however, the range of DO enhancement was limited to only 600 to 800 m, with the greater distances associated with air injection. Bandow (1986) evaluated a much larger system and found similar results. He used air injection (10.6 $m^3 \cdot min^{-1}$ to 15 Helixor® diffusers) in much larger (780 ha) Lake Elysian, Minnesota. His system created a polynya of 2 ha. Dissolved oxygen during February at the polynya and at 500 m was 2 mg L^{-1}, while DO at 1500 m had fallen to 1 mg L^{-1}. The shoreline was an additional km away which probably eliminated the possibility of shoreline effects. These data suggest that regardless of size of the aeration system, effective oxygenation from point release diffusers of surface aerators may be limited to a radius of about 1000 m from the aeration site. The discrepancy between the distance that thermal destratification occurs and that of elevated DO concentrations is likely linked to the trophic status of these aerated lakes and, to a lesser extent, to the size or type of aeration system. For example, even though air injection transported dye at approximately twice the velocity as surface aeration, elevation DO extended only 20 to 30% farther for air injection. This suggests that the inherent oxygen demand of these lakes more strongly influences the oxygenation range than does the size of the aeration system. In other words, the greater oxygen demand inherent to a lake, the more rapid the attenuation of oxygenated water in the detrainment plume. With either aeration method, however, the oxygen demand of such hypereutrophic lakes overcomes the rate at which oxygen is being delivered at a relatively short distance from the aeration site. Aspects of aeration efficiency and lake-specific oxygen depletion rates are the addressed in Chapter 4.

Vertical mixing of temperature and DO was limited to the distance underlying either the surface aerators or the diffusers. Even small depressions near the diffusers in Figure Eight Lake tended toward thermal stratification and DO loss and the shallow sill that separated the first and second basins was particularly effective in isolating the second basin from the aeration process (Figs. 2-5 and 2-6). Dye studies also confirmed the dimensions of the mixed layer during shallow placement of the aeration devices. Dye dispersal during both air injection and surface aeration in Moonshine Lake was restricted to the total depth underlying the diffusers or aerators.

Detrainment and Entrainment Patterns

The surface velocities measured using the Gurley current meter (Figs. 2-9 and 2-10) agree well with turbulent radial jet theory (Rajaratnum 1976). Subsurface velocity measurements were less consistent with theory. The maximum depth at which velocity was detectable generally increased with distance from the aerators or diffusers. This is consistent with radial jet theory and qualitative descriptions by Brown et al. (1989) and Baines (1961) where the detrainment plume was found to thicken at an angle of 10°. However, these more detailed measurements and dye observations indicated that the detrainment plume was initially steeper than previously suggested (i.e. Fast 1994, Brown et al. 1989), and contained large "standing eddies" created within the outgoing plume. Further, these standing eddies were associated with actual reversal of the detrainment angle and tended to repeat themselves at regular intervals. Using a surface aerator of similar design, Rogers (1992) reported similar variations in subsurface velocity and with similar harmonics. Further, finding dye at the bottom of East Dollar Lake (8 m) at a distance of only 10 m for either aeration device indicates that the large near-field eddies continue to penetrate the water column (beyond that measured by the velocity meter). This resulted in an actual angle of penetration at an average of about 45° rather than 10° (Figs. 2-12 and 2-13). Further, re-entrainment and dispersal in all directions had occurred within an hour of dye injection.

Dye observations at the onset of air injection in Figure Eight Lake revealed the details of how destratification begins. Dye injected at 10 m from the diffuser at a depth of 1.5 m was immediately entrained by the bubble plume (Fig. 2-19). Dye in the subsequent detrainment plume returned to the 1.5 m depth and proceeded across the lake as a thin lens at that approximate depth. This occurred despite the fact that the diffuser was located at 4.5 m deep. This was undoubtedly due to the slight stratification of natural under-ice conditions (as compared to following several days or weeks of aeration). This characteristic is typical of summer destratification where internal plumes become a thin interflow that moves rapidly across the lake (Schladow and Fisher 1995). However, this condition was temporary in Figure Eight Lake as continued operation almost totally destratified the first basin of Figure Eight Lake within just a few days (Figs. 2-5 and 2-6). After that time, Figure Eight Lake would be expected to exhibit near-field circulation typical of that shown in East Dollar Lake when the diffuser was set at the 8 m depth (Fig. 2-13).

Additional description of entrainment and detrainment was accomplished with a series of dye injections at 1 m depth intervals in Moonshine Lake. Dye injected above 2 m entered the detrainment plume and traveled away from the aerator while dye injected at or just below 2 m was drawn toward the aerator (Fig. 2-17). The spatial and temporal separation of these two masses of dye became clear as two isolated masses of dye were found leaving the aerator area and remained within the upper 2 m.

Comparison of these tracings with those from Figure Eight and East Dollar lakes suggests two different flow patterns exist and these patterns are dependant upon depth below the aeration device and the presence and degree of stratification. East Dollar Lake was nearly completely destratified during the tests when the aeration devices were located over deep water (Figs. 2-12 and 2-13). Consequently, the detrainment plume was steep, extended to near the bottom and was followed by immediate re-entrainment toward the aeration device. Conversely, where even slight stratification was present, the detrainment plume was restricted to the zone defined by the depth underlying the aeration devices (Figs. 2-14, 2-15 and 2-16). Dye that was injected deeper than the depth of the bottom underlying the surface aerator remained quite stationary (Figs. 2-17 and 2-18). The slightly denser water resisted entrainment despite its close proximity to the aerator (Fig.2-17) as was the majority of dye injected at 3.5 m in the center of Moonshine Lake (Fig. 2-18). There was some vertical movement of dye into the mixed layer. However, this movement was slow, perhaps 0.5 m d^{-1}, suggesting that the velocity is in the range of eddy diffusivity. Further, details of these tracings suggest that perhaps only the bottom several mm of the mixed layer is involved in entrainment while the top approximate 2 m of the mixed layer is involved in the detrainment plume. However, this is likely an artifact of the dye injection depth associated with slow vertical movement of dye. Rather, it is likely that the top half of the mixed layer is detrained water while the bottom half of the mixed layer is entrained water with a sheer zone very near the mid depth of the mixed layer which provides mixing of the water (and dye).

These observations add important details to and somewhat contradict the current paradigm of both near-field and whole-lake circulation (Torrest and Wen 1976, Baines 1961, Lorenzen and Fast 1977) (Fig. 2-1). Even in situations where the lake is totally destratified (similar to tank conditions), the detrainment plumes were much steeper than data from tank studies and particularly for both the medium bubble diffuser and surface aeration. Perhaps the greatest difference is the presence of large repeating standing eddies that were not mentioned by previous workers. These eddies are likely responsible for the steepness in the detrainment plume as well as periodic reversal of the plume angle. A schematic model of these modifications is presented in Fig. 20. It should be pointed out that these models apply to both surface aeration and air injection. Accordingly, a large proportion of near-field water is re-entrained and recycled within a few minutes. The remainder of the outgoing plume extends to the lake bottom near the aeration device at an approximate 45 degree angle and proceeds horizontally across the lake. Further, the presence of dye throughout the mixed zone indicates that this zone must contain components of outgoing and return flow.

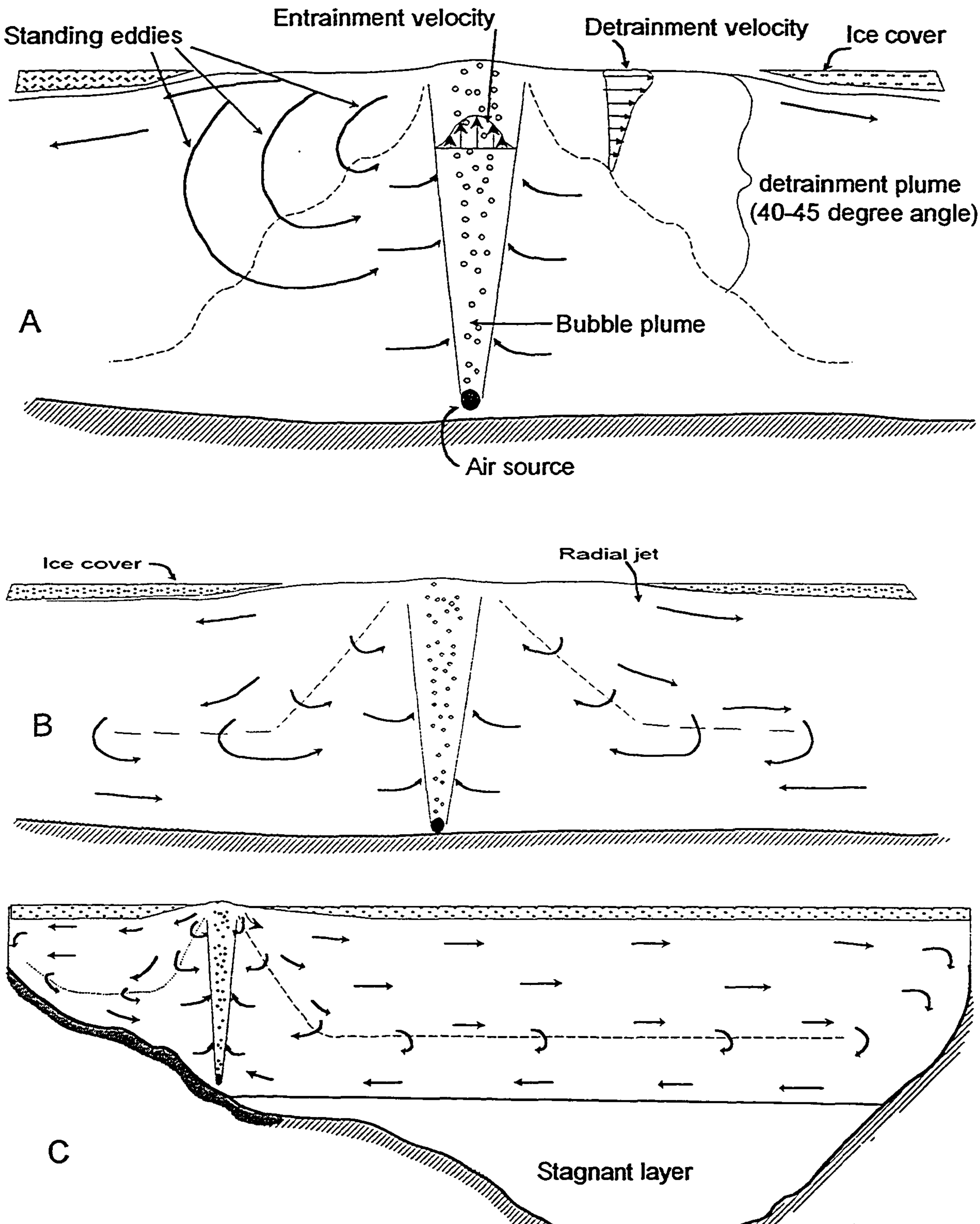

Figure 2-20. Schematic models of (A) Near-field water currents; (B) Whole-lake water currents where the aerator or diffuser is set in deepest basin; and (C) Whole-lake water currents where the aerator or diffuser is set at mid-depth. Although air injection is depicted here, the flow patterns are similar between surface aeration and air injection. Patterns are derived from dye tracings and velocity measurements reported in Figs. 2-9 to 2-18.

References

Baines, W.D. 1961. The principles of operation of bubbling systems. In: Proc. symp. on air bubbling. pp. 12-22. Technical Memo. No. 70. Canadian National Research Council. Ottawa.

Bandow, F. 1986. Evaluation of winter lake aeration techniques in Minnesota. Minnesota Dept. Nat. Resources, Div. of Fish and Wildlife. Sect. Fish. Invest. Report No. 386. 48 pp.

Brown, R.T., J.A. Gordon and C.E. Bohac. 1989. Measurement of upwelling flow from air diffuser. J. Environ. Engin. 115(6):1269-1275.

Fast, A.W. 1994. Winterkill prevention in lakes and ponds using artificial aeration. Rev. in Fish. Sci. 2:23-77.

Hodgman, C.D., R.C. Weast, and S.M. Selby (Eds.). 1961. Handbook of Chemistry and Physics. pp. 2155-2156. The Chemical Rubber Co. Cleveland OH.

Kobus, H.E. 1968. Analysis of the flow induced by air bubble systems. Coastal Eng. Conf. London. II. 1016-1031.

Lorenzen, M.W. and A.W. Fast. 1977. A guide to aeration/circulation techniques for lake management. Ecological Res. Series, EPA-600/3-77-004. (Jan.) Washington, D.C.: U.S. Environmental Protection Agency.

Rajaratnum N. 1976. Developments in water science: Turbulent jets. Elsevier Scientific Publishing Co. Amsterdam. 304 p.

Rogers, C.K. 1992. Impact of an artificial circulation device on the heat budget of an ice-covered mid-latitude lake. M.Sc. Thesis. University of British Columbia. 173 p.

Rogers, C.K., G.A. Lawrence and P.F. Hamblin. 1996. Thermal impact of artificial circulation on an ice-covered mid-latitude lake. Can. J. Civil Eng. 23:1081-1091.

Schladow, S.G. 1992 Bubble Plume dynamics in a stratified medium and the implications for water quality amelioration in lakes. Water Resources Research 28(2):313-321.

Schladow, S.G. and I.H. Fisher. 1995. The physical response of temperate lakes to artificial destratification. Limnol. Oceanogr. 40(2):359-373.

Torrest, R.S. and J. Wen. 1976. Mixing and circulation of lakes and reservoirs with air plumes. University of New Hampshire Water Resource Research Center. Durham. Report No. 13. 128 p.

Tubb, R. 1966. Limnological conditions in aerated lakes of the Turtle Mountains, North Dakota. D-J Report. Project F-2-R-13. North Dakota Fish and Game Department.

Chapter 3

Optimizing Artificial Aeration for Lake Winterkill Prevention

Introduction

The success of artificial aeration in preventing winterkill has varied greatly. Most failures result from under-sizing aeration equipment, a problem which may be exacerbated by late-season startup (Fast 1994). These problems most often arise because of aeration-induced increased oxygen depletion rates. In certain situations, air injection increased oxygen depletion rates by 4 to 10 fold (Lackey and Holmes 1972, Smith et al. 1975, Bandow 1986, Ashley 1987). In other cases, the observed winterkill was actually attributed to the aeration-induced circulation of the lake water associated with midwinter startup (e.g., Patriarche 1961).

Some sizing estimates have been reported for air injection systems. Wirth (1988) reported air flows from 0.076 to 0.091 standard m^3 min^{-1} (SCMM) ha^{-1} [0.8 to 1.3 standard cubic feet min^{-1} (SCFM) per lake surface acre] appeared to be the optimal range for Wisconsin lakes. Flows as high as 0.21 SCMM ha^{-1} (3.9 SCFM $acre^{-1}$) into coarse-bubble diffusers have been used in Alberta lakes (Schwalme 1994). Lorenzen and Fast (1977) suggested a flow of 0.091 SCMM ha^{-1} (1.3 SCFM $acre^{-1}$) will provide good mixing for summer destratification.

Successful aeration for winterkill prevention requires efficient transfer of oxygen to lake waters. Most oxygen absorption is believed to occur via the polynya surface, rather than from rising bubbles (Neilson 1974, Smith et al. 1975) or from surface spray (Ashley 1987, Rogers 1992). Neilson (1974) reported absorption estimates from medium bubbles (5 mm diameter) could only account for about 6% of lake re-aeration in a 10 m deep lake.

Similarly, Smith et al. (1975) estimated that for an 8-ha lake receiving 0.825 SCMM (27.5 SCFM), with air flow released from a depth of 8.4 m, the surface area of rising coarse bubbles (20 mm diameter) was estimated to be only 0.14% of the entire lake surface area. These data imply the extreme importance of polynya size in enabling aeration devices to add oxygen to lakes. However, the relationship of aeration method to energy use, its ability to maintain adequate polynya area and overall effectiveness in maintaining sufficient DO have never been investigated.

In this study the overall energy consumption to polynya size, lake temperature, volume of air or water pumped and the overall ability to maintain adequate DO were compared. Particularly, I describe aeration requirements during early winter when oxygen depletion rates were greatest and carefully track DO as winter progressed.

Materials and Methods

Study lakes

Aeration equipment was used in six lakes located within the Peace River Region, Northwest Alberta. These include Moonshine, East Dollar, Cummings, Figure Eight and Sulphur lakes and Thompson Pond. Details of size and morphometry are presented in Fig. 2-2.

Energy use and sizing

Proper sizing includes determining the method that maintains adequate DO for fish survival with minimal energy requirements. I compared kW ha^{-1} between lakes and method and the resultant DO content during operation. Adequate air or water flow was defined as that which maintains DO between 3.5 and 5.5 mg L^{-1} rather than that which appears to sufficiently mix the water or create the largest polynya. Although trout winterkill in Alberta lakes has not been observed until DO falls to $\leq$2.5 mg L^{-1} (David Jackson, personal observation, Alberta Conservation Association, Peace River, August, 1997), a minimum goal of 3.5 mg L^{-1} would provide for more optimal health and allow several days of oxygen depletion without causing mortality if the equipment fails. Exceeding 5.5 mg DO L^{-1} is considered unnecessarily high and a waste of energy and unnecessary equipment costs.

Experiments are summarized in Table 3-1. In East Dollar and Moonshine lakes, air injection and surface aeration were alternated within the same aeration season to eliminate the potential variability of oxygen depletion rates among different winters. These schedules are detailed in Table 3-2. During the first year of operation (1994-1995), air injection by coarse-bubble (20 to 3 mm diameter), point-release diffusers only slowed the loss of DO and further downsizing of air injection equipment was not attempted. Conversely, because DO consistently increased in all three surface-aerated lakes, considerable experimentation with downsizing was performed during the successive two winters. In Thompson Pond, the 1/2-hp Air-O-Lator® (Kansas City, MO) aerator used for the first year was replaced with a 1/6-hp Otterbine® (Emmaus, PA) surface aerator for the second and third winters.

In Cummings Lake, three surface aerators were used during the first season. These aerators were also used during the second season although they were started sequentially over an interval of several days to observe the response in DO. Accordingly, the third

Table 3-1. Number and type of aerators used in Moonshine, East Dollar, Cummings and Sulphur lakes and Thompson Pond to evaluate sizing and resultant effects on lake limnology. Kilowatts are calculated from name plate values except for the system used in Sulphur Lake.

Lake	Year	Energy use, number and type of aerators
Moonshine	1994-1995	4.2 kW (one 2-hp and one 1-hp Air-O-Lator surface aerators)
Moonshine	1995-1996	4.2 kW (same two surface aerators) but alternated with one 4.9-hp Sutorbuilt blower with two diffusers (3.65 kW)
Moonshine	1996-1997	1.8 kW (one 1-hp surface aerator)
East Dollar	1994-1995	3.75 kW (one 5-hp blower-compressor with cross-pipe course bubble diffuser)
East Dollar	1995-1996	Same blower-compressor (3.75 kW) alternated with one 1.8 kW surface aerator over deep (8 m) water (1.8 kW)
East Dollar	1996-1997	Same blower-compressor (3.75 kW) but fitted with medium-bubble diffuser, also alternated with one 1.8 kW surface aerator
Cummings	1994-1995	6.6 kW (two 2-hp and one 1-hp Air-O-Lator surface aerators)
Cummings	1995-1996	Same three surface aerators (6.6 kW) operated for approximately two weeks then reduced to two 2.4 kW aerators
Cummings	1996-1997	2.4 kW (one 2-hp surface aerator)
Thompson Pond	1994-1995	1 kW (one 1/2-hp Air-O-Lator surface aerator)
Thompson Pond	1995-1996	0.2 kW (one 1/6-hp Otterbine surface aerator)
Thompson Pond	1996-1997	Same 1/6-hp surface aerator (0.2 kW)
Sulphur	1994-1995 & 1995-1996	7.46 kW (one 20-hp Lombardini diesel motor driving two 5-hp blowers)‡ with three cross-pipe diffusers
Sulphur	1996-1997	7.2 kW (one 12-hp Kubota diesel generator supplying four 1-hp surface aerators)

‡ estimated rating

Table 3-2. Operation schedule at Moonshine and East Dollar Lakes during the 1995-1996 and 1996-1997 aeration seasons.

Lake	Aeration Method	Period of Operation					
		November	December	January	February	March	April
Moonshine (1995-96)	Air injection		—		—	—	
	Surface aeration		—	—	—	—	—
East Dollar (1995-96)	Air injection			—	—		—
	Surface aeration	—	—		xxxxxxx ****	—	—
East Dollar (1996-97)	Air injection					== —	—
	Surface aeration	—	—	—	—	—	

xxxxx no aeration.
**** Surface aerator operated submersed and fitted with a deflecting device to prevent polynya formation.
== Air diffuser anchored at 4 m followed by submersion to 8 m.

aerator was turned off after ten days of operation because the DO was rapidly increasing. A single 2.4 kW (2-hp) surface aerator was operated at Cummings Lake during the third season (Table 3-1). In Moonshine Lake, two surface aerators were used during the first winter. During the second winter, air injection using two diffusers was alternated with the two surface aerators to more accurately compare aeration effectiveness and circulation patterns (Table 3-2) Aeration was also downsized to just one surface aerator during the third season.

Surface aeration and air injection were similarly alternated in East Dollar Lake, although only one diffuser and one 1.8 kW (1-hp) surface aerator were used in this smaller lake (Table 3-1).

In Sulphur Lake, two 373 kW (5-hp) blower compressors, one feeding two diffusers and one feeding one diffuser, were used for the first two seasons. During the third season, I replaced the air injection system with four 1.8 kW surface aerators.

It should be noted that direct comparison of nominal values of horse power is misleading. For example, theoretically, a 1-hp electric motor consumes 744 watts of electricity. However, for the surface aerators, the horse power was measured at the propeller shaft (manufacturer's specifications). Therefore, actual energy requirements (measured and name plate values) were about 1000 watts for the 1/2-hp Air-O-lator, 1800 watts for the 1-hp Air-O-Lator and 2400 watts for the 2-hp Air-O-lator (See Table 3-1). On the other hand, the horse power ratings of the air compressors were directly equivalent to 744 watts per 1-hp (personal measurement). All comparisons reported here are in actual watts consumed. Therefore, replacing the air compressors in Sulphur Lake with four surface aerators represented only a slight downsizing in actual energy use (7.46 kW vs 7.2 kW).

Analytical

Samples for DO analysis were collected with a 1.2 L Kemmerer bottle from each m in depth and approximately 100 mm from the bottom and analyzed using Carpenter's (1965) modification of the Winkler method. Temperature was measured using a Barnandt thermistor calibrated to $\pm$ 0.1°C using a certified laboratory thermometer.

Results

The effect of power utilization on lake temperature and polynya size

Sizing and aerator performance are traditionally reported as energy use ha^{-1}, or as air (or water) pumped ha^{-1}. Occasionally, the resultant polynya size is provided. These and other important parameters are presented in Table 3-3. Although air-injected lakes were generally larger than surface-aerated lakes and used larger aeration systems, a similar range of power use ha^{-1} was used for both systems. Between both systems, lakes with similar energy use ha^{-1} developed similar temperature regimes (Fig. 3-1).

The polynya area was also related to energy use ha^{-1} (Table 3-3). However, in the two largest lakes, which were air injected (Figure Eight and Sulphur lakes), the polynyas were much larger than in surface-aerated lakes (Table 3-3, Fig. 3-2).

The 3.75 kW compressor at East Dollar Lake (0.76 kW ha^{-1}) and the 1.0 kW surface aerator (0.59 kW ha^{-1}) at Thompson Pond represented the two highest values for energy use ha^{-1}. Both lakes were very cold (0.1°C throughout most of the water column) and polynya areas were similarly very small (East Dollar = 13 m^2, Thompson Pond = 4 m^2; Table 3). In very cold weather, (-30°C to -40°C), an ice mound encapsulated the spray at Thompson Pond, leaving an opening of about 0.3 m^2.

Surface aeration at East Dollar Lake represented the third highest energy use (0.37 kW ha^{-1}). Although this was only about half of the energy used by the compressor, the lake was only slightly warmer (0.2°C vs 0.1°C). However, the polynya was about two times larger (28 m^2 vs 13 m^2) (Table 3-3).

Table 3-3. Summary of aeration performance and their influence on aerated lakes. Experiments included downsizing surface aeration equipment or alternating between air injection and mechanical surface aeration. See Table1 for specific aeration equipment used. Arrows in the last column indicate whether DO was increasing, decreasing or stable.

Lake	Water pumped $m^3 \cdot min^{-1}$ * (gpm) or Air flow $m^3 \cdot m^{-1}$ * (cfm)	$m^3 \cdot min^{-1} ha^{-1}$ (gpm $\cdot ac^{-1}$) or $m^3 \cdot m \cdot ha^{-1}$ (cfm $\cdot ac^{-1}$)	kW $\cdot ha^{-1}$ (kW $\cdot ac^{-1}$) (from name plate data)	Mean polynya area during Jan., Feb. (m^2)	Prop. of lake as open water	Mean temp.at 1 m during Jan., Feb. (°C)	Mean DO at 1 m at end of season (mg $\cdot L^{-1}$)
Surface aerated							
Thompson (1994-1995)	3.03 (800)	4.3 (405)	0.588 (0.238)	4	0.0003	0.1	11.5 ⇒
Thompson (1995-1996)	0.38 (120)	4.33 (58)	0.13 (0.05)	85	0.005	0.6	4.9 ⇒
Moonshine (1994-1995)	12.2 (3225)	0.40 (42.4)	0.15 (0.055)	946	0.0031	1.2	6.2 ⇑
Moonshine (1995-1996)	12.2 (3225)	0.40 (42.4)	0.15 (0.055)	1080	0.0033	1.1	5.8 ⇑♦
Moonshine (1996-1997)	5.58 (1475)	0.18 (19.4)	0.058 (0.024)	715	0.0023	1.3	5.3 ⇒
Cummings (1994-1995)	18.8 (4975)	0.78 (83.9)	0.27 (0.11)	763	0.003	0.6	7.0 ⇒
Cummings (1995-1996)	13.2 (3500)	0.51 (54.8)	0.175 (0.07)	1133	0.0047	1.0	6.7 ⇒
Cummings (1996-1997)	6.6 (1750)	0.27 (29.5)	0.1 (0.04)	1017	0.0042	1.2	3.4 ⇒
East Dollar (1996-1997)	5.58 (1475)	1.19 (123)	0.37 (0.15)	28.5	0.001	0.2	6.8 ⇑
Sulphur (1996-1997)	22.3 (5900)	0.42 (44.9)	0.14 (0.055)	1925	0.004	1.1	6.6 ⇒
Air Injected							
Moonshine (1995-1996)	0.42 (15)	0.027 (0.5)	0.121 (0.049)	1118	0.003	1.0	3.3 ⇓
East Dollar (1994-1995)	0.42 (15)	0.17 (2.6)	0.759 (0.313)	13	0.0003	0.1	3.7 ⇒
Figure Eight (1994-1995)	4.3 (152)	0.11 (1.6)	0.235 (0.098)	2520	0.0066	0.6	4.5 ⇓
Figure Eight (1995-1996)	4.3 (152)	0.11 (1.6)	0.235 (0.098)	2700	0.0071	0.6	3.5 ⇓
Sulphur (1994-1995)	3.4 (120)	0.07 (0.95)	0.15 (0.059)	4600	0.009	1.0	5.1 ⇓
Sulphur (1995-1996)	3.4 (120)	0.07 (0.95)	0.15 (0.059)	5260	0.01	1.1	2.9 ⇒°

* Manufacturer's estimate

♦ Value measured February 7, prior to switching to air injection

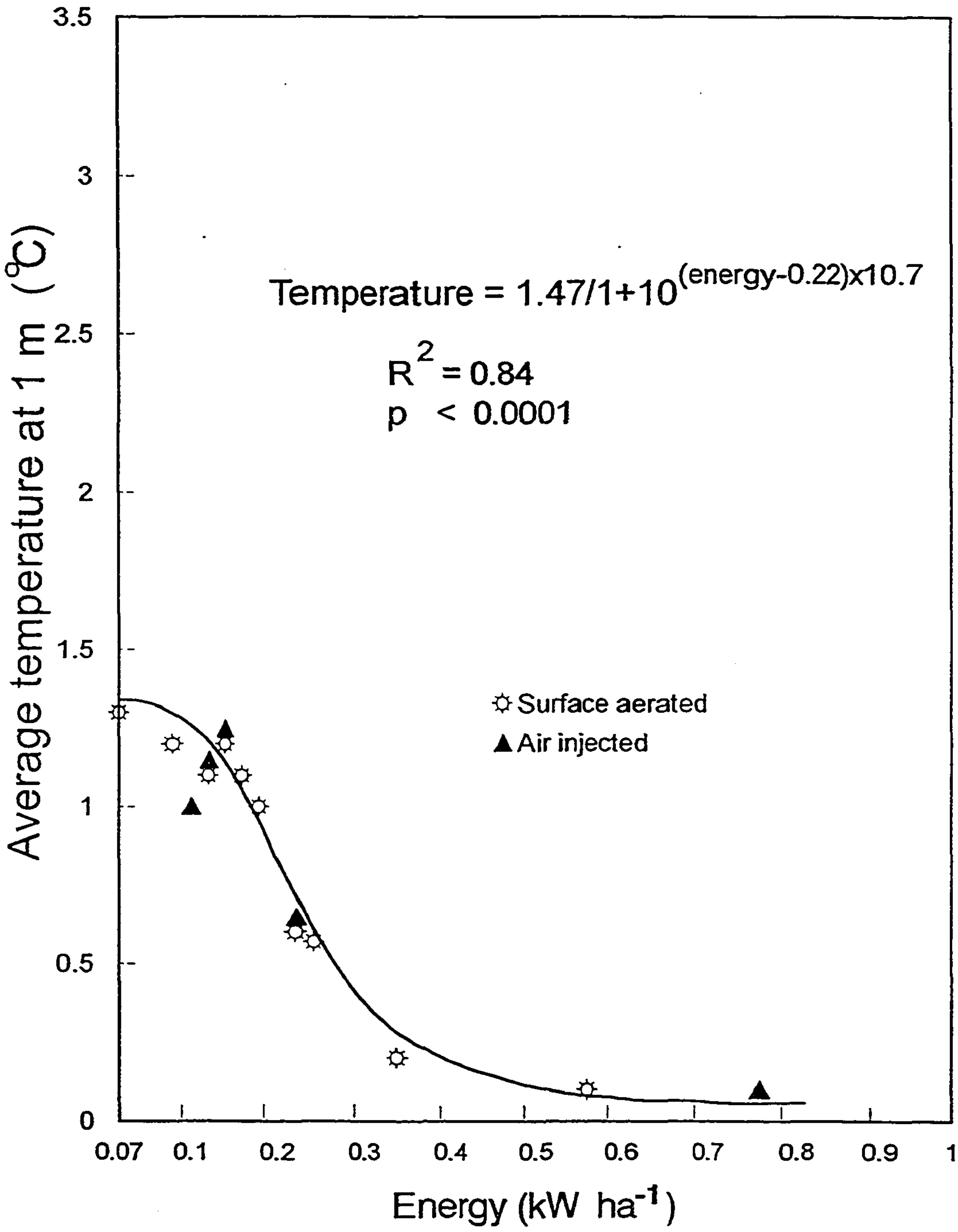

Figure 3-1. Relationship between energy use and average temperature at 1 m during January and February for both air injected and surface aerated lakes. Data from both types of aerators are included.

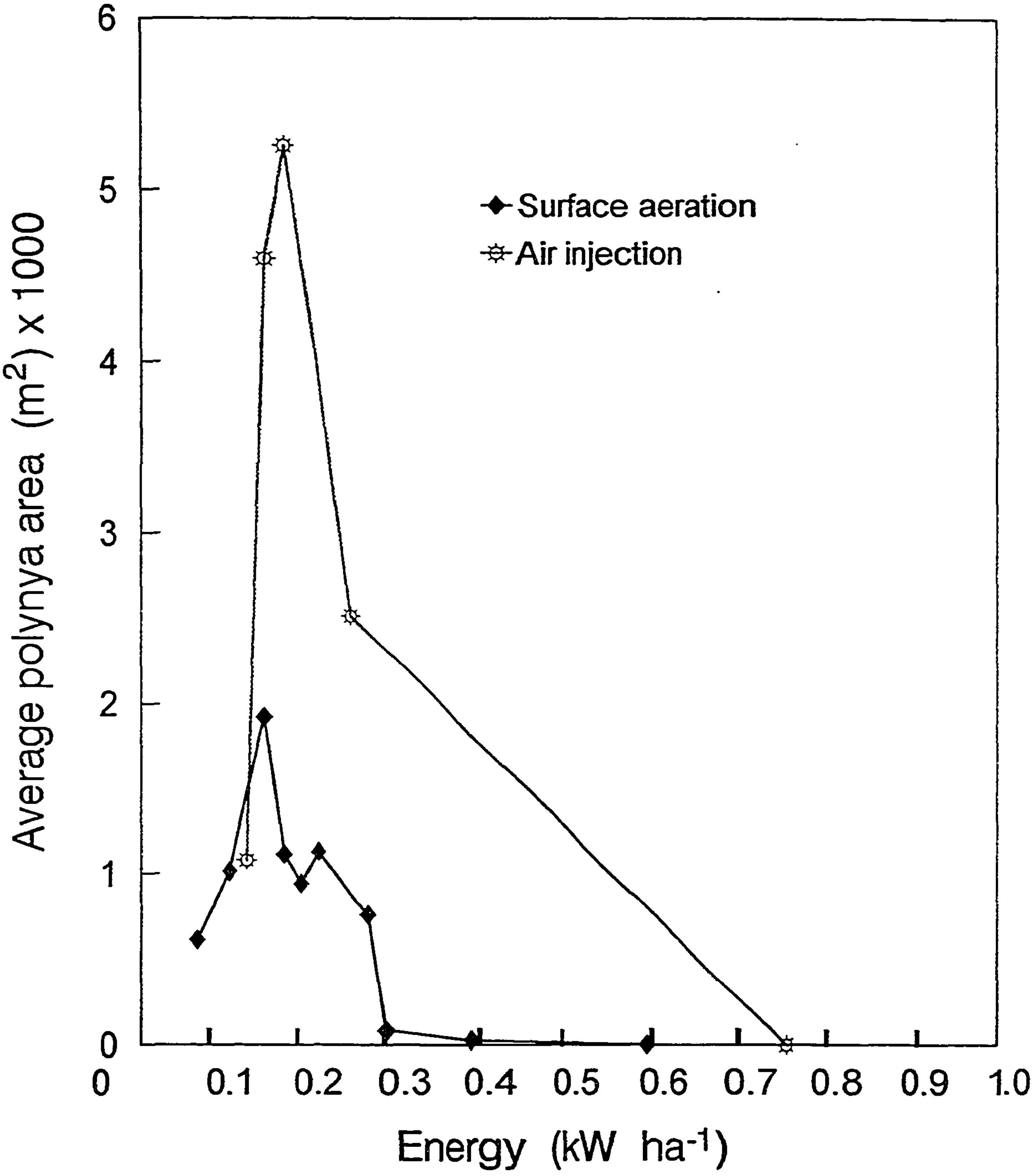

Figure 3-2. Relationship between energy use and average polynya area during January and February for both air injected and surface aerated lakes. Air injection appears to have a greater ability to maintain open water. However, configuration of aerators also influences polynya size (see text). The optimal range for either method appears to be between 0.1 and 0.3 kW ha^{-1}.

The surface aerators and diffusers in Moonshine Lake were placed in very shallow water (1.25 m). Consequently, the mixed layer included only the top 1.5 m during surface aeration. By comparison, three weeks of air injection expanded the mixed layer to include the top 2.5 m of the lake (data not shown) and the mixed layer actually began to cool. In spite of this cooling, the polynya area increased by nearly 10%. This evidence for greater mixing occurred despite the fact that the air compressor used slightly less energy than the surface aerators (0.12 kW ha^{-1} vs 0.15 kW ha^{-1}, Table 3-3). Nevertheless, DO in the mixed layer rapidly declined during this period of air injection (Table 3-3).

Relationship between power consumption and dissolved oxygen

These air injection systems with coarse bubbles only slowed rather than stopped oxygen depletion. In one instance (Sulphur Lake), DO stabilized at the dangerously low value of 2.9 mg L^{-1}. Therefore, downsizing was not possible. On the other hand, we conducted several tests with surface aerators to determine proper sizing and optimal timing for startup.

In Cummings Lake, three surface aerators (0.27 kW ha^{-1}) were used during the 1994-1995 season and started on October 10, three weeks prior to freeze-up. DO continued to decline, however, until early December, when it reached 5.6 mg L^{-1} in the mixed layer. At that time, DO began a sustained period of accretion until it reached about 7.0 mg L^{-1} (Table 3-3).

During the following year the three aerators in Cummings Lake were started nearly six weeks after freeze-up to evaluate the potential benefits of delayed start-up and observe the results of photosynthetic oxygen addition during the long snow-free period following freeze-up. In addition, the aerators were started sequentially over an interval of several days. Lake DO declined very sharply following the first snowfall and particularly following startup of the first two aerators. However, 24 hours after the second aerator was started the DO had nearly stabilized at about 4 mg L^{-1}. The third aerator was operated for ten days as a precaution. The DO immediately began to increase and this trend continued while using just two aerators (0.175 kW ha^{-1}). Six weeks later, at the end of January, the DO had stabilized at 6.7 mg L^{-1}.

I used just one aerator (0.1 kW ha^{-1}) in Cummings Lake during the last year and started it about three weeks after freeze-up, when DO was still near saturation. DO again declined when aeration was initiated. However, this decline became very slow and continued until the end of January when DO stabilized at about 3.4 mg L^{-1} in mixed layer (top 2.5 m) and 2 mg L^{-1} near the bottom.

Moonshine Lake was also downsized to one aerator during the 1996-1997 season (0.058 kW ha^{-1}). However, in this case the aerator was started approximately two weeks prior to freeze-up. As with Cummings Lake, DO slowly decreased until mid-January at which time it stabilized with most of the mixed layer containing greater than 5 mg L^{-1} (Table 3-3).

Discussion

The polynya surface has consistently been reported to be the primary avenue of oxygen transfer in lake aeration (Smith et al. 1975, Ashley 1987, Fast 1994). I found the polynya size to be highly variable, depending upon aeration method, energy use and lake and air temperature. The relationship between energy and polynya area was hyperbolic in nature (Fig. 3-2). As a result, at energy use $\geq$ 0.15 kW ha^{-1}, lake temperature was more important in dictating polynya size than energy use. For example, with 7.46 kW feeding three diffusers in Sulphur Lake (0.15 kW ha^{-1}), the lake was warmer and had a larger polynya area than where 9.35 kW and four diffusers were used in Figure Eight Lake (0.235 kW ha^{-1}). Similarly, two surface aerators used during 1994-1995 and 1995-1996 in Moonshine Lake (0.15 kW ha^{-1}) retained much more heat and resulted in a larger polynya area than three surface aerators in Cummings Lake (0.27 kW ha^{-1}). Likewise, two surface aerators in Cummings Lake (1995-1996; 0.175 kW ha^{-1}) resulted in warmer water and a much larger polynya than when three surface aerators were used during the previous year (Table 3-3). Only when reducing from two to one surface aerator, resulting in < 0.15 kW ha^{-1} (Moonshine and Cummings lakes, 1996-1997; 0.058 and 0.1 kW ha^{-1}, respectively), was the polynya area positively correlated to energy use (Fig. 3-2). This reveals a threshold of energy use, above which heat loss increases and ice-melting ability becomes less efficient. This concept is compatible with the work of Rogers et al. (1995). They found the great majority of lake cooling to be the result of conduction of heat (or cold) from ice as a result of water moving along the ice-water interface rather than heat loss through the polynya surface. The seeming contradiction occurs because only a tiny fraction of the lake surface remains ice free during winter aeration. Therefore, avenue of heat loss is greatly limited and overall lake cooling is dominated by cold transferring to the water moving along the ice-water interface. This would explain why, even as the polynya grows very small, the lake continues to cool to very low temperatures and ice thickness further increases (Chapter 2, Table 3-3).

Accordingly, the relationship between energy use and lake temperature was inversely correlated (Fig. 3-1). Lakes with lowest energy use were associated with the upper asymptote, at about 1.4°C. This temperature is similar to that in the upper strata of my unaerated control lakes (Chapter 2). The lower asymptote suggests that, although aerated lakes may become very cold at higher energy use (0.1°C), freezing of the water body is unlikely.

Overall, lakes with similar energy use ha^{-1} developed quite similar temperature regimes although within-lake comparisons for Moonshine and East Dollar lakes indicated that air injection had a tendency to cool the water body slightly more than surface aeration. In Moonshine Lake, air injection also mixed a greater portion of the water column. This occurred even though our air injection equipment used slightly less energy ha^{-1} than surface aeration (0.12 vs 0.14 kW ha^{-1} respectively). Indeed, when energy use was similar, air injection maintained larger polynya areas than surface aeration (Fig. 3-2). This was likely the result of greater velocities induced by air injection (Chapter 2, Smith 1986). Thus, greater radial velocity and impingement force on the ice surface may compensate for the slightly cooler temperature in determining the polynya size.

Never-the-less, these data suggest optimal sizing for air injection will be achieved by systems which retain about 1°C in the mixed layer. This occurred at Sulphur Lake with 0.011 SCMM ha^{-1} (0.95 SCFM $acre^{-1}$; 0.15 kW ha^{-1}). This agrees well with the recommendations of Wirth (1980) and Lorenzen and Fast (1977). Hence, an appropriate size range for coarse-bubble air injection systems is 0.15 to 0.23 kW ha^{-1}.

With surface aeration, a pump rate of about 0.51 m^3 min^{-1} ha^{-1} (55 gpm $acre^{-1}$), (Cummings Lake, 1995-1996; 0.175 kW ha^{-1}) or 0.4 m^3 min^{-1} ha^{-1} (42 gpm $acre^{-1}$), (Moonshine Lake, 1995-1996; 0.15 kW ha^{-1}), resulted in the largest polynyas. However, adequate DO was maintained using just one aerator (0.27 m^3 ha^{-1} min^{-1}; 30 gpm $acre^{-1}$); 0.1 kW ha^{-1} for Cummings Lake and 0.18 m^3 ha^{-1} min^{-1} (19 gpm $acre^{-1}$; 0.058 kW ha^{-1}) for Moonshine Lake (Table 3). These two values also represented the largest polynya area kW^{-1} and the warmest surface water using surface aeration.

Maintenance of adequate DO in Moonshine Lake while using less energy indicates that this lake is less eutrophic than Cummings Lake. This was also concluded from information obtained during previous years. Two 3.73 kW compressors did not prevent winterkill in the smaller Cummings Lake in all three years previous to this study, while one 3.65 kW compressor in Moonshine Lake was able to slow depletion rates enough to prevent winterkill. The higher energy requirement in Cummings Lake indicates that 0.1 kW ha^{-1} of surface aeration or a pump rate of 0.27 m^3 min^{-1} ha^{-1} would be the minimum requirements for such hypereutrophic lakes. Hence, an appropriate size range for surface aeration is 0.06 to 0.15 kW ha^{-1}.

The over-sizing of aeration in Thompson Pond (1.0 kW aerator; 1994-1995, 0.58 kW ha^{-1}), Cummings Lake (two 2.4 kW aerators and one 1.8 kW aerator; 1994-1995; 0.27 kW ha^{-1}) and East Dollar Lake (one 1.8 kW aerator; 1996-1997; 0.37 kW ha^{-1}), clearly shows that while the polynya area was very small, DO was higher than required. This suggests that spray volume and oxygen absorption by droplets are also important in adding DO to lakes that are surface aerated. The relative importance of spray droplets, bubbles and polynya surface area will be addressed in detail in a future report.

Except for Sulphur Lake, adequate DO concentrations were obtained using 50 to 70% less energy ha^{-1} than air injection. In Sulphur Lake, because DO was maintained quite high and had actually began to increase before three aerators were shut down (i.e. > 6.6 mg L^{-1}), aeration could be downsized to three surface aerators. This would provide a similar amount of energy savings.

Lakes up to 130 ha have successfully been aerated (seven 1.8 kW aerators; 0.1 kW ha^{-1}) using these estimates. However, the extent of the aerated cell appears to only reach a radius of 600 to 900 m before DO begins to diminish (Chapter 2). Therefore, aerating larger lakes may result in a certain proportion that is not receiving sufficient DO. Additionally, it was determined that beds of macrophytes may impede the distribution of aerated water and significantly restrict the size of the aerated cell. Macrophyte-dominated lakes may also experience greater oxygen depletion rates and hence require more aeration than phytoplankton-dominated lakes.

Finally, close monitoring of the these aeration systems revealed a greatly enhanced oxygen depletion rate at the beginning of winter, and particularly following aeration start up (approximately 4-fold). Similar or even greater increases were observed by Lackey and Holmes (1972), Smith et al. (1975), Bandow (1986) and Ashley (1987). Accurately predicting and satisfying this accelerated oxygen demand will be the limiting factor in refining techniques for sizing aeration equipment. Consequently, it is suggested that systems be initially sized toward the higher end of these ranges and started before or near the time of freeze up rather than waiting until DO has fallen to more critical levels.

References

Ashley, K. I. 1987. Artificial circulation in British Columbia: Review and evaluation. B.C. Fisheries Branch Technical Circular No. 78, 34 pp.

Bandow, F. 1986. Evaluation of winter lake aeration techniques in Minnesota. Minnesota Dept. Nat. Resources, Div. of Fish and Wildlife. Sect. Fish. Invest. Report No. 386. 48 pp.

Carpenter, J. H. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr. 10:141-143.

Fast, A. W. 1994. Winterkill prevention in lakes and ponds using artificial aeration. Rev. in Fish. Sci. 2: 23-77.

Lorenzen, M. W. and A. W. Fast. 1977. A guide to aeration/circulation techniques for lake management. Ecological Res. Series, EPA-600/3-77-004. (Jan.) Washington, D.C.: U.S. Environmental Protection Agency.

Lackey, R. T. and D. W. Holmes. 1972. Evaluation of two methods of aeration to prevent winterkill. Prog. Fish Cult. 34: 175-178.

Miller, T. G., W. C. Mackay and D. T. Walty. Under ice water movements induced by mechanical surface aeration and air injection. Lake and Reserv. Manage. 2001;17(4):263-87.

Neilson, B. J. 1974. Reaeration dynamics of reservoir destratification. J. Am. Water Works Assoc. 66: 617-620.

Patriarche, M.. H.. 1961. Air-induced circulation of two shallow Michigan lakes. J. Wildl.

Manage. 25(3): 282-289.

Rogers, C. K. 1992. Impact of an artificial circulation device on the heat budget of an ice-covered mid-latitude lake. M..Sc. Thesis. University of British Columbia. 173 p.

Rogers, C. K., G. A. Lawrence and P. F. Hamblin. 1995. Observations and numerical simulation of a shallow ice-covered mid-latitude lake. Limnol. Oceanogr. 40(2): 374-385.

Schwalme, K. 1994. A review of winterkill remediation techniques for Alberta. AECV94-R7. Vegriville, AB. 84 p.

Smith, S. A., D. R. Knauer and T. L. Wirst. 1975. Aeration as a lake management technique. Wisc. Dept. Nat. Res. Tech. Bull. 87. 39 pp.

Smith, D. W. 1986. Aeration system design protocols: a North American perspective. pp. 85-100. *In*: Boyle W.C. (ed.) Aeration systems. Design, testing, operation and control. Pollution technical review No. 127. Noyes Publications. Park Ridge, NJ.

Wirth, T. 1988. Lake aeration in Wisconsin lakes. Wisconsin Dept. of Nat. Res. Publ-WR-196. 76 p.

Chapter 4

Efficiency and Effect on Lake Metabolism of Air Injection and Surface Mechanical Aeration

Introduction

Aeration efficiency in winter lake aeration projects has never been empirically determined. Similarly, although enhanced oxygen (O_2) demand at the onset of aeration has been reported (e.g., Patriarche 1961, Smith et al. 1975, Miller et al. 2001), quantification of this demand in association with aeration efficiency has never been performed.

Most (perhaps 80%) of lake aeration projects involve some means of compressed air injection while most of the remainder use some type of surface aeration (Halsey and MacDonald 1971, Johnson and Skrypek 1975, Bandow 1986, Wirth 1988).

This preference may be linked to the fact that air injection is a more efficient "pump" than mechanical surface aerators in circulating wastewater treatment tanks as well as lakes (Doyle and Boyle 1986, Smith 1986, Miller et al. 2001). However, vastly different operating principles exist between aerating wastewater treatment tanks and ice-covered lakes. For example, reaeration coefficients (k_2 or K_La), which are used to compare the efficiency of various aeration devices are determined in open tanks or ponds (e.g. Barnhardt 1986, WPCF 1988). Using this protocol, the entire water body surface is involved in the aeration process and rapid circulation to elevate benthic water to the surface and promote rapid surface boundary layer reformation would be advantageous.

Perhaps the greatest difference between tank aeration and lake aeration is the amount of energy applied per surface area (i.e., kW ha^{-1}). Energy used in treatment tanks may be orders of magnitude greater than that used in lake aeration. Resultant pumping rates in tank aeration are often several volumes per minute, while those for winter lake aeration are on the order of one volume per several hours or even days (see Chapter 2). Consequently, the polynya is restricted to the immediate area surrounding the aeration device and may comprise only 0.0003 of the lake surface for either aeration system (Miller et al. 2001). Consequently, once the pumped water has passed under the ice, no additional gas transfer can occur. In essence, much of the benefit of turbulence or velocity is wasted, except for the possibility of water returning to the aeration device and polynya surface more frequently.

Further, water movement under the ice has often been a greater detriment than benefit by enhancing O_2 depletion rates to values greater than O_2 addition from the aeration process; (e.g., Fast 1994). Mathias and Barica (1980) estimated that nearly 90% of oxygen depletion is the result of sediment O_2 demand. They reported that O_2 depletion rates become limited by DO values less than 3 mg L^{-1}. However, experimental circulation of water over sediments increases O_2 consumption and reduces the threshold of O_2 limitation to approximately 1 mg L^{-1} (Belanger 1981, Boynton et al.1981, Campbell and Rigler 1986). This is likely accomplished by reducing the thickness of the diffusive boundary layer at the sediment-water interface (Boudreau and Buinasso 1982, Jørgensen and Revsbech 1985). This principle is the likely cause of the enhanced O_2 consumption often reported in aerated lakes (Smith et al. 1985, Ashley 1983, Lackey and Holmes 1972, Ellis and Stefan 1989, Chapter 2).

Finally, the majority of O_2 transfer is believed to be through the polynya surface rather than from bubbles (Smith et al. 1975, Fast 1994, Neilson 1974), or from spray droplets (Ashley 1987, Wirth 1988). However, because polynya surface areas are only a tiny fraction of the total lake surface, O_2 addition from bubbles or across spray droplet surfaces could be a significant contribution to the aeration process.

Hence, the most important factors influencing the success of winter lake aeration are: 1) the O_2 transfer efficiency of the devices themselves; 2) turbulence characteristics of the polynya surface; 3) the size of the polynya; and 4) the O_2 depletion rate and particularly in response to the aeration process.

In this study I tested the hypothesis that, because of different mechanisms of O_2 transfer, surface aeration is more efficient in total O_2 transfer in winter lake aeration than point release air injection. To test this hypothesis, I developed a mass-balance model of O_2 dynamics for winter lake aeration for each aeration method.

Methods and Materials

Study lakes

East Dollar Lake was the primary lake used for this comparison. It is a small (4.9 ha), relatively deep (z_{max} = 8.25 m), single-basined lake (Fig. 2-2). Some additional comparisons were made using Moonshine Lake, a larger (30.8 ha), but shallower lake (z_{max} = 4.2 m) lake (Fig. 2-3). In East Dollar Lake, the diffuser and surface aerator could be operated in the deepest portion of the basin (8.25 m) and at the mean depth (4 m).

Moonshine Lake was chosen to compare aeration efficiency using shallow placement of the aerators and diffusers. Both devices were operated in only 1.25 m of water. Based on the temperature stratification and the results of the dye studies (Chapter 3), I estimated that 60% of the sediment surface was isolated from the circulated portion of the water column.

Aeration methods

Air injection for both East Dollar and Moonshine lakes was accomplished using a 3.75 kW, Gast rotary vane compressor, Model 5565 - P 104: Free air delivery of 0.43 m^3 min^{-1} (15 SCFM) at 102 kPa (15 PSI) (manufacturer's estimate). Actual flow measurements were performed at various diffuser depths and pressure settings of the compressor using an American Meter Company model AL-1000 gas flow meter, Horsham, Pennsylvania.

Surface aerators (Air-O-Lator®, Kansas City, MO) were operated according to specification but without draft tubes. Manufacturer specifications were 8.2 amps @ 230 V for the 1-hp aerator and 10.5 amps @ 230 V for the 2-hp aerator. These values were used to calculate kW applied to the lake.

The aeration schedule for East Dollar Lake for all three test winters is summarized in Table 4-1. Both types of aerators were operated in deep (8.25 m) and in shallow (4 m) water. This was accomplished by varying the length of the diffuser anchor line and by alternatively anchoring the surface aerator in deep vs shallow (4 m) water. The air compressor delivered air approximately 80 m to a single diffuser located at the center of

Table 4-1. Aeration schedule at East Dollar Lake during the three study years.

		Period of Operation					
Year	Aeration Method	November	December	January	February	March	April
94-95	Air injection	———	———	———	———	———	———
	Surface aeration						
95-96	Air injection			———	———		
	Surface aeration	———	———		*****□□	———	———
96-97	Air injection				+++++++	OOOOOOOO	
	surface aeration	———	———	———	———		

*** Surface aerator operated submersed and fitted with a deflecting device to prevent formation of a polynya.
□□ Surface aerator operated submersed with deflector device removed to allow polynya formation.
++ medium-bubble diffuser operated at 4 m depth.
oo medium-bubble diffuser operated at 8 m depth.

the basin. During the 1994-1995 and 1995-1996 winters a cross-pipe, coarse bubble (bubble diameter = 20-40 mm) diffuser (Fig. 2-10) was used in the middle of the basin. This diffuser was operated continually throughout the winter except for a six-week period during January and February. During the second and third seasons, air injection was alternated with the operation of one 1.8 kW (1 hp) surface aerator to provide a side-by-side comparison. This included the use of the coarse-bubble diffuser during the second winter and two medium-bubble (mean bubble diameter = 5 mm) diffusers (obtained from Envirodynamics, Kansas City, MO) during the third winter. I connected the diffusers together (Fig. 2-10), which created a single bubble plume.

In addition, an exercise was performed to quantify the dynamic nature of oxygen depletion during aeration. To accomplish this, the surface aerator was suspended 0.5 m below the surface and fitted with a 1.3 m x 1.3 m sheet of plywood to deflect pumped water laterally and prevent it from reaching the surface. Operation in this fashion caused the lake to circulate but without forming a polynya.

In addition, shallow aeration was employed in East Dollar Lake during the 1996 to 1997 season. The surface aerator was anchored closer to the shoreline over 4 m of water. The diffusers were initially set at 4 m deep and operated in this manner for two weeks (Table 4-1). At that time, the diffusers were lowered and operated at 8 m.

In Moonshine Lake, the two surface aerators were operated during the first season (Table 4-2). During the second season, I alternated surface aeration with air injection using two coarse-bubble diffusers (Fig. 2-10). The surface aerators and coarse-bubble diffusers were placed about 50 m apart and located approximately 75 m from the eastern shore. Compressed air was fed to the diffusers via a 50 mm (I.D.) hose, fitted with a T coupler to split the flow to two 19 mm (I.D.) hoses. Each of these hoses extended 15 m in

Table 4-2. Operation schedule at Moonshine Lake during all three study years.

		Period of Operation					
Year	Aeration Method	November	December	January	February	March	April
94-95	Air injection	—	—				
	Surface aeration	————	□□□□□□□	□□□ ————	————	————	
95-96	Air injection	—	—		————		
	Surface aeration		————	————		————	————
96-97	Air injection						—
	Surface aeration	————	————	————	————	————	————

□□□□ Surface aerator operated while submersed, maintaining a polynya, but without creating spray.

order to separate the diffusers by approximately 30 m. During the 1996-1997 winter, only the 1.8 kW surface aerator was operated for the entire winter.

Development of the model

A simple mass balance model was used to compare aeration efficiencies. The basic equation is:

$$dM_{DO}/dt = (dM/dt)_{b\,(or\,d)} + (dM/dt)_p - (dM/dt)_r \qquad (1)$$

where M = mass of lake DO, b = O_2 addition from bubbles, d = O_2 addition from droplets, p = O_2 addition through polynya surface and r = lake respiration.

Lake DO mass

Whole-lake DO was determined by multiplying the DO concentration at each 1-m depth by the volume of that stratum. The masses were summed to determine total lake DO mass. Samples collected at approximately 100 mm above the bottom were used to estimate DO mass in the bottom 1 m stratum and hence incorporated sediment O_2 demand into water column O_2 demand over successive sampling intervals. These samples were collected using a 1.2 L Kemmerer bottle, stored and fixed in 60 mL BOD bottles in the field and analyzed later that evening using Carpenter's (1965) modification of the Winkler method. Approximately 10% of samples were duplicated (split samples from the Kemmerer bottle) to determine analytical variability. Most duplicates were within 0.05 mg L^{-1} (mean difference of 150 randomly selected duplicates = 0.038 mg L^{-1}; S.D. = 0.006). The majority of exceptions to this were samples collected near the sediment surface where it was suspected that the sharp vertical DO gradient was preserved within the Kemmerer bottle.

Oxygen absorption from bubbles

Off-gas measurements were performed during the third winter. The O_2 transfer efficiency was determined by measuring off-gas O_2 content after the bubbles reached the surface. A collection device was assembled by drilling a hole through the bottom of a 2 L plastic beaker and sealing a 12.7 mm x 6.4 mm (0.5 in. x 0.25 in.) teflon coupler in the hole. The teflon coupler was then sealed with a silicon plug. This beaker was immersed in the lake, inverted and positioned over the bubble plum. After about 1 L of gas accumulated in the head space, a sample was withdrawn into a 60 mL syringe. This sample was then injected into an FEP gas bag (Chemware Laboratory Products). Three individual samples were collected and pooled into one gas bag and triplicate gas bags were used for each sampling run. Off-gas samples were also collected from the medium bubble diffuser anchored at 4 and 8 m depths. In order to estimate gas transfer from a coarse bubble diffuser anchored at 8 m deep, samples were collected from a coarse-bubble diffuser anchored at 4.5 m (obtained from the aeration system at nearby Figure Eight Lake). This value was increased by 60% (the approximate difference in O_2 absorption between 4 m and 8 m for the medium bubble diffuser), to estimate the amount diffusing out of coarse bubbles released at 8 m. On one occasion, triplicate samples of ambient air were collected above East Dollar Lake as a control. The FEP bags were transported to the University of Alberta Limnology Laboratory and analyzed on a Perkin

Elmer model 5890 II Gas Chromatograph fitted with a 1 m Supelco 60 mole./sieve 5A column. Three samples from each FEP bag were injected into the GC.

Air flow through the diffusers was 0.42 $m^3 min^{-1}$ @ 95.2 kPa (15 SCFM @14 PSI) when the diffusers were set at 4 m and 5 m and 0.35 $m^3 min^{-1}$ @ 102 kPa (12.5 SCFM @ 15 PSI) when the diffuser was set at 8 m. Total O_2 transferred day^{-1} was determined (e.g. as follows):

424.8 L min^{-1} x 20.95% O_2	=	89 L O_2 min^{-1}
÷ 22.4 L O_2 $mole^{-1}$	=	3.97 moles O_2 min^{-1}
	=	127 g O_2 min^{-1}
x 2.28% absorption	=	2.89 g O_2 min^{-1}
	=	1.3 kg O_2 d^{-1}

Oxygen transfer efficiency was determined using the equation (Ewing 1986):

$$OTE = (MR_{O/N} \text{ injected} - MR_{O/N} \text{ off gas}) / MR_{O/N} \text{ injected} \quad (2)$$

where MR = molecular ratio. Hence, the ratio of O_2/N_2 in the ambient air vs the O_2/N_2 in the off gas was used to determine the amount of O_2 transferred from the bubbles to the water.

Oxygen absorption by spray droplets

Spray droplets were collected from a 1.8 kW and a 2.4 kW surface aerator several times over the three study years. A collection device was assembled in the same fashion as for the gas samples. The only difference was that the teflon connector was fitted with a short piece of flexible tygon tubing and a clamp. The device was positioned to receive the droplets at the lake surface. After about 300 mL were collected the sample was drained into a 60 mL BOD bottle. Approximately two volumes were flushed through the BOD bottle before the sample was capped and samples were fixed in the field and analyzed using Carpenter's (1965) method. These samples were collected in duplicate. Total oxygen transferred to the droplets was determined by the equation:

$$\text{oxygen transferred} = \text{droplet DO} - \text{lake DO} \times \text{volume sprayed}/\ t_2 - t_1 \qquad (3)$$

Oxygen absorption through the polynya surface

Research on the oxygen transfer efficiency of artificial aeration has lead to development of the term K_La or k_2. This term, known as the overall transfer coefficient, is described by the equation:

$$dc/dt = k_2(c_s\text{-}c), \qquad (4)$$

where, c is the measured concentration of DO (mg L^{-1}), c_s is the DO saturation value at a given temperature, t is time and k_2 is the overall coefficient of re-aeration or overall mass transfer coefficient time^{-1}. The subscript 2 denotes this value as the second coefficient in the Streeter and Phelps (1925) formulation for the deoxygenation (k_1) and reaeration (k_2)

of polluted streams. In the case of artificial aeration, the term K_La is generally used, where K_L is the surface (liquid film) transfer coefficient (used here in units of m day^{-1}) and the term a is an abbreviation for the term A/V where A = surface area of the body of water and V = volume. Boyle (1979) proposed a standardized method of comparing oxygen transfer efficiency of aeration devices in tank or pond systems through solving the differential equation, $dc/dt = K_La(c_s - c)$ for K_La,

$$K_La = \frac{ln(c_s - c_1) - ln(c_s - c_2)}{t_2 - t_1} \quad (5)$$

Where c_1 = dissolved oxygen concentration at time, t_1 and c_2 = dissolved oxygen concentration at time, t_2. Hence, values for K_La provide a direct comparison of aeration efficiency among various devices.

More recently, DeMoyer et al. (2001) modified this equation as $dc/dt = K_LA(c_s - c)$, where K_LA is defined as m^3 s^{-1}. This allows comparison of data from tanks having different volumes. However, application of K_La or K_LA is only appropriate where the entire surface area and volume of the water body are involved in the aeration process, such as tanks or small ponds. Winter aeration involves most of the entire lake volume (to the depth underlying the aeration device). However, only a very small proportion of the lake surface remains ice-free and open to the atmosphere. Hence, use of K_La or K_LA are not appropriate for winter lake aeration studies.

Therefore, I used the surface transfer coefficient, K_L for the polynya surface. The mass transfer rate for a lake surface has been defined as (Holley 1977):

$$F_s = K_L(c_s - c)A_s \tag{6}$$

Where F_s = flux of oxygen across the surface and A_s = the surface area of the lake. I defined A_s as the polynya area. This equation is used to determine $(dM/dt)_p$ in equation (1). A "baseline" K_L for the polynya surface (not including the secondary effects of bubbles bursting or droplet splashing) was determined by the empirical equation developed by Fang and Stephan (1994):

$$K_L = 0.02256[0.10656\, e^{(0.0627T)} + 0.06495]^{-0.5}\, U_{10}^{1.64} \tag{7}$$

where K_L is in m d^{-1}, T = °K and U_{10} = wind velocity (m s^{-1}) measured at 10 m above the lake surface. Mean daily wind velocity was obtained from Environment Canada which was measured at the Grand Prairie airport, approximately 50 km away from the study lakes. These values were averaged over the sampling interval.

I also accounted for the combined effect of water velocity and wind on K_L. Mattingly (1977) found that wind speed greatly enhanced K_La and particularly at low water velocities. For example, at water velocities of 0 to 45 mm s^{-1} increasing the wind velocity from 0 to 3.75 m s^{-1} increased K_La by 5 fold (from 0.1 to 0.5 hr^{-1}). However, at higher water velocities (90 and 180 mm s^{-1}), the influence of wind was less dramatic, increasing K_La by 30 to 50%. Because the velocity of the polynya surface encompassed the entire range of those reported by Mattingly (1977), the value calculated from Fang and Stefan (1994) was doubled when used into the mass balance equation to more accurately reflect the combined effect of water and wind velocity on K_L.

Measurements of oxygen depletion rates and $(dM/dt)_d$ made it possible to solve equation (1) for $(dM/dt)_p$. It was important to accurately measure oxygen depletion rates and its variability following aeration start up. In East Dollar Lake, this was accomplished by submersing the surface aerator approximately 0.5 m to prevent spray and affixing a 1.3 m^2 piece of plywood to the deflecting cone to prevent the propelled water from reaching the surface and melting the ice. Operation in this fashion provided mixing, but without an open water surface. Changes in DO content were also measured throughout the first few days of air injection, during which the polynya ranged from 0 to about 3 m in diameter. These measurements of O_2 depletion rates and $(dM/dt)_{b \text{ or } d}$ made it possible to solve equation (1) for $(dM/dt)_p$. In turn, this value for polynya O_2 flux was used in equation (6) to determine polynya K_L values and compare these values between the two aeration methods and for different polynya sizes.

Results

Parameter values for East Dollar Lake

Oxygen depletion rates

During the first season, the compressor was started on October 14, two weeks prior to freeze up and operated continually for about three months. During the period when the compressor was shut down (January 10 to February 27), the depletion rate was quite constant and averaged 13.9 kg O_2 $lake^{-1}$ d^{-1} (Table 4-3). Restarting the compressor

Table 4-3. Values for parameters used to compare aeration efficiency of air injection vs surface sprayers in East Dollar Lake. One diffuser was used for coarse bubble diffusion Two diffusers were combined to create one medium bubble plume. Estimates for depletion rate were from: (1) measurements of depletion immediately after startup of compressor (while the polynya was < 1.5 m diam.) and following six weeks of natural depletion (January 13 to February 27, 1995); and (2) circulation of the lake while the surface aerator was submersed and modified to prevent polynya formation (February 26 to March 3, 1996).

Period	Depletion ($kg\ d^{-1}$)	dM_{DO}/dt ($kg\ d^{-1}$)	DO added ($kg\ d^{-1}$)			Polynya area (m^2)	K_L ($m\ d^{-1}$)
			bubbles	droplets	polynya		
			(1994-1995)				
D11-J13	25.0	-9.3	1.3	-	14.4	347	6.4
"	-	-	-	-	7.6	"	3.6#
J13-F27	13.9##	-13.9	-	-	-	-	-
F27-F28	39.5	-38.2	1.3	-	-	-	-
F28-M8	17.5	-3.1	1.3	-	12.1	113	11.6
"	"	"	"	-	3.2	113	3.4#
			(1995-1996)				
N11-N24	37.2##	-37.2	-	-	-	-	-
N24-N25	149.6	-117.9	-	24.7	7.0	50	19.2
N25-N26	81.5	+5.2	-	24.2	62.5	491	15.1
N26-D27	53.0	+4.4	-	22.6	34.7	1520	2.8
D27-D30	37.1	+15.6	-	20.1	32.6	1256	3.3
D30-J10	29.8	-2.6	1.4	-	25.8	706	4.4
F22-F26##	19.4##	-19.4	-	-	-	-	-
F26-F27	68.6	-68.6	-	-	-	-	-
F27-F28	38.1	-38.1	-	-	-	-	-
F28-F29	32.4	-32.4	-	-	-	-	
F29-M3	21.5	-21.5	-	-	-	-	-
M3-M9	19.0	-20.9	-	33.9	6.0	28	20.2
"	-	-	-	-	1.0	"	3.4#
M9-M29	17.5	+23.0	-	24.2	16.3	378	6.6
"	"	"	-	"	10.1	"	3.3#
			(1996-1997) Shallow circulation				
N15-N20##	35.4	-35.4	-	-	-	-	-
N20-D4	59.8+26.8*	-28.9	-	32.2	25.5	803	3.7
D4-D19	45.0+3.0*	+12.6	-	30.2	30.4	615	5.1
D19-J8	30.0	+13.4	-	23.4	20.0	178	13.9
J8-J23	25.0	+6.3	-	21.2	11.1	79	17.2
J23-F4	21.5	+7.2	-	20.2	8.5	39	28.3
F4-F13	20.5	+5.1	-	20.2	5.4	28	25.0
			Whole lake circulation				
F19-M5	34.9**	-24.4	3.0	-	9.7	64	15.9
"	20.5+26.8*	-24.4	3.0	-	19.9	"	32.8
M5-M14	17.5	+2.6	4.8	-	15.3	64	24.5
"	"	"	"	-	1.9	"	3.2#

2x the Polynya oxygen transfer estimated according to Fang and Stefan (1994).

Natural depletion rate.

* 26.8 kg day^{-1} was added to depletion rate at the initiation of aeration to account for estimated rate of CH_4 oxidation. This rate was reduced to 3 kg day^{-1} after 2 weeks of aeration when CH_4 in the mixed layer fell to 3 $\mu M\ L^{-1}$ (see Chapter 5).

** Volume weighted oxygen depletion rate based on 83% of volume (top 5 m) having been circulated and hence experiencing minimal depletion ($0.07\ g{\cdot}m^{3}{\cdot}day^{-1}$) and 17% (bottom 3 m) being circulated for the first time that winter and hence experiencing maximal depletion ($0.69\ g\ m^{-3}\ day^{-1}$).

increased the depletion rate by three-fold (39.5 kg O_2 lake^{-1} d^{-1}). However, because of the growing polynya it became increasingly difficult to isolate O_2 depletion from addition through the polynya surface. Aeration was interrupted for a similar time period during the following year. Restarting the surface aerator beneath the ice prevented formation of a polynya and allowed direct measurement of the circulating O_2 depletion rate for several successive days. The depletion rate in this case initially increased by a factor of 3.5 (from 19.4 to 68.6 kg DO lake^{-1} d^{-1}; Table 4-3, February 26, 1996), a similar increase as that induced by the onset of air injection during the same period of previous winter (Table 4-3). However, after eight days of operation, the O_2 depletion rate had fallen back to pre-circulation values (Fig. 4-1, Table 4-3).

This model was adjusted to describe the operation of both air injection and surface aeration earlier in the season (Table 4-3). The y intercept was adjusted upward to account for greater early-season O_2 depletion rates and the slope was slightly decreased to account for a longer period of declining O_2 depletion rate at that earlier time of winter. In addition, a relatively high K_L value (19.5 m d^{-1}) was used to calculate the initial O_2 transfer through the small, turbulent polynya (see below). The sum of this value and the droplet O_2 contribution was added to the measured loss in lake DO to estimate the total circulation depletion rate of 149.6 kg DO lake^{-1} d^{-1} (Table 4-3; November 24 and 25, 1995). O_2 depletion during the second day of aeration was calculated as the same percentage of reduction as that during the second day of experimental circulation with the submersed aerator (Feb. 27 to Feb. 28, 1996; Table 3). This power regression model, 123.5 x day of aeration$^{-0.40}$, was then used to calculate early-season O_2 depletion values for all

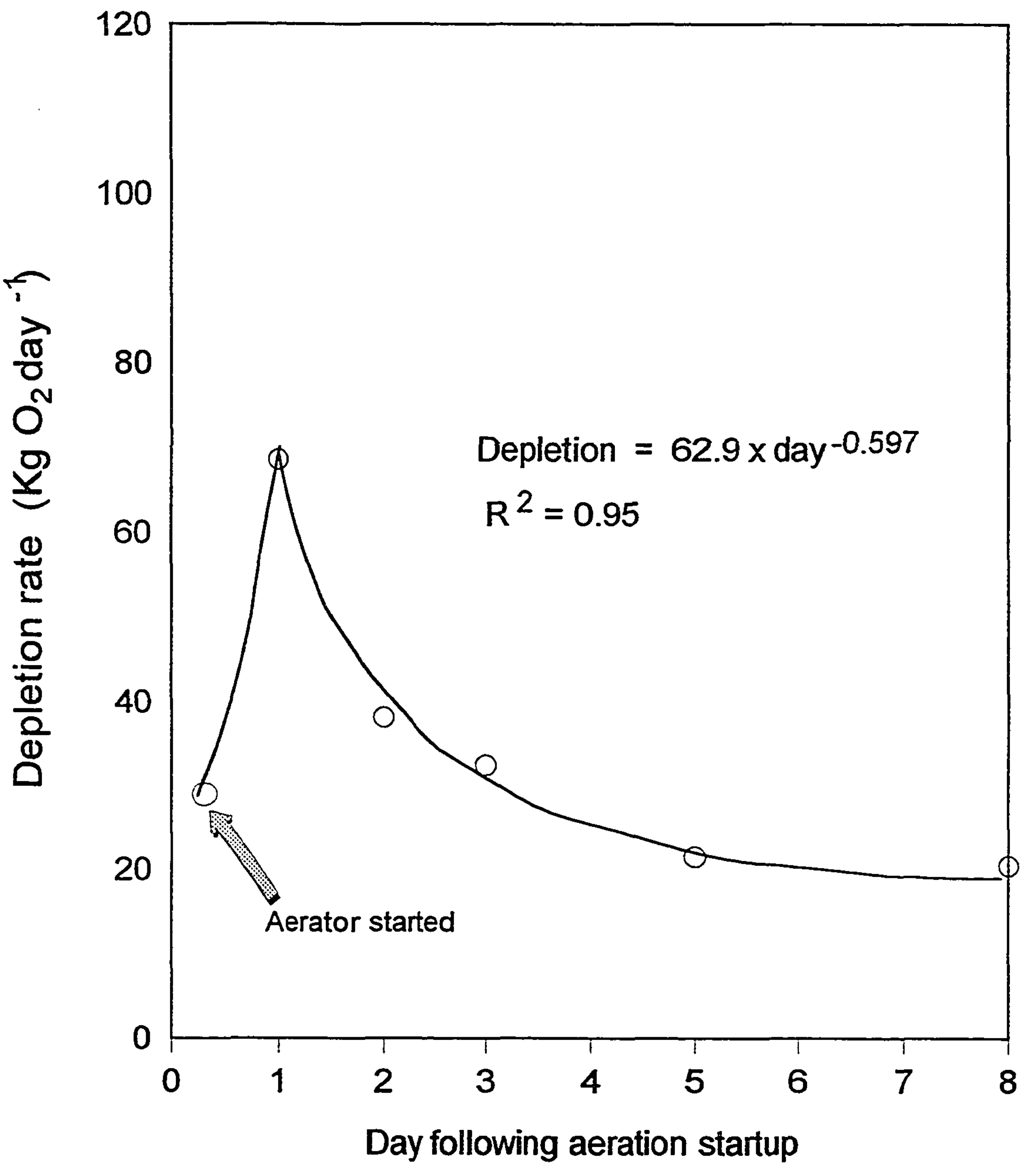

Figure 4-1. Response of oxygen depletion rate to the onset of circulation in East Dollar Lake. Circulation was accomplished using a submersed and modified surface aerator which prevented formation of a polynya. This allowed measurement of depletion without interference of oxygenation from the aerator or atmosphere (see text for details). These values are used in the mass balance model described in Table 4.3.

three winters for East Dollar Lake (Table 4-3).

Oxygen transfer through the polynya

Isolation of polynya flux using the mass-balance equation and inserting into equation (6) allowed for successive calculations of K_L throughout the aeration season and for different polynya sizes. These equations predict a wide range of K_L values. However, regressing these values against polynya surface area revealed that these K_L values had a strong correlation with the inverse of the polynya area (Fig. 4-2).

For comparison, K_L values for natural lake surfaces (Equation 7; and multiplied by 2) are included in Table 4-3. K_L values ranged from 3.4 to 3.6 m d^{-1}, depending on wind velocity. For example, with a moderately-sized polynya of 347 m^2 (December 11, 1994 to January 13, 1995), the Fang and Stephan model (multiplied by 2) predicts a K_L of 3.6 m d^{-1}. Using this K_L value in equation (6) resulted in an estimated polynya oxygen flux of only 7.6 kg DO d^{-1}, about 50% of the value which satisfies the mass-balance equation (Table 4-3). Using the same procedure for the period of February 28 to March 8, when a smaller polynya existed, an even larger disparity occurred between these methods. Surface aeration from March 3 to March 9 and March 9 to March 29 provided a similar comparison between two polynya sizes. In short, even doubling the K_L value obtained using Fang and Stephan's model could not account for the high polynya O_2 transfer as shown to be occurring by the mass-balance equation. However, where very large polynya areas existed (November 26 to December 30, 1995), results from the Fang and Stephan equation more closely approximated the K_L obtained from quantitative

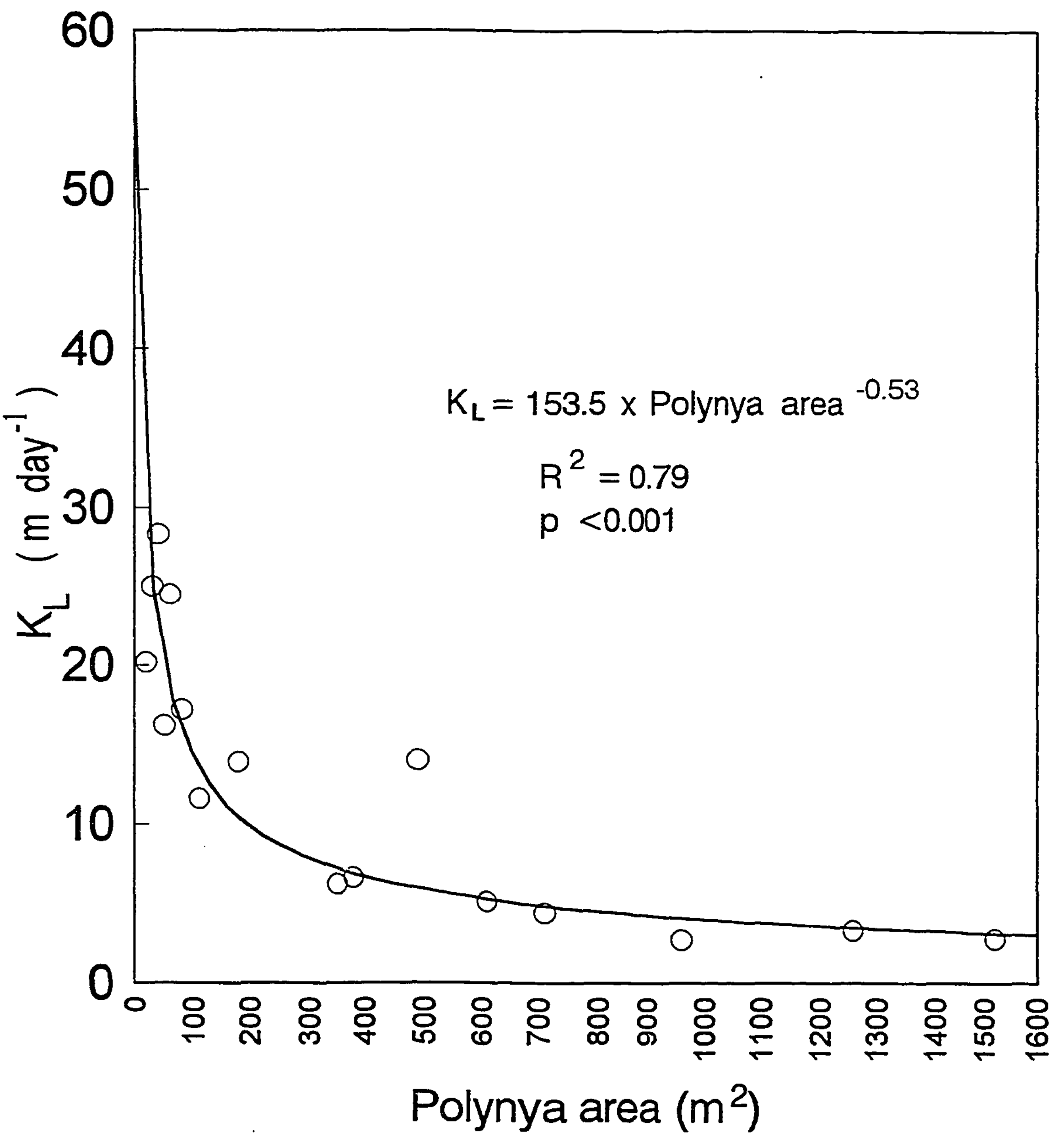

Figure 4-2. The relationship between surface transfer coefficient (K_L) and the polynya surface area for East Dollar Lake. Data from all three study years and both surface aeration and air injection are included.

measurements (Table 4-3).

Oxygen transfer via droplets and bubbles

Oxygen absorption by droplets was measured several times to include a wide range of ambient lake DO concentrations. The resultant regression equation (Fig. 4-3) was used to estimate droplet O_2 absorption for each sampling event and mass-balance calculation. Values ranged from 20.2 to 33.9 kg DO aerator^{-1} lake^{-1} d^{-1}, an increase of 35 to 60% above ambient lake DO. In addition because $(dM/dt)_d$ in equation (6) was measured, equation (6) could be solved for the actual K_L values for the droplet surfaces. Total instantaneous droplet surface area was estimated to be 60 m^2. Droplet K_L values throughout the range of lake DO values ranged from 19.2 to 23.1 m d^{-1}. This relatively uniform K_L throughout the range of lake DO values suggests that the relationship expressed in Fig. 4-3 is quite accurate.

A similar range in ambient lake DO did not occur during air injection. Instead, DO was 3.8 and 4.1 mg L^{-1} during the two times that coarse bubbles were collected from the Figure Eight Lake diffusers and 4.1 and 4.3 mg L^{-1} during the two times that medium-sized bubbles were collected in East Dollar Lake. Yet, even with this favorable gradient, comparatively small amounts of DO were absorbed from the bubbles. Coarse bubbles imparted 0.9 kg O_2 d^{-1} (0.5% transfer efficiency) when the diffuser was set at 4.5 m and an estimated 1.4 kg O_2 d^{-1} (0.8% transfer efficiency) if the diffuser was to be set at 8 m. The medium-bubble diffuser was more efficient. While set at 4 m, it added 3 kg DO d^{-1} (transfer efficiency of 1.7%). When reset at 8 m, it added 4.8 kg DO d^{-1} (transfer

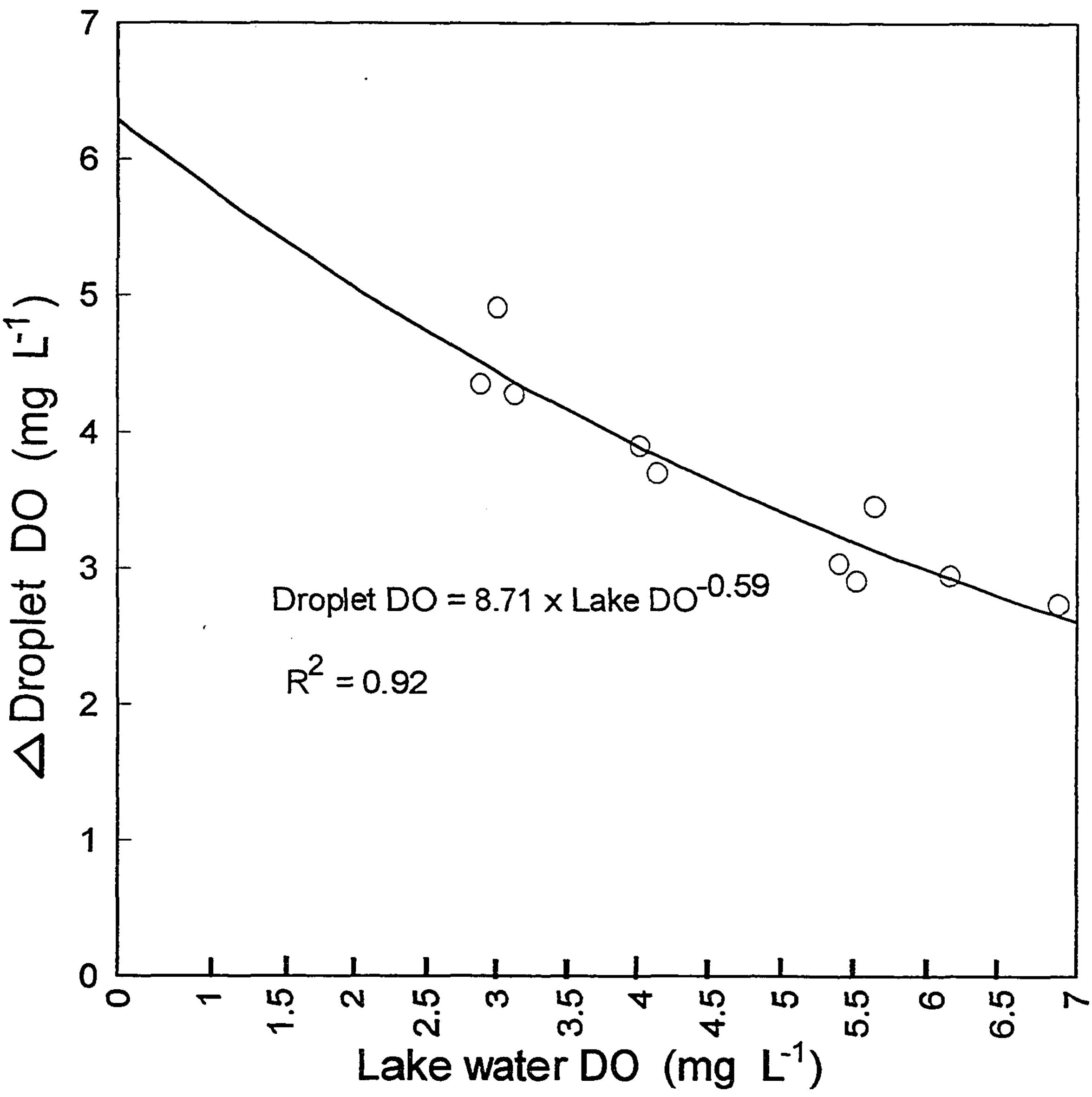

Figure 4-3. Relationship between ambient lake DO in or near the polynya and the absorption of oxygen by spray droplets.

efficiency of 2.8%) (Table 3). This deep set was the only design where air injection caused a net increase in lake DO content.

Data are not presented for the early part of the 1996 to 1997 season for East Dollar Lake. Sampling for CH_4 revealed that a substantial quantity of CH_4 had been trapped beneath the ice following freeze up. As a result, methane oxidation significantly increased O_2 depletion rates during this time, which reduced overall aeration efficiency. These data are presented in Chapter 5.

Parameter values for Moonshine Lake

Values used for mass-balance calculations for Moonshine Lake are listed in Table 4-4. The diffusers and surface aerators were consistently set at the 1.25 m depth, slightly less than mean depth. As a result, an estimated 2/3 of the lake volume was circulated and only about 40% of the sediment surface was exposed to circulating water. Electrical problems, causing intermittent operation of the surface aerators during the first season, made estimates for O_2 depletion and aeration efficiency impossible. In addition, data from the first and second seasons indicated that, although the O_2 depletion rate followed a similar exponential decline as that of East Dollar Lake, the depletion rate continued to decline for several weeks following the onset of aeration. Therefore, lake-specific circulating O_2 depletion measurements, similar to East Dollar Lake, could not be performed without causing a complete fish kill. Nevertheless, accurate estimates of O_2 depletion were possible at the beginning of the season, when the polynya was small. As such, K_L values calculated from the Fig. 4-2 equation were used to determine polynya O_2

Table 4-4. Values for parameters used to compare aeration efficiency of air injection vs surface sprayers in Moonshine Lake. Two diffusers were used with air injection. One surface aerator was used December 12 to 14 and during the entirety of the 1996 to1997 season. Two aerators were used otherwise. Depletion rates were directly measured or were obtained from the regression model displayed in Fig. 4-4.

Period	Depletion ($kg\ O_2\ d^{-1}$)	dM_{DO}/dt ($kg\ d^{-1}$)	DO added ($kg\ d^{-1}$) bubbles	DO added droplets	DO added polynya	Polynya area (m^2)	K_L ($m\ d^{-1}$)
		(1995-1996)					
N19-28	312.8	-312.8	-	-	-	-	-
N28-D5	205.2	-205.2	-	-	-	-	-
D5-D6[+]	432	-427.4	-*	-	4.6	157	3.1[#]
D6-7	261.5	-250.9	-*	-	11.5	353	3.4[#]
D7-12	189.2	-165.1	-*	-	24.2	745	2.9[#]
D12-14	113.4	0	-	33.9	79.5	1115	7.5[Φ]
D14-24	99	+59.8	-	71.9	86.9	1440	5.8[Φ]
D24-J10	95	+40.3	-	58.7	76.6	1350	6.9[Φ]
J10-F7	90	+11.7	-	54.0	47.7	1410	4.5[Φ]
F7-F12	186	-132.2	-*	-	54.2	1554	3.3[#]
		(1996-97)					
J7-J22	95	-1.4	-	35.2	64.8	615	12.0[Φ]
F21-M6[0]	80	+0.7	-	35.2	65.5	665	10.1[Φ]
"	-	-	-	-	20.3	"	3.4[#]

[+] First day of aeration was Dec. 5 using air injection.

* There was no measurable gain of DO from bubbles.

[#] Calculated from Fang and Stephan (1994) and doubled to account the for accumulative effect of wind and water velocity (Mattingly 1977).

[Φ] values determined from mass balance equation.

flux. Thus, with values for O_2 addition and lake DO mass, back calculation through the mass-balance equation (1), provided estimates of circulation depletion rates. The resultant regression (Fig. 4-4) had a high R^2 value.

Startup was delayed during the second season in order to obtain estimates of natural O_2 depletion during early winter. However, O_2 depletion rates became so high after the first snowfall and particularly after air injection was initiated that we switched to surface aeration on the sixth day of aeration in the belief that it would halt the loss of DO. This was indeed the case as just one surface aerator had stabilized DO within 48 hours and after a second aerator was started, a long period of DO accretion began.

When aeration was switched back to air injection on February 7, 1996, the lake immediately began losing DO at an extraordinary rate of 132.2 kg d^{-1}. This was a 115% increase in the O_2 depletion rate as compared to surface aeration and it occurred even though the polynya absorbed slightly more O_2 than during surface aeration (Table 4-4). Notably, however, there was no detectable diffusion of O_2 from bubbles and there was evidence that air injection had begun circulating the stagnant layer near the bottom (see below). Frequent thaw periods later in February and March, with concomitant under-ice photosynthesis prevented additional accurate measurements of O_2 depletion and mechanisms of reaeration during that season.

During the final winter, only one surface aerator was used in Moonshine Lake for the entire season. This aerator was anchored over the same depth as previous years but was started about two weeks prior to freeze up. The DO fell very slowly as winter progressed until it stabilized at about 5.2 mg L^{-1}. Estimates of O_2 depletion (from Fig. 4-4) were used for two representative sampling intervals. Predictably, the polynya area was approximately 50% of that measured during the previous winter, when two surface aerators or diffusers were used. Also, with K_L values obtained from the Fig. 4-2 equation and inserted into the mass balance equation (1), a lower value for O_2 depletion, as compared to previous years, was determined.

Two estimates of K_L using equation (7) (and then doubled), from December 5 to 6, 1995 and February 21 to March 6, 1997, are also included for comparison with that

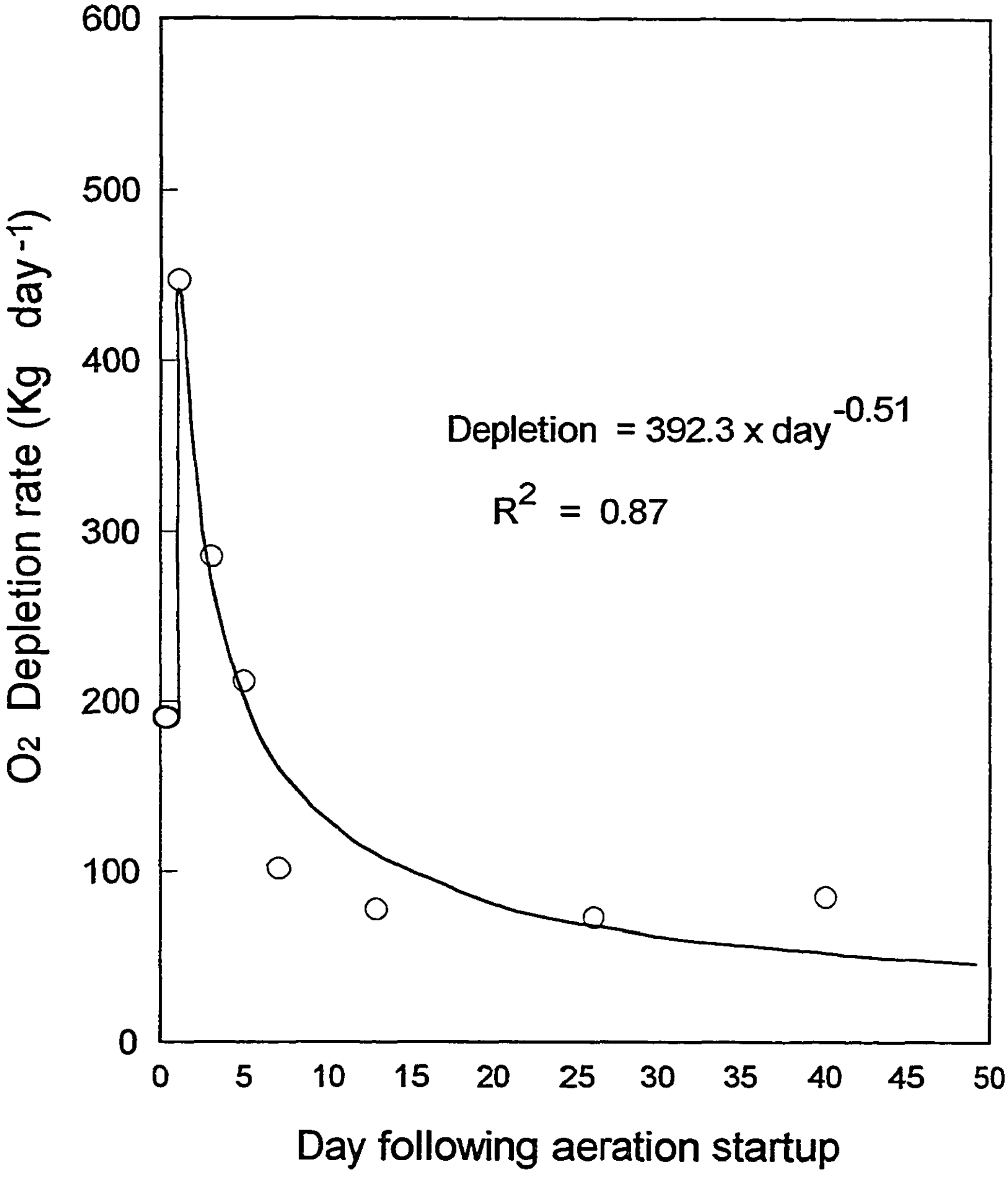

Figure 4-4. Response in oxygen depletion rate following the onset of aeration in Moonshine Lake during the 1995-1996 season. The first four data points are measured values. The last four are estimates obtained from the Fig. 4-2 equation to determine polynya flux and then back calculation through the mass balance model (see text for details).

obtained from the mass-balance equation (Table 4-4). These values again revealed the very strong turbulence and associated high K_L values induced by aeration in order to satisfy the mass-balance equation.

Discussion

Efficiency of aeration

The medium-bubble diffuser set at 8 m demonstrated the highest O_2 transfer efficiency for air injection (2.8% or 4.8 kg DO day^{-1}). This is comparable to diffusers used in aeration tanks. Ewing (1986) reported efficiencies of ceramic fine-bubble diffusers ranging from 1.2 to 2.5%. Transfer efficiency of a spiral roll coarse bubble diffuser was 0.78 to 1.08%. The depths of the aeration tanks ranged from 3 to 5 m deep. This explains why Ewing's values were similar to mine where the diffuser was set at 4 m but less than mine when the diffuser was set it at 8 m.

Conversely, there are no known estimates for O_2 transfer into spray droplets. Undoubtedly, such estimates will vary with sampling technique, sprayer design and droplet size. For example, the splash zone consists of a continuous, highly turbulent condition and presents an opportunity for rapid gas exchange in addition to the exposure of droplets passing through the atmosphere or rising bubbles from a diffuser. This splashing is arguably represented within the beaker during sample collection. However, the wall of the beaker undoubtedly provides some additional surface area for gas exchange. One might suggest that this sampling artifact may increase gas exchange measurements by perhaps 10%. However, solution of the mass balance equation would dictate that, if transfer through droplets were to be reduced by 10%, then transfer through the polynya would have to be increased proportionately. Therefore the extremely high estimates of K_L would actually be even higher. The point is that the artificially turbulent surfaces created by aeration provides a very favorable condition for gas transfer, regardless of how this transfer is apportioned (i.e., between droplets or bubbles and the splash zone of the polynya). The 1.8 and 2.4 kW Air-O-Lator® units used here (without draft tubes) emitted droplets ranging between 10 and 20 mm diameter that were sprayed in a radial fountain. DO in collected droplets increased by 35 to 60%, depending upon ambient lake DO, or 20.1 to 33.9 kg DO aerator^{-1} d^{-1}. This added 5 to 7 times more DO d^{-1} than bubbles from the air injection system. This explains why M_{DO} consistently increased while using surface aerators and nearly always decreased while using air injection.

There was also a large difference in success between the two systems operating in Moonshine Lake. Natural depletion rates became extremely high (circa 1.5 g m^{-3} d^{-1}) following the post-freeze up algal bloom that occurred during November 1995 (Chapter 2). Air injection further doubled this depletion rate and after just a few days, lake DO had fallen to about 2.8 g m^{-3} in the mixed layer. Despite this favorable gradient, there was no measurable transfer of O_2 from ascending bubbles. Switching to surface aeration stabilized the DO with the first aerator and added DO after the second aerator was started. This reversal was the result of at least three factors: 1) The circulation O_2 depletion rate had continued to decline quite sharply (Fig. 4-4); 2) Spray droplets added an additional 33.9 kg DO d^{-1} with the first aerator and a total of 71.9 kg DO d^{-1} when both aerators were operating, as compared to immeasurable amounts added by air injection; and 3) The growing polynya added an additional 33.8 kg DO d^{-1} above that estimated during air injection. In addition, surface aeration results in a lower circulation velocity than air injection and in Moonshine Lake, this also resulted in a shallower mixing zone (Chapter 2; see below).

The dynamic O_2 depletion rate and shallow vs whole-lake aeration

Although other researchers have reported accelerated O_2 depletion rates in response to aeration, the duration of this acceleration has never been evaluated. The onset of whole-lake circulation was found to nearly quadruple the depletion rate in East Dollar Lake. This occurred on February 27, 1995, November 24, 1995 and February 26, 1996. These dates include both early winter, when natural depletion was relatively high, and late winter, when depletion had reached a more stable "baseline" rate. In each case, the depletion rate fell nearly 50% by the end of the second day and after the mid-season startup in East Dollar Lake under ice (February 26, 1996), depletion rates fell to near-natural rates after only 8 days of aeration in this small lake.

Notably, with the shallow aeration of Moonshine Lake, start up only caused about a doubling of the oxygen depletion rate. This is likely the result of isolation of a significant portion of the sediment surface. This conclusion was reached after comparing circulation patterns between mechanical surface aeration and air injection. Although both systems were operating in 1.25 m-deep water, air injection caused a much greater circulation velocity and deeper mixing (Miller et al. 2001). The significance of this characteristic became apparent when aeration was switched from surface aeration to air injection on February 7, 1996. Six days of air injection changed the O_2 balance from a net daily gain in DO to a dramatic loss of DO to 132.2 kg DO lake^{-1} d^{-1}. Accounting for O_2 absorption through the polynya surface, the actual O_2 depletion rate had increased by more than 2-fold, to 194.3 kg DO lake^{-1} d^{-1}. Tracking dye movements revealed the increased depth of mixing during air injection (Chapter 2) and this disturbance actually reached the sediment surface. For example, the sediment surface at 3.75 m cooled by 0.5°C to 4.0°C during the first three days of operation and to 3.6°C. after six days. Predictably, the DO at the sediment surface fell from 3.17 to 2.82 g m^{-3} during these six days. Thus, a deeper set of aeration equipment would likely have caused an accelerated depletion rate similar to that in East Dollar Lake. The erosion of this thick, stagnant boundary layer only exacerbated the poor performance of the submersed air injection system.

Lake vs tank aeration

Despite the similarity in O_2 transfer efficiency between the two systems in tank or wastewater treatment conditions (Doyle and Boyle 1986, Boone and Chambers 1986), results of this investigation identify the great differences when these systems are applied to winter lake aeration. Spray droplets absorbed several times more O_2 than was diffused from coarse or medium bubbles. In addition, the greater volume of water vs air pumped resulted in a several-fold greater contribution of O_2 to the lake than injected air. These factors alone can explain the dramatic differences in accumulation or depletion with each aeration technique in these two lakes. In comparison, in confined tank conditions, the greater circulation velocity and surface boundary layer reformation provided by air injection must be far superior than that provided by surface aeration in order for overall aeration efficiency to be similar between these systems. The shallow water, very small polynya surface areas in winter and lower lake volume circulation rates are simply not conducive to optimal operation of air injection systems in shallow winterkill lakes.

Mattingly, (1977) demonstrated the enhanced effects of combined air and water movement on k_2 in laboratory conditions. Similar effects on k_2 from wind or from moving water were reported by Belanger et al. (1999), although wind and water flow were not used in combination. Clearly, however, the highly turbulent polynya surface adds greater amounts of O_2 m^{-2} than do natural lake surfaces. Only with larger polynya areas, with a greater proportion of the polynya surface more closely resembled natural lake surfaces, did the K_L approximate those predicted by the results of the Fang and Stephan (1994) model. Within these larger polynyas, the radial jet velocity had diminished to 0.02 to 0.04 m s^{-1} near the ice edge (Chapter 2). With very small polynyas, a much greater proportion of the polynya surface is involved in the primary and secondary splash of spray droplets and bursting bubbles and their associated turbulence, resulting in extraordinarily high K_L values. This explains why, even with very small polynyas, relatively large amounts of O_2 are still transferred into the lake.

References

Ashley, K.I. 1983. Hypolimnetic aeration of a naturally eutrophic lake: Physical and chemical effects. Can. J. Fish. Aquat. Sci. 40:1343-59.

Ashley, K.I. 1987. Artificial circulation in British Columbia: Review and evaluation. B.C. Fisheries Branch Technical Circular No. 78. 34 p.

Bandow, F. 1986. Evaluation of winter lake aeration techniques in Minnesota. Minnesota Department Natural Resources, Division of Fish and Wildlife. Fish. Invest. Report No. 386.

Barnhart, E.L. 1986. An overview of oxygen transfer systems. In: Boyle W.C., editor. Aeration systems, design, testing, operation and control. Pollution technical review No. 127. Noyes publications. Park Ridge, NJ. p. 2-6.

Belanger, T. V. 1981. Benthic oxygen demand in Lake Apopka, Florida. Water Res. 15:267-74.

Belanger, T.V., J.B.A Meyer, M.G. Von Canal and M.V. Desik. 1999. A simple field technique for accurate reaeration estimates in aquatic systems. Lake and Reserv. Manage. 15(3):185-199.

Boon, A.G. and B. Chambers.1986. Design protocol for aeration systems - UK perspective. In: Boyle, W.C., editor. Aeration systems. Design, testing, operation and control. Pollution technical review No. 127. Noyes Publications. Park Ridge, NJ. p. 102-140.

Boudreau, B. P. and N. L.Guinasso. 1982. The influence of a diffusive sublayer on accretion, dissolution, and diagenesis at the sea floor. In: Fanning K.A. and F.T.

Manheim, editors. The dynamic environment of the ocean floor. Lexington. p. 115-145.

Boyle, W.C. 1979. Proceedings: Workshop towards a oxygen transfer standard. EPA-600/9-78-021. Nat Tech Inform Serv. Springfield, VA.

Boyle, W.C.1986. Aeration systems, design, testing, operation and control. Pollution technical review No. 127. Noyes publications. Park Ridge, NJ.

Boynton, W.R, W.M. Kemp, C.G. Osborne, K.R. Kaumeyer and M.C. Jenkins. 1981. Influence of water circulation rate on *in situ* measurements of benthic community respiration. Marine Biology. 65:185-90.

Campbell, P.J. and F.H. Rigler.1986. Effect of ambient oxygen concentration on measurement of sediment oxygen consumption. Can. J. Fish. Aquat. Sci.43:1340-49.

Carpenter, J.H. 1965. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr.10:141-143.

DeMoyer, C.D., J.S. Gulliver and S.C. Wilhelms. 2001. Comparison of submersed aerator effectiveness. Lake and Reserv. Manage.17(2):139-152.

Doyle, M.L. and W.C. Boyle. 1986. Translation of clean to dirty water oxygen transfer rates. pp.48-62 In: Boyle, W.C. editor. Aeration systems, design, testing, operation and control. Pollution technical review No. 127. Noyes publications. Park Ridge, NJ.

Ellis, C.R. and H.G. Stefan. 1989. Oxygen demand in ice covered lakes as it pertains to winter aeration. Water Resources Bulletin. 25(6)1169-1176.

Ewing, L. 1986. New direction - off-gas methods. In: Boyle W.C. editor. Aeration systems. Design, testing, operation and control. Pollution technical review No. 127. Noyes Publications. Park Ridge, NJ. p. 414-433.

Fang, X. and H.G. Stefan. 1994. Modeling of dissolved oxygen stratification dynamics in Minnesota lakes under different climate scenarios. Project Report No. 339. Prepared for Environ Res Lab. U.S. Environmental Protection Agency. Duluth, MN.

Fast, A.W. 1994. Winterkill prevention in lakes and ponds using artificial aeration. Rev. in Fish Sci. 2:23-77.

Halsey, T.G. and S.J. MacDonald. 1971. Experimental trout introductions and artificial circulation of Yellow Lake, British Columbia. Fish. Manage. Rep. No. 63. British Columbia Fish and Wildlife Branch, Victoria, B.C.

Johnson, R. and J. Skrypek. 1975. Prevention of winterkill of fish in a southern Minnesota lake through use of a Helixor aeration and mixing system. Minnesota Department Natural Resources Division. Fish Wildlife Section, Fish Invest Rep 336.

Holley, E.R. 1977. Oxygen transfer at the air-water interface. In: Gibbs R.J., editor. Transport processes in lakes and oceans. Plenum, NY. p.117-50.

Jørgensen, B.B. and N.P. Revsbech. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol. Oceanogr. 30(1):111-22.

Lackey, R.T. and D.W. Holmes. 1972. Evaluation of two methods of aeration to prevent winterkill. Prog. Fish. Cult. 34:175-78.

Mathias, J.A. and J. Barica. 1980. Factors controlling oxygen depletion in ice-covered lakes. Can. J. Fish. Aquat. Sci. 37:185-192.

Mattingly, G.E.1977. Experimental study of wind effects on reaeration. J. Hydraulic Div. ASCE.103(HY3), 311-323.

Miller, T.G., W.C. Mackay and D.T. Walty. 2001. Under ice water movements induced by mechanical surface aeration and air injection. Lake and Reserv. Manage.17(4):263-287.

Neilson, B.J.1974. Reaeration dynamics of reservoir destratification. J. Am. Water Works Assoc. 66:617-20.

Patriarche, M.H.1961. Air-induced circulation of two shallow Michigan lakes. J. Wildl. Manage. 25(3):282-89.

Rogers, C.K. 1992. Impact of an artificial circulation device on the heat budget of an ice-covered mid-latitude lake. M Sc Thesis. University of British Columbia.

Smith, D.W. 1986. Aeration system design protocols: a North American perspective. In: Boyle W.C., editor. Aeration systems. Design, testing, operation and control. Pollution technical review No. 127. Noyes Publications. Park Ridge, NJ. p. 85-100.

Smith, S.A., D.R. Knauer and T Wirst. 1975. Aeration as a lake management technique. Wisconsin Department Natural Resources. Tech. Bull. 87.

Streeter, H.W. and E.B.1925. Phelps A study of the pollution and natural purification of the Ohio River. Bull. 146. U.S. Public Health Service. Washington.

Water Pollution Control Federation. 1988. Aeration, a wastewater treatment process. Water Pollution Control Federation and the American Society of Civil Engineers. WPCF Manual of Practice No. FD-13 ASCE manuals and reports on engineering practice No. 68.

Wirth, T. 1988. Lake aeration in Wisconsin lakes. Wisconsin Department of Natural Resource Publ-WR-196.

Chapter 5

Elevated Methane Concentrations Impede Success of Artificial Aeration

Introduction

The role that methane (CH_4) plays in winter oxygen depletion in lakes is largely unknown and its impact on the success of aeration has never been studied. Yet, as the terminal product of anaerobic decomposition of organic carbon, CH_4 plays a key role in the carbon cycle of eutrophic lakes (Rudd and Hamilton 1978, Fallon et al. 1980, Molongoski and Klug 1980, Utsumi et al. 1998). In this role CH_4 oxidation may become a primary source of oxygen depletion and greatly increase the risk of aquatic life to winterkill (Rudd and Hamilton 1978).

As with oxygen depletion rates, lakes with high organic carbon input exhibit higher rates of CH_4 production than lakes with low sediment organic content or input (Molongoski and Klug 1980, Kelly and Chynoweth 1981, Smith and Lewis 1992). Methanogenesis occurs within anaerobic sediments. Its production involves the systematic decomposition of complex organic molecules of polysaccharides, lipids and proteins. These compounds are first hydrolyzed into soluble mono and oligomeric sugars, amino acids, peptides, etc. and then acidified by fermentative bacteria into volatile fatty acids, alcohols, CO_2 and H^+. As oxygen is further depleted in eutrophic sediments, other micro-organisms consume these simple compounds and mediate terminal electron accepters, generally in the order of nitrate, sulfate, and CO_2 (Molongoski and Klug 1980, Jones et al.1980). Each shift in electron accepter is associated with biochemically distinct bacteria (i.e. nitrate reducers, sulfate reducers and methanogenic bacteria; Zehner 1978). Sulfate reducers, for example, can reduce the concentrations of H_2 to the level that methanogens cannot use it (Cord-Ruwisch et al. 1988). The major fermentative products from this conversion are acetate, CO_2 and H_2. Longer-chain fatty acids such as proprionate and butyrate are also produced, although concentrations of these products have been found in the range of 0.1 to to 0.3 of that for acetate concentrations in lakes sediments (Molongoski and Klug 1980) and from 0.1 to 0.01 of that for acetate in marine sediments (Sansone and Martens 1982). In the terminal step of methanogenesis, approximately 60% of the carbon source is acetate, while most of the remainder is via CO_2 reduction using H_2 or interspecies H_2/formate transfer (Zinder 1993).

One factor limiting the conversion of organic matter to CH_4 is the slow growth of fermentative fatty acid degraders and acetotrophic methanogens. For example, bacterial groups that use proprionate or butyrate have doubling times of several days and acetotrophic methanogens in anaerobic bioreactors have a doubling time in excess of 3.5 days (Zinder 1993). Considering the ideal temperature for bioreactors is 35°C, such reactions in temperate lakes with sediment temperatures of 5 to 10°C would take much longer. Temperature, as well as timing and rate of organic matter deposition promote a seasonal effect on acetogenesis and methanogenesis. For example, sediment acetate concentrations reached a maximum of 100 μM during summer and CH_4 concentrations ranged from 120 uM in winter to about 750 uM in summer in Lake Constance, Switzerland (Schulz and Conrad 1995). Three-month incubations of sediment cores covered with phytoplankton suspensions resulted in similarly high acetate and CH_4 concentrations (Schulz and Conrad 1995). Molongoski and Klug (1980) linked methanogenesis directly to the rate of sedimentation in Wintergreen Lake in Michigan. However, following an episode of extraordinary sedimentation, methanogenesis was temporarily halted for two to three weeks. They attributed this temporary decline to the tight coupling of fermentative and methanogenic phases of anaerobic digestion.

The seasonality of primary production and deposition, followed by the considerable time necessary to degrade complex organic molecules is the likely cause of the delay and seasonality of CH_4 oxidation. For example, Harrits and Hanson, (1980) and Utsumi et al. (1998a, 1998b) found CH_4 oxidation to be distinctly seasonal with peak oxidation rates occurring in fall. Notably, these data were obtained from a dimictic lake (Harrits and Hanson 1980, Utsumi et al. 1998a) and a shallow, oligomictic lake (Utsumi et al. 1998b).

The CH_4 that is produced readily diffuses into overlying anoxic waters (Rudd and Hamilton 1975, 1978, Rudd and Taylor 1980, Michmerhuizen and Striegl 1996). CH_4 accumulates in hypoxic hypolimnia during summer stratification. Some of this CH_4 is oxidized within a thin layer at the bottom of the thermocline at the interface of hypolimnetic CH_4 and low DO (Patt et al. 1974, Rudd et al. 1974, Harrits and Hanson 1980). Oxidation is restricted to this layer during summer due to a combination of low DO and limited nutrients (dissolved inorganic nitrogen). In this situation, methanotrophs can fix their own nitrogen (Rudd et al. 1974, Rudd and Hamilton 1975, Harrits and Hanson 1980), but this process can only occur in the presence of low DO concentrations because of its inhibitory effect on the nitrogenase enzyme complex. Nutrient limitation of methanotrophs was further elucidated by Welch et al. (1980). They concluded that low concentrations of N and P restricted oxidation of a large quantity of CH_4 that was added to an oligotrophic arctic lake and oxygen consumption was not altered. Never the less, summer oxidation is a minor avenue of CH_4 loss (usually <10%) as the majority of CH_4 is oxidized during fall overturn, when CH_4 and adequate nutrients are more equally distributed throughout the water column (Rudd and Hamilton 1978, Fallon 1980, Utsumi, et al. 1998a) and the requirement for nitrogen fixation is eliminated.

Most oxygen depletion studies, however, have generally been concerned with the dynamics and prediction of oxygen depletion (e.g. Babin and Prepas 1985, Jackson and Lasenby 1982, Mathias and Barica 1980, Charlton 1980, Cornett and Rigler 1980), rather than specific underlying mechanisms, such as the contribution of CH_4 oxidation. Various regression models have related oxygen depletion to lake morphometry (Mathias and Barica 1980, Babin and Prepas 1985), trophic state (Charlton 1980, Cornett and Rigler 1980, Babin and Prepas 1985), temperature (Charlton 1980) and oxygen storage (Jackson and Lasenby 1982, Trimbee and Prepas 1988), while the importance of CH_4 oxidation in the developing oxygen deficit has not been mentioned. Rather, the study of CH_4 production and oxidation has developed under the auspices of the biogeochemical processes of carbon cycling (e.g. Rudd et al. 1974, Rudd and Hamilton 1978, Fallon et al. 1980, Iversen et al. 1987, Bartlett et al. 1992, Kuivila et al. 1992, Smith and Lewis 1992, Michmerhuizen and Striegl 1996). Hence, although these two disciplines may include measurement of similar parameters (i.e. morphometry and DO profiles), study design and objectives are most often vastly different.

Both lines of research have produced similar observations. One of the most basic features of oxygen dynamics within lakes is the occurrence of greater rates of sediment oxygen demand (SOD) than water column oxygen demand (WOD) in shallow lakes (Greenbank 1935, Hargrave 1972, Rudd et al. 1974, Welch et al. 1976, Mathias and Barica 1980, Jackson and Lasenby 1982, Cornett and Rigler 1987, Prowse and Stephenson 1986). This has been attributed to the accumulation of particulate organic matter on the sediment surface and subsequent aerobic decomposition of the detritus (Hargrave 1969, 1972, Brewer et al. 1977, Ellis and Stefan 1986, Mathias and Barica 1980). Hence, the general paradigm attributes oxygen depletion to aerobic decomposition in the oxidized microzone.

This paradigm characterizes oxygen consumption as remaining linear or slightly exponential as winter progresses until ambient DO falls below about 3 g m^{-3} (Martin and Bella 1971, Welch et al. 1976, Barica and Mathias 1979, Mathias and Barica 1980, Wang 1981). The onset of oxygen consumption dependency on ambient DO is related to the DO concentration gradient across the diffusive boundary layer associated with the oxidized microzone (Bouldin 1968). This boundary layer may vary from several mm in deep calm environments to less than 1 mm in shallow turbulent environments (Boudreau and Guinasso 1982, Jørgensen and Revsbech 1985). Indeed, experimental circulation of water over the sediment surface has reduced the threshold of oxygen limitation from 3 g m^{-3} to about 1 g m^{-3} (Martin and Bella 1971 , Belanger 1981, Campbell and Rigler 1986). This reduction in boundary layer thickness would enhance oxygen consumption in organic sediments and should provide increased opportunity for reduced substances to enter the water column if the adjacent water layer is near anoxia (Hargrave 1969). Further, it can be hypothesized that the enhanced oxygen consumption often reported at the onset of lake aeration (i.e. Lackey and Holmes 1972, Smith et al. 1975, Chapters 2 and 3) is the result of aeration-induced erosion of this boundary layer. Similarly, it has been proposed that aeration devices designed to isolate the sediment surface from the circulating water would reduce oxygen depletion rates and thereby improve aeration efficiency and reduce costs (Ellis and Stefan 1989).

However, this hypothesis ignores the possibility that an undisturbed boundary layer may still acquire and transport large amounts of oxygen-demanding CH_4 and small chain fatty acids, as a result of fermentation, to the water column. Rudd and Hamilton (1978) estimated 55% of total carbon input in ELA Lake 227 was regenerated as CH_4 and 36% of this CH_4 was oxidized to CO_2. In similarly eutrophic Lake Mendota, Wisconsin, Fallon et al. (1980) reported 54% of sedimented organic carbon returned as CH_4. Areal CH_4 production was estimated to be 10.8 mmol m^{-2} d^{-1} in Lake 227 and 35.8 mmol m^{-2} d^{-1} in Lake Mendota.

The great majority of summer CH_4 production is usually oxidized and a much smaller proportion (circa 10%) is vented to the atmosphere during fall turnover (Rudd and Hamilton 1978, Fallon 1980, Utsumi et al.1998a). However, in one instance, Rudd and Hamilton (1978) found a substantial quantity of CH_4 remaining in the water column after freeze up. They attributed this to a shortened fall mixing period, caused by early ice formation. This trapped CH_4 significantly increased oxygen depletion rates, resulting in total lake anoxia and severe fish winterkill (96.6% of the total lake DO was consumed within 77 days following freeze up). Forty-five percent of the consumed DO was directly attributed to CH_4 oxidation (Rudd and Hamilton 1978).

Because the need for aeration is linked to high productivity and subsequent high oxygen depletion rates, I hypothesized that CH_4 production is common in winterkill lakes. Secondly, CH_4 entrapment or the resumption of diffusive flux into the water column under ice may significantly increase oxygen consumption and adversely affect the success of artificial aeration. In this study, I measured CH_4 concentrations in relation to timing of oxygen depletion rates, I hypothesized that CH_4 production is common in winterkill lakes. Secondly, CH_4 entrapment or the resumption of diffusive flux into the water column under ice may significantly increase oxygen consumption and adversely affect the success of artificial aeration. In this study, I measured CH_4 concentrations in relation to timing of freeze up, aeration startup and shallow vs deep placement of aeration devices. I incorporated this data into the mass balance model that was developed in Chapter 4 in order to estimate rates of CH_4 production and compare avenues of CH_4 loss, including oxidation and atmospheric diffusive flux through the polynya surface and the surfaces of droplets and bubbles.

Methods and Materials

Study lakes

East Dollar Lake was used to compare CH_4 concentration and distribution throughout various aeration scenarios. It is a small (4.9 ha), single-basin, hyper-eutrophic lake with mean and maximum depth of 4.2 m and 8.25 m, respectively (Fig. 2-6). At least one CH_4 profile was determined in three other aerated lakes, Figure Eight Lake (38.6 ha, z_{max}=6.2 m), Moonshine Lake (24 ha, z_{max}= 4.25 m), and Sulphur Lake (51 ha, z_{max}= 8 m), and two unaerated control lakes, West Dollar Lake (5.1 ha, z_{max}= 5 m) and Swan Lake (140 ha, z_{max}= 5.5 m) (Figs. 2-2 to 2-9). Data from East Dollar and Figure Eight lakes are presented and discussed here. Profiles from Moonshine, Sulphur, West Dollar and Swan lakes are presented and discussed in Appendix C.

Aeration design

Methane concentrations were measured during the 1996-1997 winter. In East Dollar Lake the surface aerator was anchored near the shoreline in 4 m-deep water. This was intended to allow stratification and isolation of a large portion of the sediment surface from the mixed layer. I also replaced the coarse-bubble diffuser with a commercial medium-bubble diffuser (bubble diameter = approximately 5 mm, Fig. 2-10; Envirodynamics, Kansas City, MO). It was anchored in the middle of the lake but was initially suspended at 4 m with the assumption also that only the top 4 to 5 m would be mixed.

The surface aerator was started November 20 (two weeks after freeze up), and was operated until February 19. The air injection system was started at that time and operated with the diffuser in the shallow position until March 5. The diffuser was then lowered to 8 m and operated until March 17, at which time all aeration was terminated.

In Figure Eight Lake, I continued using the coarse-bubble diffusers and at the same location as previous years. The diffusers were placed in the largest and deepest of three basins (z_{max} = 6.2 m). The two largest basins are separated by a shallow (2 m) sill. Sharp stratification occurred in the middle basin below the 2 m depth, allowing near-anoxic conditions to develop near the sediment surface (see Chapters 2 and 3).

Methane and dissolved oxygen measurements

Samples for both CH_4 and DO analysis were obtained from the same grab sample (1.2 L Kemmerer bottle) using 60 mL BOD bottles. Each bottle was flushed with two to three volumes before sealing. Dissolved oxygen samples were fixed in the field and titrated later that evening using Carpenter's (1965) modification of the Winkler method. CH_4 samples were preserved with NaOH to pH >10 and were transported to the lab at approximately 4 °C. They were immediately partitioned into the gas (nitrogen) phase and stored in 10 mL glass serum vials. These samples were refrigerated until analysis which was within ten days after sampling. Samples and standards were prepared according to Rudd et al. (1974). Measurements were made using a HP 5890 II gas chromatograph equipped with an FID detector and a Supelco 2 m x 1/8 in. 80 to 100 molecular sieve column and quantified using an HP 3390A integrator by comparing peak areas for samples with peak areas for standards. The coefficient of variation among replicates was 5 to 10% with concentrations < 1 μM and 3 to 5% among replicates with concentrations > 1 μM.

In East Dollar Lake CH_4 concentrations were measured twice prior to freeze up, twice during surface aeration and once during each of shallow and deep operation of the diffuser. Methane profiles were also measured twice after aeration was terminated. Sampling depths varied within the top 5 m stratum of East Dollar Lake, after it was determined that this portion was well mixed, although at least two depths were sampled in this stratum during each visit. Sampling depths were at 1 m or 0.5 m intervals at depths ranging from 5 m to the bottom (8.25 m).

In Figure Eight Lake, CH_4 was measured twice during the aerated period and in both the aerated and middle basins. Measurements were made at 1 m intervals in the mixed zone and at 0.5 m intervals in the second basin.

The total mass of CH_4 was calculated by multiplying the concentration at each depth interval by the volume of that depth interval and then summing the masses for all depth intervals. Methane oxidation rates were not measured directly. Rather, initial estimates were obtained by measuring the decline in the CH_4 concentration in the 2 to 5 m stratum, and adding the estimated diffusive flux from lower strata. This was deemed appropriate in that the slightly higher concentration at 1 m (likely due to dissolution of CH_4 bubbles under the ice) prevented CH_4 from diffusing upward and accurate estimates of diffusion from below could be obtained. In addition, DO concentrations were relatively high (circa 5 g m^{-3}) and the recent fall turnover would have redistributed nutrients throughout the water column (Rudd and Hamilton 1978).

Methane production rates

Several methods were used to estimate CH_4 production rates. In East Dollar Lake, CH_4 was initially measured shortly after freeze up. That value was subtracted from CH_4 measurement at aeration startup (a period of 5 days). The accretion in the 5 to 8 m stratum was used as an estimate of production rates during early winter.

I also estimated diffusive flux across a horizontal plane near the sediment surface (Strayer and Tiedge 1978, Molongoski and Klug 1980). This was performed by applying Fick's Law (Hutchinson 1957, Mortimer 1941):

$$ds/dt = -K_z(ds/dz), \qquad (1)$$

where *ds/dt* is the rate of passage of a substance across a plane of unit area, K_z is the coefficient of eddy diffusivity at depth *z* and *ds/dz* is the concentration gradient of the substance across the plane of interest. I determined the concentration gradient across the 6 m-depth plane by taking the average of the measured concentrations of CH_4 at the 5 and 6 m depths and that of the 6 and 7 m depths. Several methods were reviewed for the purpose of estimating K_z, including the flux gradient methods of Mortimer (1941), Hutchinson (1941) and a modification of Hutchinson's method by Powell and Jassby (1974). Powell and Jassby's (1974) method is the most commonly used today. However, this method requires numerous temperature profiles beginning with the onset of stratification (typically during the summer) to evaluate *ds/dt* over several time intervals as well as *ds/dz*. Because aeration disturbs the stratification process, determination of *ds/dt* was only practicable for about six weeks after freeze up. Therefore the method of Mortimer (1941) was also applied to the temperature data and the modifications of Mortimer (1941) as applied by Mathias and Barica (1980) and Kelly and Chenowyth (1979) were applied to the DO and CH_4 gradient data near the sediment surface. The method described by Mathias and Barica (1980) assumes that the rate of oxygen supply to the sediment surface is the same as the SOD and hence the sediment surface is used as the plane across which flux occurs. In addition, the depletion rate measured immediately above the bottom was reduced by 5% to correct for WOD at that depth (Linsey and Lasenby 1985).

Atmospheric methane transfer

CH_4 loss to the atmosphere was estimated using the gas-liquid transfer equations developed by Danckwerts (1970), Fang and Stephen (1994), and Chapter 4. Molecular diffusion coefficients (D) for CH_4 and O_2 have been reported as 1.45 x 10^{-9} m^2 s^{-1} and 1.67 x 10^{-9} m^2 s^{-1} respectively, at 15°C. (Lide 2002). The surface transfer coefficient (K_L), has been described as Danckwerts (1970):

$$K_L = \sqrt{(D \cdot s)} \quad (1)$$

Where D is the diffusion coefficient and s = the reciprocal of time. Further, the ratio of K_L values for different gasses can be described as Danckwerts (1970):

$$K_{L(gas\ 1)}/K_{L(gas\ 2)} = \sqrt{D_{(gas1)} / D_{(gas2)}} \quad (2)$$

Re-arranging and inserting D values for CH_4 and O_2:

$$K_{L(CH4)} = \sqrt{1.45x10^{-9} / 1.67x10^{-9}} \text{ x } K_{L(O2)} \quad (3)$$

$$K_{L(CH4)} = 0.93 \text{ x } K_{L(O2)}$$

It follows that:

$$\left(\frac{dM}{dt}\right)_{CH_4} = \frac{K_{L_{CH_4}}(C_{aCH4} - C_{LCH_4})}{K_{LO_2}(C_{aO_2} - C_{LO_2})}\left(\frac{dM}{dt}\right)_{O_2} \quad (4)$$

Where M = mass, C_a and C_L = concentration of CH_4 and O_2 in the atmosphere and the lake water, respectively. These relationships were then integrated into the equations presented in Chapter 4. In review, the equation for the oxygen budget in aerated lakes is:

$$dM_{DO}/dt = (dM/dt)_{b\ (or\ d)} + (dM/dt)_p - (dM/dt)_r \quad (5)$$

where M is the mass of lake DO, b = addition from bubbles, d is the addition from droplets, p is the polynya surface and r is lake respiration.

By solving for $(dM/dt)_p$ and evaluating for K_L in the equation (Holly 1977):

$$F_s = K_L(C_s - C_l)A_s \quad (6)$$

where A_s is the polynya surface area, I determined a range of K_L values for oxygen that varied with the polynya surface area (Fig. 4-2):

$$K_L = 153.5 \times \text{polynya area}^{-0.53} \qquad (7)$$

The appropriate K_L values were then inserted into equations (3) and (4) to estimate flux of CH_4 leaving the polynya surface. Similarly, because $(dM/dt)_{d\ or\ b}$ from equation (5) was measured, equation (6) could be solved for the actual K_L values for the droplet surface and bubble surfaces. Total instantaneous droplet surface area was estimated to be 60 m^3 (see Chapter 4). Droplet K_L values throughout the range of lake DO values ranged from 19.2 to 23.1 m d^{-1}. This relatively uniform K_L among all measurement conditions suggests that the relationship expressed in Fig. 4.3 is quite accurate Therefore, equation (4) was also used to determine CH_4 flux through droplet surfaces.

Results

East Dollar Lake

Profiles of temperature and DO prior to freeze up indicated that fall turnover probably lasted three to four weeks (Table 5-1). However, the initial CH_4 samples from November 15 (nine days after freeze up) indicated that considerable CH_4 remained in the lake after turnover (Fig. 5-1A). Concentrations of CH_4 ranged from 10 to 15 μM in the top 4 m and

Table 5-1. Dissolved oxygen (g m^{-3}) and temperature (°C) for East Dollar Lake during the fall, 1996. Freeze up occurred on November 6.

Depth (m)	Oct. 8 Temp.	Oct. 8 DO	Oct. 23 Temp.	Oct. 23 DO	Nov. 15 Temp.	Nov. 15 DO
1	9.0	4.29	5.2	7.27	2.2	6.68
2	8.6	4.34	4.2	7.24	2.4	6.70
3	8.3	4.24	3.9	7.10	2.6	6.05
4	8.2	4.31	3.6	7.18	2.7	5.91
5	7.7	4.25	3.5	7.14	2.8	5.76
6	7.4	2.20	3.5	7.23	2.8	5.38
7	7.3	2.28	3.4	7.14	2.9	3.77
8	7.2	1.41	3.4	7.10	3.0	3.55

from 30 to 210 µM from 5 m to the bottom (8.25 m). Methane profiles measured five days later indicated that CH_4 at 1 m had increased (from 15 to 18 µM). Values within the 2 to 5 m stratum had substantially declined with a total loss over the five-day period of 691 moles. However, CH_4 increased substantially within the bottom 3 m. As a result, whole lake CH_4 increased from 5.86 x 10^{-3} to 6.20 x 10^{-3} moles during these five days (Fig. 5-2). The whole-lake oxygen depletion rate during this time was quite high (883 mol $lake^{-1}$ d^{-1}). Notably, the greatest oxygen depletion rate occurred in the top 2 m (508 mol day^{-1}; 5.6 mmol m^{-3} d^{-1}). There was a loss of 236 mol d^{-1} in the 2 to 5 m stratum (2.5 mmol m^{-3} d^{-1}) and 139 mol d^{-1} were lost in the 5 to 8 m stratum (4.7 x mmol m^{-3} d^{-1}).

These high rates of oxygen depletion prompted the initiation of aeration on November 20. The first two weeks of aeration did not reduce the oxygen depletion rate. The December 4 samples indicated that DO continued to decrease throughout the entire water

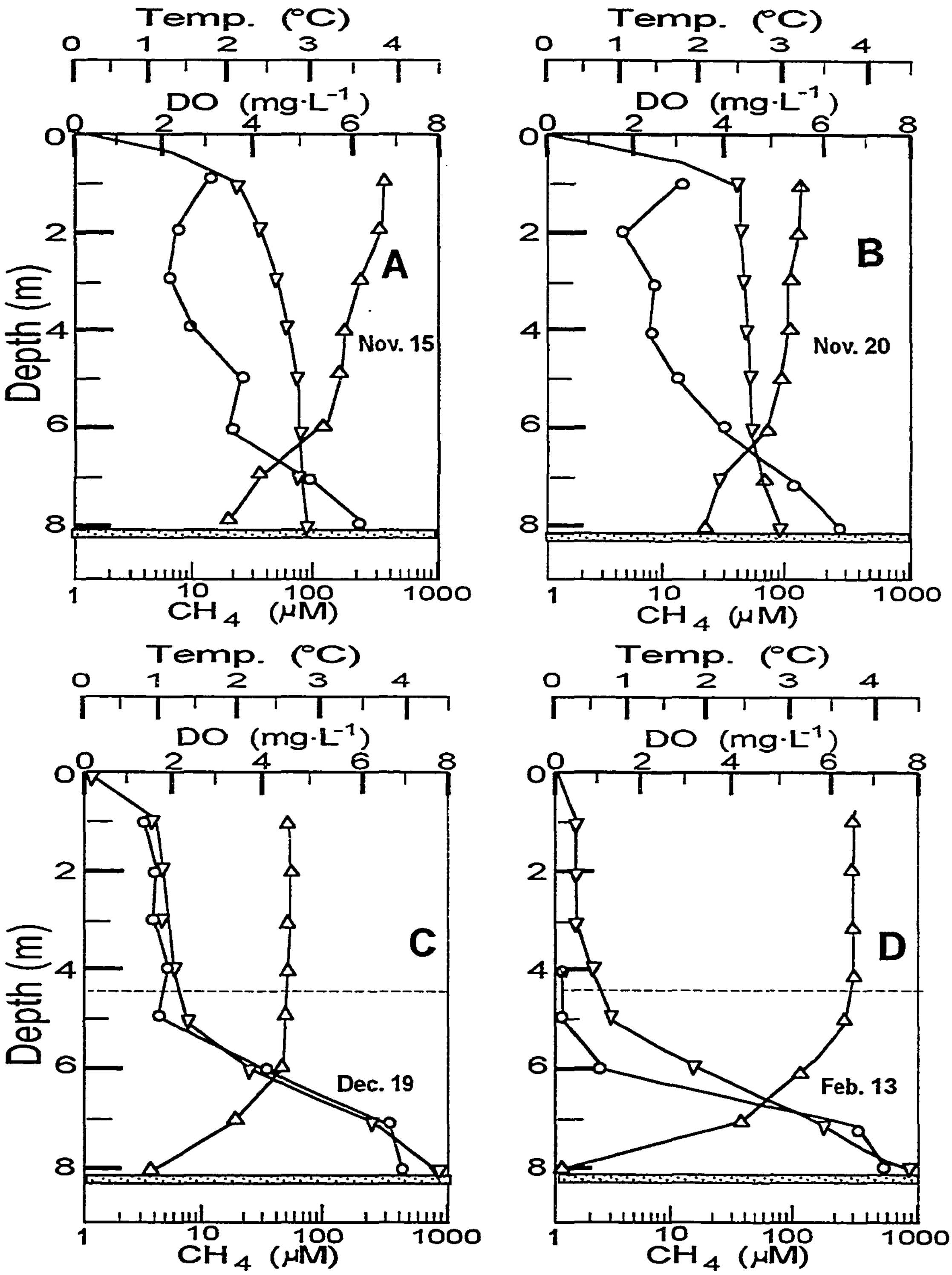

Figure 5-1. Temperature (▽), DO (△) and CH_4 (○) profiles measured in East Dollar Lake during the 1996-1997 winter. (A) and (B) were measured prior to aeration; (C) and (D) were measured while the surface aerator was anchored over 4 m of water (dashed line); (E) was measured while compressor was suspended at 4 m but in the deepest part of the basin (z_{max}= 8.25 m); (F) was measured after the diffuser was lowered to 8 m; (G) was measured 4 days after aeration was terminated; (H) was measured 17 days after aeration was terminated. See text for more details.

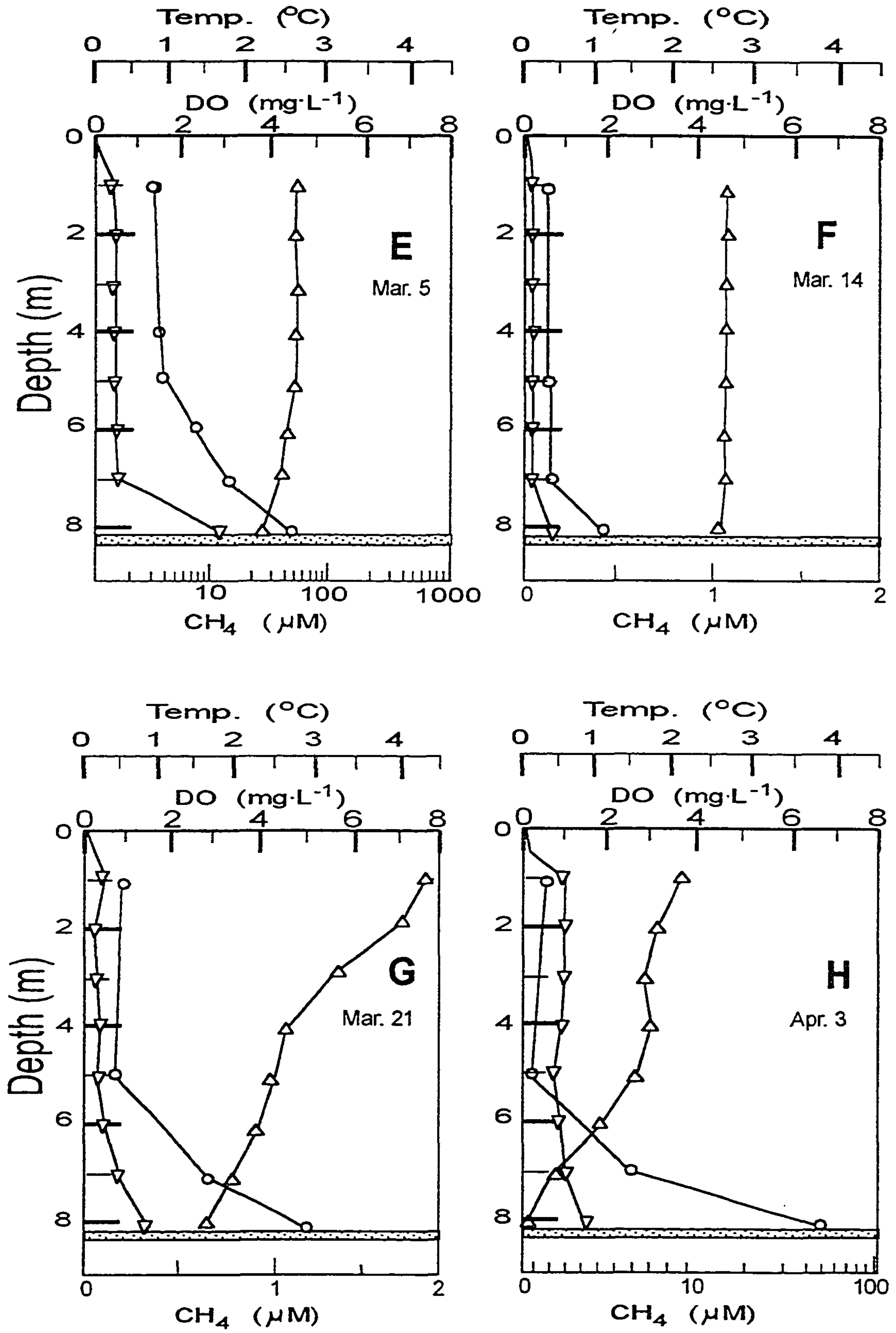

Figure 5-1. (Cont.).

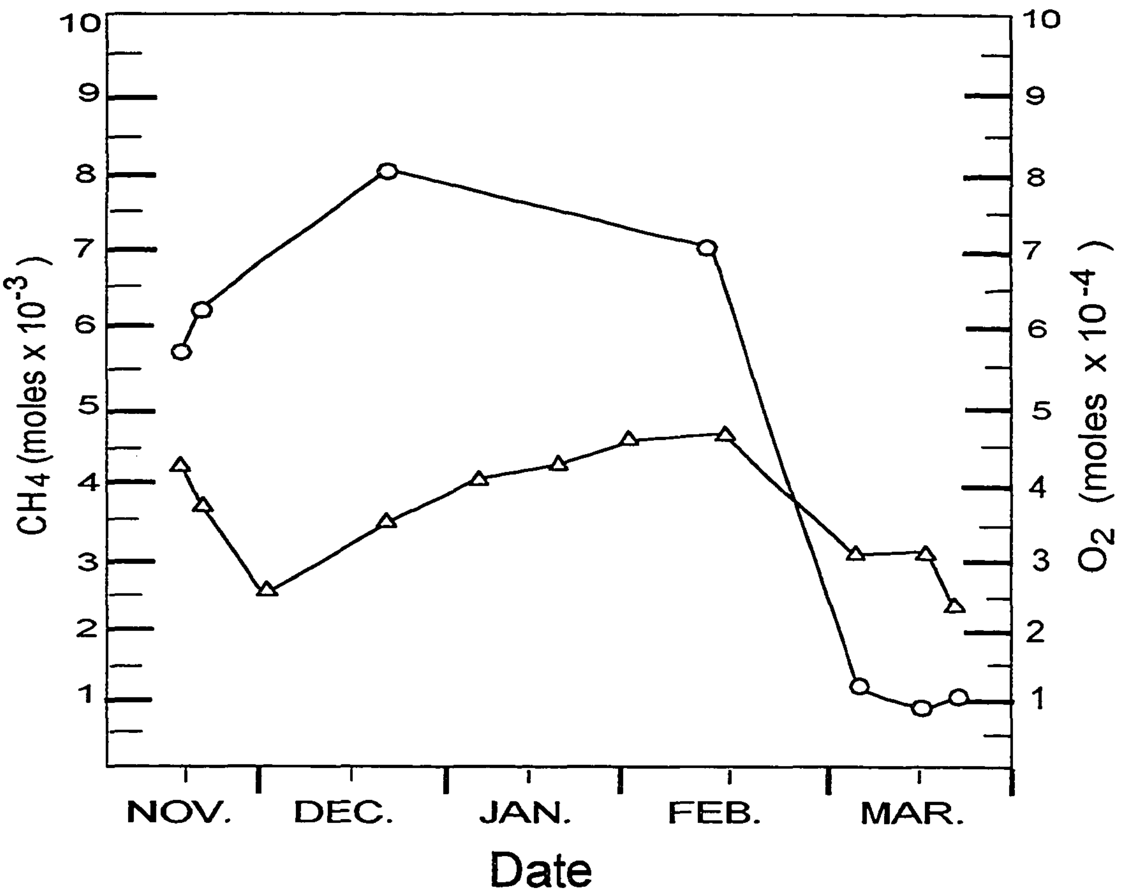

Figure 5-2. Total mass of methane (○) and DO (△) in East Dollar Lake during the 1996-1997 aeration season. Surface aeration (anchored at mean depth) was conducted from November 20 to February 13. Air injection (anchored over 8.25 m) was conducted February 13 to March 14.

column and at a very similar rate as during the pre-aeration period (Fig. 5-1C, Fig. 5-2). The whole-lake oxygen depletion rate was 909 mol d^{-1}, 800 of which were lost in the 1 to 5 m (mixed) strata (4.3 mmol m^{-3} d^{-1}) and 109 mol d^{-1} were lost in the 5 to 8 m strata (3.8 mmol m^{-3} d^{-1}). The only noticeable impact of aeration was to homogenize the top 5 m of the water column. Methane concentrations were not measured during the December 4 visit. Between December 4 and 19 total DO content began a steady increase although this was due to addition of DO in the upper 5 m. A total of 369 mol DO d^{-1} were added to the top 5 m of the lake. Dissolved oxygen values at greater depths continued to decrease (Fig. 5-1C). However, this depletion rate was substantially lower than during the previous sampling interval, since DO fell below 3 g m^{-3} (0.9 mmol m^{-3} d^{-1} vs 3.8 mmol m^{-3} d^{-1}). This lower rate of oxygen depletion continued until January 8, following which, the sediment surface at 8 m cycled in and out of anoxia.

Sampling on December 19 revealed a continued decrease in CH_4 in the top 5 m while CH_4 increased by 3.6 x 10^3 moles (10.3 mmol m^{-2} d^{-1}) between November 20 and December 19. Despite the smaller zone of observable CH_4 production, total CH_4 mass in the lake continued to increase to 8.2 x10^3 moles (Fig. 5-2). This occurred despite the fact that DO even near the sediment surface remained above 1 g m^{-3} (Fig. 5-1C). As shallow aeration continued, the mixed layer slightly deepened and CH_4 concentrations at 6 m began to decrease (Fig. 5-1D). Only the concentration near the 8 m sediment surface increased and this increase was moderate (from 420 to 510 μM). Consequently, whole lake CH_4 had begun to decrease by February 13.

Surface aeration was replaced with air injection on February 19. The diffuser was initially suspended at 4 m with the intent that this shallow placement would preserve the temperature, DO and CH_4 stratification. However, March 5 samples indicated that the lake was being mixed to the bottom. Temperature ranged from 0.26 to 0.32°C from 1 to 7 m and was 1.71°C at the sediment surface. This was a decrease of nearly 3°C at the sediment surface. Methane was similarly mixed. Concentrations had increased throughout the upper strata and the sharp gradient that was previously present from 6 to 8 m had greatly diminished. Concentrations ranged from 3.0 µM at 1 m to 14.5 µM at 7 m and increased to only 65 µM near the bottom (Fig. 5-1E). Total lake CH_4 decreased from 7.0 x 10^3 moles on February 13 to 1.2 x 10^3 moles on March 5 (Fig. 5-2), an average of 253 mol day^{-1}. The greatest decline was in the 6 to 8 m stratum, which decreased from 6.8 x 10^3 moles to 457 moles (20.5 mmol m^{-3} day^{-1}).

The diffuser was lowered to 8 m on March 5 and by March 14 the lake was completely homogeneous to the 8 m depth with the temperature at 0.17°C. At the sediment surface (8.25 m) the temperature was 0.76°C. Methane concentrations fell to about 0.2 µM throughout the top 7 m and to 0.43 µM at 8 m.

Total DO in East Dollar Lake began to decrease as soon as the aeration method was switched to air injection. However, 12 days after the diffuser was lowered (March 17), total lake DO had increased slightly. These trends and associated aeration efficiency are addressed in detail in Chapter 4.

Sediment flux of CH_4

Despite the initiation of aeration on November 20, the bottom 3 m remained stratified and continued to warm until water at the sediment surface reached 4.25°C. This provided about six weeks of usable temperature flux data, until December 19, for the methods of Mortimer (1941) and Powell and Jasby (1974). Solute gradients continued to intensify within these lower strata, and the method of Mathias and Barica (1980), revealed a dramatic decline in K (Table 5-2). After January 8, water immediately above the sediment surface cycled into and out of anoxia until February 19. For comparison, the value obtained from the thermocline of Lake 227 by Hesslein and Quay (1973) using McEwan's (1929) temperature method as described by Hutchinson (1957) is also listed in Table 5-2. This comparison seemed appropriate in that the temperature gradient in the thermocline of Lake 227 was similar to that near the bottom of East Dollar Lake throughout the early part of winter.

The measured values for CH_4 sediment flux were simply the net accumulation in the bottom 2 m of the lake. These estimates are clearly minimal in that diffusive losses out of this stratum as well as oxidation within this stratum were occurring. However, because the CH_4 gradient and DO concentration were quite stable during November and December it is logical to assume that diffusion and oxidation were quite stable during this period. Therefore, the continued increase in CH_4 concentrations near the sediment surface suggests that sediment flux continually increased during the early part of winter and slowed somewhat between December 19 and February 13.

Termination of aeration on March 17 resulted in an immediate tendency toward restratification (Figs. 5-1 G, H). Methane concentrations at the sediment surface began to increase and DO began to decrease. Methane accumulated in the 6 to 8 m stratum at the rate of 1.7 mmol m^{-2} d^{-1}. This was somewhat lower than the flux measured between

Table 5-2. Estimates of the diffusion coefficient (K) and subsequent estimates of methane flux from the sediment surface. (A) = Mortimer (1941), (B) = Powell and Jassby (1974), (C) = Mathias and Barica (1980), (D) Hesslein and Quay (1973)*.

Period	Method	K ($m^2 d^{-1} x10^{-3}$)	K ($cm^2 s^{-1} x10^{-3}$)	CH_4 flux ($mmol\ m^{-2} d^{-1}$)	
				Calc.	Measured**
N. 15-D. 19	A	18	21	21.8	8.4
	B	13	15	15.7	8.4
N. 15-D. 4	C	31	36	63.2	8.4
	D	2.9	3.4	6.0	8.4
D. 4-D. 19	C	7.1	8.2	15.3	11.7
	D	2.9	3.4	6.3	11.7
D. 19-J. 8	C	5.4	6.3	13.4	2.5
	D	2.9	3.4	6.0	2.5

* The value of $2.9 \times 10^{-2}\ m^{-2}\ d^{-1}$ was obtained by Hesslein and Quay (1973) using the "temperature method" described by Hutchinson (1941, 1957) with summer thermocline data of Lake 227.

** Measured values of CH_4 flux include accumulation in the 6 m to 8 m stratum. The three periods were determined based on the change in CH_4 accumulation from November 15 to November 20; November 20 to December 19; and December 19 to February 13. These values are minimal in that both diffusive flux out of this stratum and oxidation have not been accounted for.

December 19 and February 13 (2.5 mmol $m^{-2} d^{-1}$; Table 5-2).

Figure Eight Lake

Methane, temperature and DO profiles were measured twice in the two largest basins of Figure Eight Lake (Fig. 5-3). Concentrations were clearly influenced by the depth of the diffusers or the depth of the sill separating the two basins. These profiles, including strong gradients near the sediment surface, indicate substantial CH_4 flux from

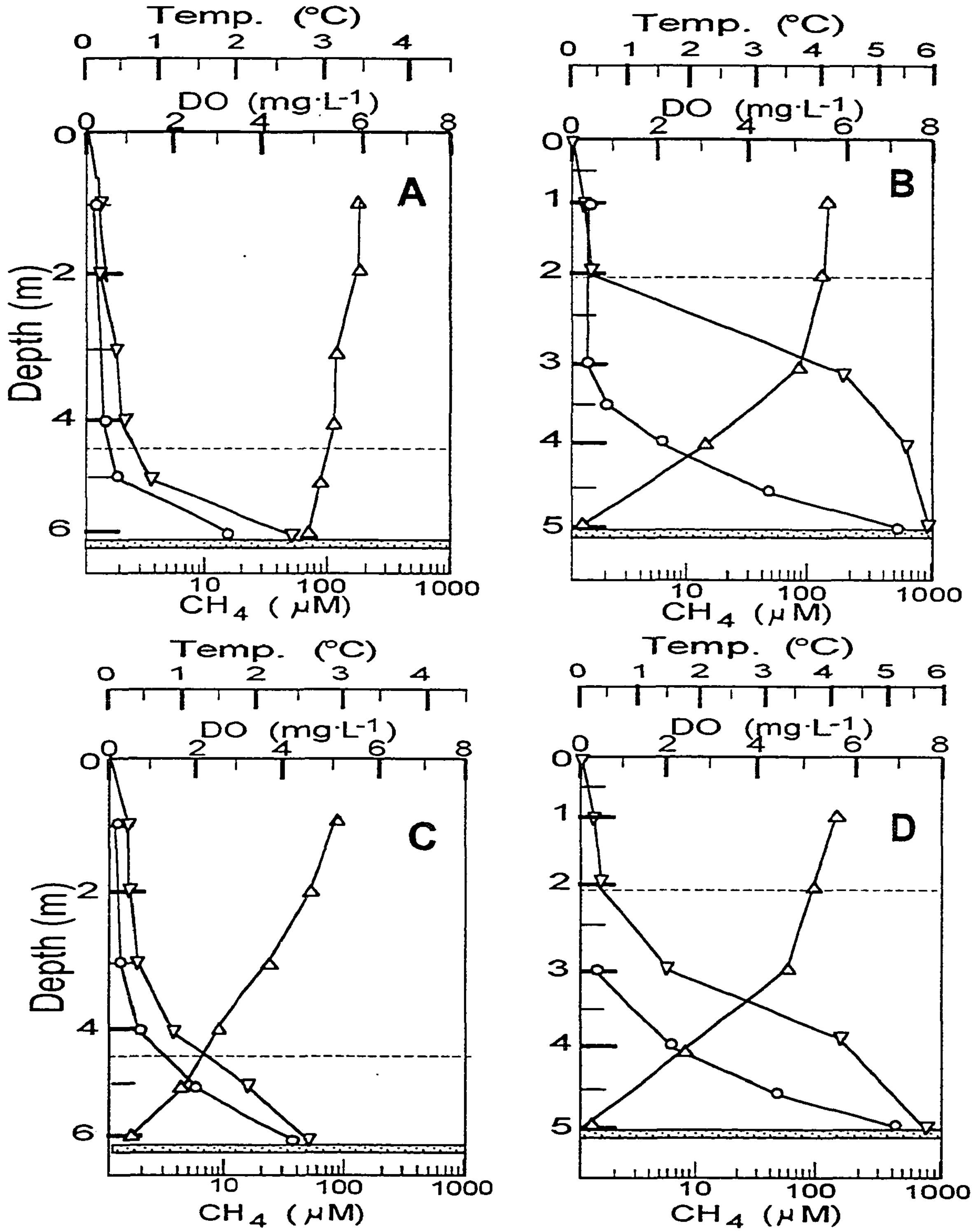

Figure 5-3. Profiles of temperature (▽), DO (△) and methane (○) in the aerated (A and C) and middle basin (B and D) of Figure Eight Lake. (A) and (B) were measured February 13, 1997. (C) and (D) were measured March 20. The diffusers were suspended 0.5 m above the bottom (4.5 m). The two basins are isolated by a shallow (2 m) sill. Note stratification of constituents at depths below the diffusers and particularly below the sill in the middle basin.

the sediment. Because aeration was initiated early in the season in Figure Eight Lake, lake-specific values for K could not be calculated. However, using the median of all calculated K values of 21.9 x 10^{-3} m^2 day^{-1} (Table 5-2), and the observed CH_4 gradients between 4 and 6 m in the large basin and between 3 and 5 m in the middle basin, CH_4 fluxes of 1.92 mmol m^{-2} d^{-1} and 28.4 mmol m^{-2} d^{-1}, respectively, were estimated.

Discussion

Methane and oxygen dynamics prior to aeration

Data from East Dollar Lake were the most useful for evaluating CH_4 production, diffusion, its influence on oxygen depletion and relationship to aeration. Total lake CH_4 increased from 5.7 x 10^3 moles on November 15 to 6.2 x 10^3 moles in just five days. If this accumulation rate (96 mol d^{-1}) is extended back 14 days (to the time of freeze up) an estimated 1.3x10^3 moles would have accumulated since freeze up. Hence, the substantial quantity of 4.4x10^3 moles of CH_4 likely remained in the water column despite a turnover period of three to four weeks (Table 5-1). A similar situation occurred in ELA Lake 227 where a shortened period of turnover caused by an early freeze was attributed to trapping an estimated 1.7x10^4 moles under ice cover (Rudd and Hamilton 1978). This had severe consequences to aquatic life as total lake DO (mean lake DO concentration of 8.8 mg L^{-1}) was reduced by 96.6% within 77 days of freeze up. Using their measured values for CH_4

oxidation rates and a molar ratio of 1.5:1 for oxygen utilization during CH_4 oxidation, Rudd and Hamilton (1978) reported that 110% of the DO in the lake at freeze up would have been consumed by CH_4 oxidation. This is opposite the situation observed the following year where a more typical fall turnover resulted in elimination of virtually all of accumulated CH_4 with 95% being oxidized and 5% being vented to the atmosphere prior to freeze up (Rudd and Hamilton 1978). Comparatively, if the oxygen depletion rate observed in East Dollar Lake during November and early December (Fig. 5-2) had been allowed to continue (i.e. without aeration), East Dollar Lake would have experienced winterkill by late December or early January (Fig. 5-2).

Most CH_4 accumulation in East Dollar Lake occurred in the benthic strata but CH_4 also increased at 1 m (Figure 5-2B). This shallow accumulation was likely due to ebullition and subsequent dissolution of bubbles beneath the ice rather than diffusion through the water column. This value was estimated by measuring the increase in CH_4 concentrations at 1 m between November 15 and 20 (3 mmol m^{-3} d^{-1}). This value is obviously very conservative in that a large but interminable amount of CH_4 would remain as bubbles lying against the ice. Never the less, this estimate of total lake ebullition (235 mol d^{-1}) was incorporated into the overall CH_4 and oxygen mass balance calculations presented in Table 5-3. Although variable in its occurrence, ebullition has been found to be as much as 1 to 2 orders of magnitude greater than water-air diffusive flux (Strayer and Tiedge 1978, Molongoski and Klug 1980, Scranton et al. 1993). Ebullition in these cases ranged from 1.9 to 81 mmol m^{-2} day^{-1}. Strayer and Tiedge (1978) reported similarly high CH_4 concentrations near the ice-water interface as in East Dollar Lake.

Methane actually decreased in the 2 to 5 m stratum at a rate of 137 mol d^{-1} (1.5

Table 5-3. Summary of DO and CH_4 mass balance for East Dollar Lake. Diffusion varied with the concentration gradient and diffusion coefficients (K). Ebullition was systematically reduced by a similar percentage as diffusion to account for the progressive oxygenation of the sediment surface. All values are in mol d^{-1} except for oxidation rate, which is in mmol m^{-3} d^{-1}. The median diffusion coefficient (K), among all the methods, from each appropriate time period (Table 5-2) was used to calculate diffusion into the mixed layer.

Period	CH_4 added by		measured loss	CH_4 oxidized	oxidation rate	CH_4 emitted by			DO		
	Ebul.	Diffusion				Droplets	Bubbles	Polynya	added	consumed by	
										CH_4 Oxid.	other
(Pre-aeration; 1-5 m stratum)											
N15-N20	235	36	92	363*	2.0*	-	-	-	-	581	244
(Shallow spray aeration)											
N20-D4	235	584	91	818	4.6	58.7	-	33.7	1396	1309	905
D4-D19	235	595	37	759	4.3	51.7	-	56.5	1893	1214	681
D19-J23	235	324	14	550	2.6	10.2	-	12.4	1146	881	51
J23-F13	235	245	9	485	2.0	3.8	-	0.3	1031	776	58
(Air injection; Whole lake circulation)											
F19-M5	45	139	415	590	3.1	-	5.6	3.5	715	945	540
M5-M14	20	43	144	205	1.2	-	1.0	0.3	618	328	285
(Post aeration; Whole lake)											
M17-M21	1	7.7	-4.8	3.9	0.02	-	-	-	-	6	97
M21-A3	6.6	107	-35.0	78.6	0.4	-	-	-	-	126	444

*The estimated rate of loss in the 2 to 5 m stratum. This value was then multiplied by the volume of the 1 to 5 m stratum to obtain the rate of 363 mol d^{-1}.

mmol m^{-3} d^{-1}), over the five-day period. This was despite a calculated diffusive flux from lower strata (across the 5 m plane) of 22 to 49 mol d^{-1} (1.1 to 2.5 mmol m^{-2} d^{-1}). Hence, the loss of CH_4 to oxidation in the 2 to 5 m stratum was in the range of 159 to 186 mol d^{-1} or 1.75 to 2.0 mmol m^{-3} d^{-1}. These values approach the highest measured rate for methane oxidation during winter (2.4 mmol m^{-3} d^{-1} for Lake 227; Rudd and Hamilton 1978). Lake 227 is of similar size, volume, latitude and had similar estimates of CH_4 production as East Dollar Lake. Further, this high CH_4 oxidation rate in Lake 227 was also measured immediately after freeze up-providing a very similar temperature profile as East Dollar Lake during early winter.

In comparison, Harris and Hanson (1980) measured CH_4 oxidation several times in Lake Mendota during summer stratification and fall turnover. In one experiment they collected water samples on September 1, 1977 from the portion of the thermocline that exhibited the highest rate of CH_4 oxidation and incubated these samples at temperatures ranging from 4 to 47°C. Notably, while a Q_{10} of about 2.0 could be estimated for the temperature range of 17.5 to 35°C, the Q_{10} from 7 and 17.5°C increased to 4.8 and the Q_{10} for the temperature range of 4 to 17.5°C was about 5.4 (from 0.04 mmol m^{-3} d^{-1} at 4°C to 0.3 mmol m^{-3} d^{-1} at 17.5°C). Hence, CH_4 oxidation slows substantially as the temperature cools. Harrits and Hanson (1980) measured much higher oxidation rates four weeks later, after fall turnover began (28.8 mmol m^{-3} d^{-1}). Applying the Q_{10} of 5.4 to this rate, an estimated 5.3 mmol CH_4 m^{-3} d^{-1} would have been oxidized at 4°C. Cool-water measurements of CH_4 oxidation have also been made by Utsumi et al. (1998a). They measured rates of approximately 10 mmol m^{-3} d^{-1} in Lake Nojiri, Japan during fall turnover, when the lake was 6°C and the ambient CH_4 concentration was 10 μM. My estimate of 2.0 mM m^{-3} d^{-1} was determined when East Dollar Lake was isothermal at 3°C and CH_4 concentrations were similar at about 10 μM. The combined effects of temperature and substrate concentration are discussed further below.

Using the value of 2.0 mM m^{-3} d^{-1} for the CH_4 oxidation rate and a molar ratio of O_2:CH_4 of 1.6:1 for the oxidation process (Amaral et al. 1995, Joergensen and Degn 1983, Kuivila et al. 1988), the estimated consumption of CH_4 in the 2 to 5 m stratum would require 254 to 298 mol O_2 d^{-1}. DO in the 2 to 5 m stratum actually decreased at a rate of 246 mol d^{-1}, suggesting that CH_4 oxidation could have caused nearly all of the oxygen depletion in this stratum. Further, applying this oxidation rate to the entire lake volume resulted in an estimate of 581 mol O_2 consumed d^{-1} from CH_4 oxidation (Table 5-3). At this rate, the stored oxygen present on November 15 would have been completely consumed after about 90 days. However, the actual oxygen depletion rate measured between November 15 and 20 was much higher, at 825 mol $lake^{-1}$ d^{-1} indicating that either much greater CH_4 oxidation rates were occurring than were estimated (i.e., where CH_4 concentrations were higher) or that a substantial quantity of additional substrates was being oxidized. The latter is more likely in that the lake certainly would have contained some additional oxidizable substrates. This was the case in Lake 227 where Rudd and Hamilton (1978) estimated that 45% of oxygen loss was due to oxidation of substrates other than CH_4 (see below). Further, stratum-specific oxygen depletion rates in East Dollar Lake were actually lowest in the lower strata, where the greatest concentrations of CH_4 occurred, while the greatest oxygen depletion rates actually occurred in the 0 to 2 m stratum. With either possibility, however, it is apparent that the time required to reach complete anoxia would actually have been much less than 90 days (Fig. 5-2).

Relationship of aeration to methane and oxygen dynamics

Aeration greatly altered the distribution of CH_4 and caused some remarkable changes in both CH_4 dynamics and the oxygen budget. Anchoring the surface aerator over 4 m of water mixed only the top 5 m (Fig. 5-1C). Consequently, CH_4 declined exponentially in this stratum. This contrasted with rapidly increasing concentrations near the sediment surface and resultant increase in the concentration gradient between the sediment surface and the 5 m plane (Fig. 5-1,Table 5-3). Consequently, diffusive flux into the mixed zone increased by more than an order of magnitude within the first few weeks. Accounting for this increase in flux, circulation caused CH_4 oxidation rates to more than double and oxygen consumption by other oxidizable substrates increased by nearly 4-fold (Table 5-3). These enhanced oxidative processes temporarily consumed more oxygen than the considerable amount that was being delivered by the surface aerator (Table 5-3). This provides another explanation for the aeration-enhanced depletion rate in situations where aeration equipment may have been undersized or initiated long after freeze up (e.g. Patriarche 1961, Smith et al. 1975). This likely enhances the contact frequency of oxygen with various oxidizable substrates - such as stirring enhances the rate of chemical reactions in a beaker.

Oxygen addition finally exceeded oxygen consumption between December 19 and January 23. This recovery was due to the decline in oxygen consumption by methanotrophs as well oxidation of other substrates (Table 5-3). Secondly, there was an increase in the oxygen transfer due to the growing polynya surface area and an increase in the diffusive gradient at the air-water interface (from the decreasing DO concentration; i.e. See Chapter 4). It is probable that the transient but significant contribution of oxygen consumption by other substrates was at least partially associated with phytoplankton populations and particularly following periods of photosynthesis. For example, there was another dramatic surge in oxygen consumption after a short thaw between March 19 and 21. The absence of snow had allowed light penetration and significant photosynthetic oxygen production. Yet, this was immediately followed by a substantial reduction in DO after a 120 mm snowfall on about March 21 (Figs. 5-1 G and H) that could not be attributed to CH_4 oxidation. During this time, CH_4 concentrations increased only slightly and most of this increase was within the benthic strata. Also, it is unlikely that this brief period of primary production would result in the immediate release of intermediate degradation productions such as acetate or proprionate as these products require a lag time of at least a few weeks after sedimentation occurs and these fermentative processes occur in anaerobic zones with sediments (Molungoski and Klug 1980). A similar spike in DO also occurred in East Dollar and Moonshine lakes immediately following freeze up and after brief spring thaw periods during the 1995-1996 season (see Chapter 2, Appendix A).

Air injection was initiated February 19 with the diffuser set at 4 m (mid-depth). Despite this shallow set, the entire water column began mixing. This entrained the large amount of CH_4 that had continued to accumulate in the benthic layers and caused another surge in oxidation rates of both CH_4 and other substrates (Figs. 5-2 C and D, Table 5-3). This resulted in a mean loss of about 2 g DO m^{-3} d^{-1} in the top 6 m (> 1400 mol O_2 $lake^{-1}$ d^{-1}), although the bottom 2 m experienced a substantial increase in DO.

From March 5 to March 17 the diffuser was operated at the 8-m depth. This deep set further reduced CH_4 content, resulting in an average concentration of about 0.3 μM (Fig. 5-1F). This low concentration and reduction in diffusion rates reduced estimated CH_4 oxidation rates by about two thirds. This was supported by the fact that there was no oxygen depletion measured for the 1 to 5 m stratum from March 14 to 19 (after the compressor was turned off; data not shown). In addition, although the oxygen depletion rate in the 5 to 8 m stratum was greater than early-winter rates (0.21 vs 0.10 g m^{-3} d^{-1}), the majority of depletion was likely due to oxidation of substrates other than CH_4 (Table 5-3). This is because of CH_4 concentrations during March were about 3 orders of magnitude less than during early winter. Yet oxygen consumption was twice as great at the sediment surface.

Figure Eight Lake

In Figure Eight Lake strong gradients developed at depths greater than where the diffusers were set and particularly in the second basin, where a shallow (2 m) sill restricted mixing at greater depths (Fig. 5-3). The relatively high benthic CH_4 concentration and sharp concentration gradients suggest a hypereutrophic condition, similar to East Dollar Lake. This explains the need for a much larger aeration system for this larger lake (See Chapters 3 and 4).

Data from Figure Eight Lake offers additional evidence of the link between CH_4 oxidation and the performance of aeration equipment. There was a horizontal limit to the oxygenation process (see Chapter 2) and this limit is likely the consequence of CH_4 diffusion into the mixed layer. A sharp concentration gradient existed at depths greater than 3 m but only a very small amount of CH_4 existed in the mixed layer of the middle basin (Fig. 5-3). This indicates that although an estimated flux of 28.4 mM CH_4 m^{-2} d^{-1} entered the mixed zone it was rapidly and nearly completely oxidized. Considering that the middle basin of Figure Eight Lake contains 8.8 ha of sediment surface below 3 m, there was a total flux of 2.3×10^3 M d^{-1} entering the mixed zone. In turn, using the oxidation rate of 2.0 mM m^{-3} d^{-1} (estimated for East Dollar Lake), CH_4 entering the mixed zone would have consumed 3.1×10^3 M or 100 kg DO d^{-1}. This value appeared to be quite accurate. For example, water in the mixed zone lost an average of 1 g DO m^{-3} between the entrance and exit of the middle basin (See Chapter 2). This was equivalent to 136 kg of DO. The approximate time for water to travel this distance (300 m) is 1.5 days (Chapter 4), which would yield an oxygen consumption rate due to CH_4 oxidation of 91.6 kg DO d^{-1}. Hence,

CH_4 oxidation in the mixed zone appears to account for the majority of DO loss at that large distance from the aerator.

Mechanisms of methane loss

These data also reveal the relative importance of the various mechanisms of CH_4 loss. For example, using the average polynya surface area during the first two weeks of aeration (November 20 to December 4; 803 m^2), and equation (6), K_L was estimated to be 4.4 m d^{-1}. Using the measured surface CH_4 concentration of 10 μM, equation (4) indicated that 33.7 mol d^{-1} was emitted through the polynya surface (Table 5-3). Similarly, applying equation (5) to sprayed droplets, 58.7 mol CH_4 d^{-1} were emitted through droplet surfaces (Table 5-3). Thus, a total of approximately 92.4 mol CH_4 d^{-1} was emitted to the atmosphere from aeration. This is only accounted for about 10% of the total CH_4 loss in the mixed zone during that time. Hence, the greater benefit from aeration is adding oxygen into the water column to replace its consumption from CH_4 oxidation rather than providing a direct avenue for CH_4 emission to the atmosphere. Never the less the aeration process greatly enhanced CH4 transfer to the atmosphere. For example, a similarly low percentage (circa 5%) of CH_4 was lost to the atmosphere during fall turnover when the respective lakes were still open (Rudd and Hamilton 1978, Fallon et al. 1980, Utsumi et al. 1998). During winter aeration of East Dollar Lake, the polynya surface only represented about 0.4% of the lake surface.

Mechanisms of oxygen loss

Previous reports identify SOD as the primary source of oxygen depletion (e.g. Mathias and Barica 1979, Barica and Mathias 1980, Trimbee and Prepas 1985, Cornet and

Rigler 1980, and others). Yet, evidence here indicates that WOD can be much greater than SOD during periods such as immediately following freeze up or after late winter thaw periods which melt the snow cover and allow brief periods of photosynthesis (e.g. see Appendix A). Hence, phytoplankton respiration also appears to contribute to oxygen depletion. Further, if turnover was relatively short, or if aeration startup occurs after CH_4 is re-supplied to the water column, CH_4 may play a significant role in the oxygen budget and CH_4 oxidation and/or that of other substrates may exceed SOD of either aerated or natural lakes.

Harrits and Hanson (1980) noted that CH_4 oxidation activity is directly related to CH_4 concentrations if nutrients are not limiting. They found oxidation rates to stabilize at CH_4 concentrations > 5 uM. Where such conditions appear to be optimal, Ks have ranged between 4.1 and 10 uM and Vmax values have ranged between 12.7 and 35 mmol m^{-3} h^{-1} (Buchholz et al. 1995, Kuivila et al. 1988, Listrom and Somers 1984). During these studies temperature ranged from 6°C to room temperature.

Possible substrates involved in additional oxygen consumption would include metabolism of small-chain fatty acids such as acetate, proprionate and butyrate. Molongoski and Klug (1980) found acetate and proprionate in the interstitial spaces of Wintergreen Lake to be about an order of magnitude less than that of CH_4. This might be the result of rapid metabolism of these small-chain fatty acids. There is also some evidence, developing from the wastewater treatment field, that acetate uptake may occur in response to cycling from anaerobic to aerobic conditions. This uptake is linked to enhanced biological phosphorus removal in the activated sludge of wastewater treatment systems. Initial models describing acetate uptake, conversion to the storage molecules of polyhydroxybutyrate and polyhydroxyvalerate were proposed by Comeau et al. (1986), Wentzel et al. (1986) and Pereira et al. (1986). More recent models by Mino et al. (1987) and Louie et al. (2000), follow the same tenet that uptake and storage of molecules derived from acetate metabolism occurs during an anaerobic phase. During a subsequent aerobic phase, polyhydroxybutyrate and polyhydroxyvalerate enter the citric acid cycle at appropriate positions and participate in gluconeogenesis or provide reducing power for the electron transport chain (see, e.g. Periera et al. 1996 and Smolders et al. 1994). These immediate reactions, in themselves, do not consume ambient oxygen. Rather, H^+ delivered by NADH and $FADH_2$ to the electron transport chain will ultimately require oxygen as the final electron accepter during aerobic metabolism. Although the details of these metabolic pathways are the subject of active research in the wastewater engineering field, no parallel research currently exists in natural or aerated lakes.

Temperature and substrate concentrations obviously play a prominent role in methane metabolism. Yet, there are few studies that report seasonal variability in oxidation rates in relation to temperature and CH_4 concentration (e.g. Utsumi et al. 1998b, Rudd and Hamilton 1978). Both of these studies identify hysteresis in methane oxidation. For example, data from Utsumi et al. (1998b) shows very low oxidation rates until mid to late summer. At this time, both temperature and depositional rates of organic matter are increasing and subsequent fall oxidation rates are very high (Fig. 5-4). Oxidation rates remain elevated even after winter temperatures have declined considerably. This is likely because CH_4 concentrations remain high throughout this period. Finally, as the temperature approaches minimal winter values, the oxidation rate falls back to baseline values.

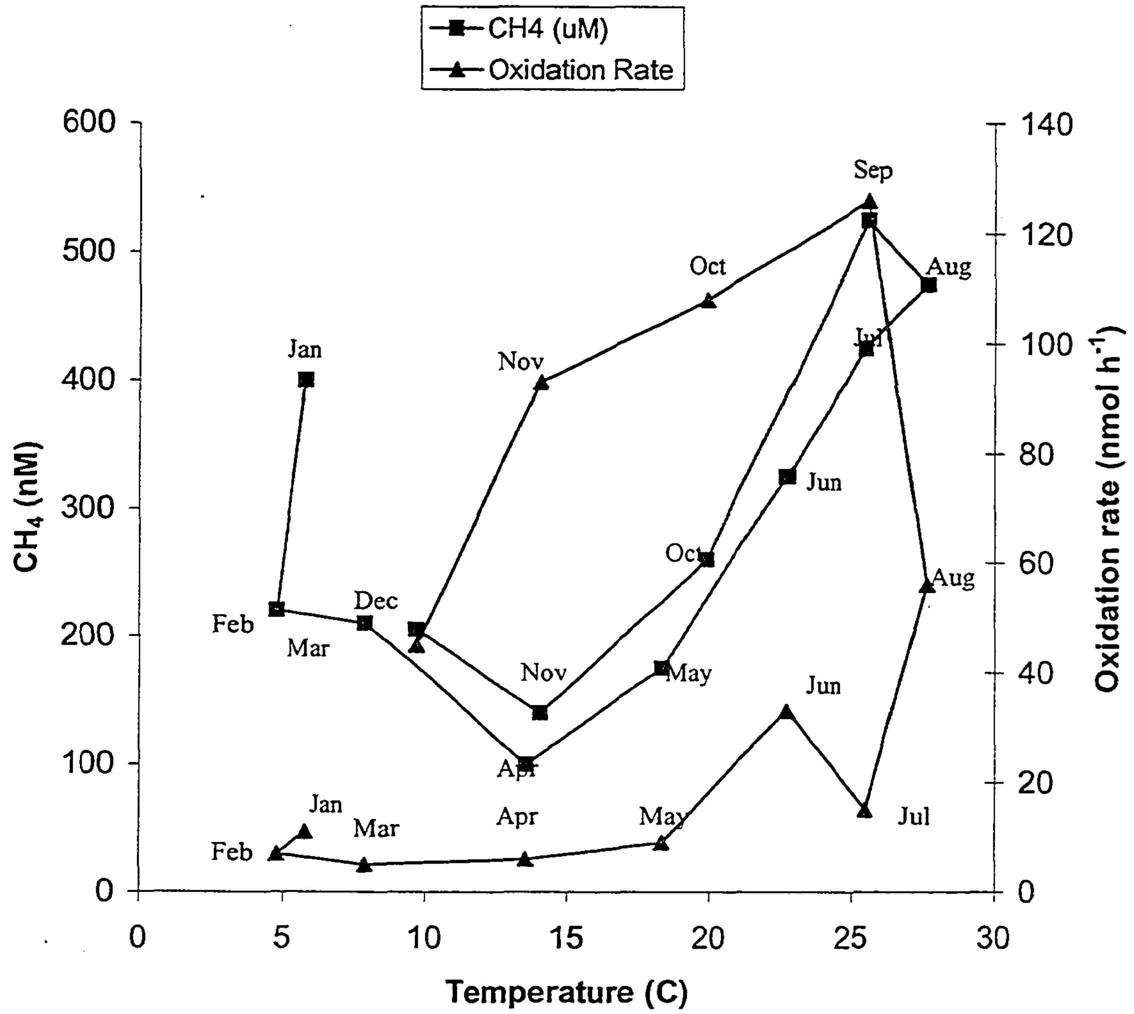

Figure 5-4. Plot of CH_4 concentrations and oxidation rates in Lake Kasumigaura, Japan illustrating hysteresis in relation to temperature and sample timing (data from Utsumi 1998b).

Significance of diffusion

The accuracy of CH_4 production estimates clearly depends on the accuracy of estimating K. Several methods were used here to estimate K whenever possible to illustrate the variability in this important variable. The sediment oxygen demand method of Mathias and Barica (1980) could be used for separate and shorter time intervals and this revealed the seasonal variability of K. For example, during early development of stratification the relatively weak gradient in DO and high value for oxygen flux (sediment oxygen depletion rate) resulted in a high estimate for K. Subsequent increases in the oxygen (density) gradient resulted in lower K values which were more similar to those of Mortimer (1941; Method A) and Powell and Jassby (1974; Method B). These latter two methods account for variations in flux and gradient by measuring temperature profiles and integrating over depth and several weeks of time. Therefore, these methods reflect more of an average over that usable time period.

The continued sharp gradients of both DO and CH_4 after isothermy indicates both high rates of CH_4 diffusion from sediments as well as and oxygen consumption near the sediment surface. This also occurred following the onset of turnover and total isothermy in Lake Nojiri, Japan (Utsumi et al. 1998a). The eventual decrease in CH_4 diffusion into the water column as winter progressed was likely one or a combination of the following: 1) DO at the sediment surface eventually diffused into the sediments - transferring oxidative processes to shallow sediment layers (e.g. Buchholz et al. 1995, Kuivila et al. 1988); 2) the cooling of sediments during fall overturn may have reduced the rate of methanogenesis (Kelly and Chynoweth 1981); or 3) the eventual consumption of usable substrate (i.e. acetate).

Kelly and Chynoweth (1981) reported a relatively high average Q_{10} of 2.4 for methanogenic bacteria. Their data encompassed a temperature range from about 4.5 to 29°C, although they reported particularly high Q_{10} values (up to 5.7) in the temperature range of 4.5 to 9°C. Hence, although temperature affects the rate of methanogenesis, it did not reduce the rate of CH_4 accumulation in East Dollar Lake until after December 19 - long after turnover and freeze up. In other words, the high rate of CH_4 diffusion occurred in spite of the cooler temperature. This suggests that very high CH_4 concentrations remained in the sediments after fall turnover that were actually produced during summer, when the sediments were warmer. In turn, high rates of diffusion of this stored CH_4 continued for several weeks into winter. Summer sediment temperatures are much higher (8 to 10°C) than during winter. This would theoretically allow 2 to 5 times the rate of CH_4 production as that which would occur during winter. Further, this cooling effect on CH_4 production would have been even more pronounced after air injection in February reduced sediment surface temperatures to < 1°C. Yet, CH_4 immediately began to accumulate in benthic layers following the termination of aeration.

Finally, although the frequency of occurrence of incomplete fall turnover is unpredictable, this factor alone may explain the variability in winterkill, the year-to-year success of aeration, or even the successful sizing of aeration equipment. Secondly, the onset of aeration itself has been found here to enhance the rate of oxygen depletion, presumably by enhancing the contact frequency of oxygen with substrate molecules or respiring cells. Hence, although mixing has been found to erode the diffusive boundary layer and enhance oxygen transfer to substrates on the sediment surface, the enhanced contact in the water column may be an even greater source of the enhanced oxygen depletion that has been described by other workers in this field (i.e. Patriarche, 1961, Smith et al. 1975).

Conclusions and Recommendations

Although one would intuitively suspect that most CH_4 would be lost to the atmosphere during the aeration process, most CH_4 loss in aerated lakes appears to be the result of oxidation. Hence, CH_4 production and potential for continued release following freeze up, along with myriad other substrates and the enhanced oxidation rate due to mixing itself, are likely responsible for the difficulty in sizing aeration equipment to individual lakes.

The importance of temperature, substrate concentration and nutrient availability have all been found to be important in dictating methane oxidation rates. Yet, the interrelation of these factors has not been studied. For example, although fermentative processes leading to the production of small chain fatty acids and CH_4 have been performed in marine and freshwater sediments, oxygen consumption studies have only focused on CH_4 oxidation and this has primarily been in the water column. Yet the information presented here and elsewhere (e.g. Rudd et al. 1974, Rudd and Hamilton 1978, Fallon et al. 1980), suggest important and variable contributions to the oxygen budget by unquantified, and yet highly labile substrates. For example, ^{14}C-tracing has linked CH_4 and CO_2 to the precursor, acetate, but have not continued to the subsequent metabolism of CH_4; nor has the impact of intercepting fermentation by reoxidizing the environment been investigated. At a minimum these would include measurement of oxidation of intermediate fermentative products, as well as phytoplankton respiration (see Appendix A). Essential studies need to include seasonal measurements of the generation and oxidation of these substrates in relation to water column and shallow sediment profiles and in relation to freeze up and periods of light penetration. Specifically, seasonal, simultaneous measurement of acetate, proprionate and butyrate turnover rates along with CH_4 oxidation rates, using ^{14}C-labelled substrates would link these substrates metabolically and compare the importance of these substrates in organic matter metabolism and the oxygen budget. Additionally, concurrent measurement of temperature, inorganic nitrogen species and phosphorus would provide information concerning limitations of ambient conditions. Quantifying concentrations and rates of conversion would significantly contribute to our understanding of the biogeochemistry of carbon cycling and lake respiration as well as assist in the assessment of artificial aeration design and sizing requirements.

Currently, in light of such variability, several years of preliminary DO and CH_4 sampling during and immediately following turnover as well as throughout winter would be necessary to accurately predict CH_4 production and its contribution to oxygen depletion.

Implications for aeration design

It has been hypothesized that shallow aeration (See Chapter 3) or aerating the middle strata of lakes (Ellis and Stefan 1989), while preserving the stratification and isolating the sediment surface from the mixing process would reduce aeration requirements by avoiding the SOD. The present data suggest that this concept may have merit for less eutrophic lakes, such as Moonshine Lake, where shallow aeration may be able to maintain considerable DO at the sediment surface and minimal quantities of CH_4 enter the water column. However, isolating the sediments of more eutrophic lakes only promotes anoxia of surficial sediment, production of potentially large quantities of CH_4 and subsequent diffusion into the stagnant layer. In short order, this CH_4 will reach the mixed layer where it will greatly increase oxygen consumption. Together with the 2 to 4 fold aeration-induced increase in oxygen demand, this design would still require a substantial system for successful aeration. On the other hand, aerating the entire water column keeps the sediment surface oxidized and meets the CH_4 oxidative demands within surficial sediments. Such subsurface CH_4 oxidation has been observed by Buchholz et al. (1995) and Kuivila (1998). Therefore, it is a matter of paying the CH_4 oxidative debt either sooner or later, but a similar debt must be met with either design to successfully aerate a lake. Thus, there is no inherent advantage to shallow aeration.

Methane concentrations were found to vary among both aerated and control lakes. Greater CH_4 concentrations in the aerated lakes were associated with greater eutrophy as indicated by higher oxygen depletion rates and the need for larger aeration systems. Estimated CH_4 oxidation rates during unaerated conditions in East Dollar Lake were among the highest rates reported in the literature at cool temperatures (Rudd and Hamilton 1978, Fallon et al. 1980, Utsumi et al. 1998). Yet, aeration increased this rate by more than two-fold and oxidation of "other" substrates increase by nearly 4-fold following the onset of aeration. This water-column oxidation was much greater than that associated with sediments. Accordingly, oxidation was the primary mechanism of CH_4 loss. Emission through the polynya surface comprised only about 10% of the CH_4 that diffused or ebullated into the water column.

Such potentially high rates of WOD explain why shallow aeration did not show greater efficiency than whole lake aeration. In fact, the DO sag following shallow aeration startup lasted nearly two weeks and resulted in an average water column loss of approximately 3 g m^{-3}. Conversely, whole lake aeration startup the previous year resulted in a DO sag lasting only 24 hours which resulted in a mean water column DO loss of less than 1 g m^{-3}. For these reasons shallow aeration does not appear to improve aeration effectiveness or the ability to downsize to smaller equipment in hypereutrophic lakes. Similarly, the unpredictability of summer CH_4 accumulation or the completeness of fall turnover in oxidizing CH_4 or venting it to the atmosphere strongly support the recommendation that aeration equipment should be started one-two weeks prior to the anticipated time of freeze up. This will facilitate mixing, enhance various oxidative processes and reaerate the water column during the open water season when atmospheric oxygen transfer is available to the entire lake surface.

References

Amaral, J.A. and R Knowles. 1995. Growth of methanotrophs in methane and oxygen counter gradients. FEMS Microbiol. Lett. 126:215-220.

Babin, J., and E.E. Prepas. 1985. Modeling winter oxygen depletion rates in ice-covered temperate zone lakes in Canada. Can. J. Fish. Aquat. Sci. 42:239-249

Barica, J., and J.A. Mathias. 1979. Oxygen depletion and winterkill in small prairie lakes under extended ice cover. J. Fish. Res. Board Can. 36:980-986.

Bartlett, K.B., P.M. Crill, R.L. Sass, R.C. Harris and N.B. Dise. 1992. Methane emission from tundra environments in the Yukon and Kuskokwim Delta, Alaska. J. Geophys. Res. 97:16645-16660.

Belanger, T.V. 1981. Benthic oxygen demand in Lake Apopka, Florida. Water Research. 15: 267-274.

Boudreau, B.P. and N.L. Guinasso. 1982. The influence of a diffusive sublayer on accretion, dissolution, and diagenesis at the sea floor. P. 115-145. In: K.A. Fanning and F.T. Manheim, editors. The dynamic environment of the ocean floor. Lexington.

Bouldin D.R. 1968. Models for describing the diffusion of oxygen and other mobile constituents across the mud-water interface. J. Ecol. 56:77-87.

Brewer, W.S., A.R. Abernathy, and M.J.B. Poynter. 1977. Oxygen consumption by freshwater sediments. Wat. Res. 11:471-473.

Buchholz, L.A., J.V. Klump, J.L.P. Collins, C.A. Branter and C.C. Remsen. 1995. Activity of methanotrophic bacteria in Green Bay sediments. FEMS Microbiol. Ecol. 16:1-8.

Campbell, P.J. and F.H. Rigler. 1986. Effect of ambient oxygen concentration on measurement of sediment oxygen consumption. Can. J. Fish. Aquat. Sci. 43:1340-

1349.

Carpenter, J.H. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr. 10:141-143.

Charlton, M.N. 1980. Hypolimnion oxygen consumption in lakes: discussion of productivity and morphometry effects. Can. J. Fish. Aquat. Sci. 37:1531-1539.

Comeau, Y., K.K. Hall, R.E.W. Hancock and W.K. Oldham. 1986. Biochemical model for enhanced biological phosphorus removal. Wat. Res. 20:1511-1521.

Cornett, R.J. and F.H. Rigler. 1980. The areal hypolimnetic oxygen deficit: an empirical test of the model. Limnol. Oceanogr. 25:672-679.

Ellis, C.R. and H.G. Stefan. 1989. Oxygen demand in ice covered lakes as it pertains to winter aeration. Water Resources Bulletin 25(6):1169-1176.

Fallon, R.D., S. Harrits, R.S. Hanson and T.D. Brock. 1980. The role of methane in internal carbon cycling in Lake Mendota during summer stratification. Limnol. Oceanogr. 25: 357-360.

Fang, X. and H.G. Stefan. 1995. Interaction between oxygen transfer mechanisms in lake models. J. Envir. Engrg. 121(6): 447-454.

Fast, A.W. 1994. Winterkill prevention in lakes and ponds using artificial aeration. Rev. in Fish. Sci. 2:23-77.

Greenbank, J. 1945. Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. Ecol. Mon. 15(04):343-392.

Hargrave, B.T. 1969. Similarity of oxygen uptake by benthic communities. Limnol. Oceanogr. 14: 801-805.

Hargrave, B.T. 1972. A comparison of sediment oxygen uptake, hypolimnetic oxygen deficit and primary production on lake Esrom, Denmark. Verh. Internat. Verein. Limnol. 18: 134-139.

Harrits, S.M. and R.S. Hanson. 1980. Stratification of aerobic methane oxidizing organisms in Lake Mendota, Madison, Wisconsin. Limnol. Oceanogr. 25:412-421.

Hesslein, R. and P. Quay. 1973. Vertical eddy diffusion studies in the thermocline of a small stratified lake. F. Fish. Res. Board Can. 30:1491-1500.

Holley, E.R. 1977. Oxygen transfer at the air-water interface. PP. 117-150. IN: Gibbs, R.J. (Ed.) Transport processes in lakes and oceans. Plenum, NY.

Howard, D.L., J.I. Frea and R.M. Pfister. 1971. The potential for methane-carbon cycling in Lake Erie. Proc. 14th Conf. Great Lakes res. (Int. Assoc. Great Lakes Res. 1971: 236-240.

Hutchinson, G.E. 1941. Limnological studies in Connecticut. IV. The mechanisms of intermediary metabolism in stratified lakes. Ecol. Monogr. 11::21-60.

Hutchinson, G.E. 1957. A treatise on limnology. 1 Geography, physics and chemistry. John Wiley and Sons, Inc. New York. 1015 p.

Iversen, N., R.S. Oremland and M.J. Klug. 1987. Big Soda Lake (Nevada). # 1. Pelagic methanogenesis and anearobic methane oxidation. Limnol. Oceanogr. 32: 804-814.

Jorgensen, B.B. and N.P. Revsbech. 1985. Diffusive boundary layers and the oxygen uptake of sediments and detritus. Limnol. Oceanogr. 30(1):111-122.

Jackson, M.B. and D.C. Lasenby. 1982. A method for predicting winter oxygen profiles in ice-covered Ontario lakes. Can. J. Fish. Aquat. Sci. 39:1267-1272.

Joergensen, L. and H. Degn. 1983. Mass spectrometric measurements of methane and oxygen utilization by methanotrophic bacteria. FEMS Microbiol. Lett. 20:331-335.

Jones, J.G., B.M. Simon and S Gardener. 1982. Factors affecting methanogenesis and associated anaerobic processes in the sediments of stratified eutrophic lake. J. Gen. Microbiol. 128:1-11.

Kelly, C.A. and D.P. Chynoweth. 1979. Methanogenesis: A measure of chemoorganotrophic (heterotrophic) activity in anaerobic lake sediments. In: Costerton, J.W. and R.R. Colwell (Eds). Native aquatic bacteria: Enumeration activity and ecology. ASTM STP 695. pp. 164-179.

Kuivila, K.M., J.W. Murray, A.H. Devol, M.E. Lidstrom and C.E. Reimers. 1988. Methan cycling in the sediments of Lake Washington. Limnol. Oceanogr. 33: 571-581.

Lackey, R.T. and D. W. Holmes. 1972. Evaluation of two methods of aeration to prevent winterkill. Prog. Fish Cult. 34: 175-178.

Lide, D.R. 2002. (Ed). CRC Handbook of chemistry and physics. Knovel. Norwich, N.Y. 83rd Edition.

Linsey, G.A. and D.C. Lasenby. 1985. Comparison of summer and winter oxygen consumption rates in a temperate dimictic lake. Can. J. Fish. Aquat. Sci. 42:1634-1639.

Mathias, J.A. and J. Barica. 1980. Factors controlling oxygen depletion in ice-covered lakes. Can J. Fish. Aquat. Sci. 37:185-192.

Martin, D.C. and D.A. Bella. 1971. Effect of mixing on oxygen uptake rate of estuarine bottom deposits. J. Wat. Pollut. Control Fed. 43:1865-1876.

McEwan, G.F. 1929. Bull. Scripps Inst. Oceanogr. Univ. Calif. (Tech. Ser.)2:306.

Michmerhuizen, C.M. and R.G. Striegl. 1996. Potential methane emmision from north-temperate lakes following ice melt. Limnol. and Oceanogr. 41(5):985-991.

Mino, T., V. Arun, Y. Tsuzuki and T. Matsuo. 1987. Effect of phosphorus accumulation on acetate metabolism in the biological phosphorus removal process. In: Ramadori R. Ed. Biological Phosphate removal from Wastewater; Advances in Water Pollution control Vol 4:27-38. Pergamon Press. Oxford.

Molongoski, J.J. and M.J. Klug. 1980. Anaerobic metabolism of particulate organic matter in the sediments of a hypereutrophic lake. Freshwater Biology. 10:507-518.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. J. Ecol. 29:280-329.

Patriarche, M.H. 1961. Air-induced circulation of two shallow Michigan lakes. J. Wildl. Manage. 25(3):282-289.

Patt, T.E., G.C. Cole, J. Bland and R.S. Hanson. 1974. Isolation and characterization of bacteria that grow on methane and organic carbon compounds as sole sources of carbon and energy. J. Bacteriol. 120:357-364.

Powell, T. and A. Jassby. 1974. The estimation of vertical eddy diffusivities below the thermocline in lakes. Wat. Resources Res. 10(2):191-198.

Pereira, H., P.C.,Lemos, M.A.M. Reis, J.P.S.G. Crespo, M.J.T. Carrondo and H. Santos. 1996. Model for carbon metabolism in biological phosphorus removal processes based on *in vivo* ^{13}C-NMR labeling experiments. Wat. Res. 30(9):2128-2138.

Prowse, T.D. and R.L. Stephenson. 1986. The relationship between winter lake cover radiation receipts and the oxygen deficit in temperate lakes. Atmosphere-Ocean 24(4):386-403.

Rudd, J.W.M., R.D. Hamilton and N.E.R. Campbell. 1974. Measurement of microbial oxidation of methane in lake water. Limnol. Oceanogr. 19(3):519-524.

Rudd, J.W.M. and R.D. Hamilton. 1975. Factors controlling rates of methane oxidation and the distribution of the methane oxidizers in a small stratified lake. Arch. Hydrobiol. 75:522-538.

Rudd, J.W.M. and R.D. Hamilton. 1978. Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism. Limnol. Oceanogr. 23(2):337-348.

Rudd, J.W.M. and C.D. Taylor. 1980. Methane cycling in aquatic environments. Adv. Aquat. Microbiol. 2:77-150.

Sansone F.J. and C.S. Martens. 1982. Volatile fatty acidcycling in organic-rich marine sediments. Geochimaca et Cosmochimica Acta 46:1575-1589.

Scranton, M.I., P. Crill, M.A. de Angelis, P.L. Donaghay and J.M. Sieburth. 1993. The importance of episodic events in controlling the flux of methane from an anoxic basin. Global Biogeochem. Cycles. 7(3):491-507.

Sebacher, D.I., R.C. Harris and K.B. Bartlett. 1983. Methane flux across the air-water interface: Air velocity effects. Tellus 35B:103-109.

Smith, S.A., D.R. Knauer and T.L. Wirst. 1975. Aeration as a lake management technique. Wisc. Dept. Nat. res. Tech. Bull. 87. 39 pp.

Smith, L.K. and W.M. Lewis. 1992. Seasonality of methane emissions from five lakes and associated wetlands of the Colorado Rockies. Global. Biogeochem. Cycles. 6(4): 323-338.

Smolders, G.J.F., J. van der Meij, M.C.M. Loosdrecht and J.J. Heijnen. 1994. Stoichiometric model of the aerobic metabolism of the biological phosphorus removal process. Biotechnol. Bioeng. 44:837-848.

Strayer, R.F. and J.M. Tiedje. 1978. In situ methane production in a small, hypereutrophic, hard-water lake: Loss of methane from sediments by vertical diffusion and ebullition. Limnol. Oceanogr. 23(6):1201-1206.

Trimbee, A.M. and E.E. Prepas. 1988. Dependence of lake oxygen depletion rates on maximum oxygen storage in a partially meromictic lake in Alberta. Can. J. Fish. Aquat. Sci. 45:571-576.

Utsumi, M., Y Nojiro, T. Nakamura, T. Nozawa, A. Otsuki, N. Takamura, M. Watanabe, and H. Seki. 1998. Dynamics of dissolved methane and methane oxidation in dimictic Lake Nojiri during winter. Limnol. Oceanogr. 43(1):10-17.

Utsumi, M., Y Nojiri, T. Nakamura, T Nazawa, A. Otsuki and H Seki. 1998. Oxidation of dissolved methane in a eutrophic, shallow lake: Lake Kasumigaura, Japan. Limnol. Oceanogr. 43(3):471-480.

Wang, W. 1981. Kinetics of sediment oxygen demand. Wat. Res. 15:475-482.

Welch, H.E., P.J. Dillon, and A. Sreedharan. 1976. Factors affecting winter respiration in Ontario lakes. J. Fish Res. Bd. Can. 33:1809-1813.

Welch, H.E., J.W.M. Rudd. And D.W. Schindler. 1980. Methane addition to an arctic lake in winter. Limnol. Oceanogr. 25(1):100-113.

Wentzel, M.C., L.H. Lotter, R.E. Loewenthal and G.V.R. Marais. 1986. Metabolic behavior of *Acinetobacter spp.* in enhanced biological phosphorus removal – a biochemical model. Water SA 12:209-224.

Zehnder, A.J.B. 1978. Ecology of methane formation. In: R. Mitchel (Ed.) Water Pollution Microbiology. Vol. 2, 248-276. John Wiley and Sons, London.

Chapter 6

General conclusions

General Conclusions

Despite the widespread use of lake aeration for winterkill prevention, details of the underlying operating principles have received little attention. I compared near and far-field circulation patterns, mechanisms and efficiency of oxygen transfer, aspects of oxygen depletion and appropriate equipment sizing between mechanical surface aeration and submersed air injection.

Air injection has traditionally been the favored design in winter lake aeration applications. This is likely an extension of the preference for air injection in waste water treatment systems. Air injection appeared to be more favorable in many respects. It produced greater velocity and circulation rates which maintained larger polynya surface areas. This has been considered advantageous in that the polynya surface is believed to be the principle avenue for oxygen transfer. In addition, in aeration tanks, greater circulation rates have been associated with more rapid surface boundary layer reformation and hence, greater reaeration rates (i.e. Smith 1986).

However, throughout the first year of investigation, air-injected lakes continually lost DO while surface-aerated lakes gained considerable amounts of DO. This was a significant finding in that power utilization ha^{-1} was much greater in the air-injection systems than with surface aeration. Investigations during the following two years focused on identifying the underlying causes of this difference. The most important discovery was that oxygen transfer into spray droplets was substantial, with a transfer efficiency of 35 to 60%. This provided 20 to 35 kg O_2 aerator^{-1} lake^{-1} d^{-1}. This was generally more than oxygen transfer through the polynya. On the other hand, oxygen transferred from ascending bubbles ranged from 0 to 2.8% efficient, or up to 4.8 kg O_2 lake^{-1} d^{-1}. Smith et al. (1975) concluded that the polynya surface provides a much greater proportion of oxygen transfer than from bubble surfaces. In my study lakes, bubble surfaces provided 0 to 15% of oxygen transfer while spray droplets absorbed 48 to 79% of the total oxygen that was transferred. This was the most important factor contributing to the greater success of surface aeration. Secondly, there was a much greater volume of water pumped (sprayed) than the volume of air released from the diffuser. Among the various aeration designs, surface spray volume ranged from 4 to10 times more per ha than volume of injected air. Application of the mass balance equation with quantitative measurements of lake DO mass confirmed these measurements.

The mass balance equation also allowed the calculation of the surface transfer coefficient (K_L) for the polynya surface. K_L values were similar between these two aeration methods. However, K_L varied inversely with the polynya surface area with extremely high K_L values associated with very small polynyas. This is the result of an increasing proportion of these small polynyas becoming involved in the highly turbulent splash zone (i.e. the zone of bursting bubbles or where spray droplets impact the lake surface). Beyond the splash zone, radial jet velocity diminishes exponentially (Chapter 2, Rogers 1992) and K_L values in large polynyas approach those reported for natural lake surfaces (e.g. Fang and Stefan 1994). Despite this rapid decline in velocity, however, the radial jet still travels several hundred m per day, with the velocity of air injection being about double that for surface aeration (Figs. 2-16 and 2-15). More importantly, although the polynya surface maintained by air injection was larger than that for surface aeration, the great majority of the lake surface (> 99%) remains ice-covered. Thus, the greater velocity observed with air injection and its expected more frequent surface boundary reformation plays a significantly restricted role in winter lake aeration as the expected benefit from greater circulation velocity is not realized. Moreover, the greater velocity induced by air injection was found to be an impediment to reaeration efficiency because it enhanced oxygen depletion rates. This was particularly evident when the diffuser was anchored over depths less than z_{max}. This is attributed to erosion of the stagnant boundary layer and increased contact frequency with oxidizable substrates.

Oxygen depletion rates were dynamic and the result of several types of oxygen-demanding components. Elevated depletion rates at the beginning of winter have been well documented and several mathematical models describe this relationship as linear or slightly curvilinear (e.g. Babin and Prepas 1985, Barica and Mathias 1979, Jackson and Lasenby 1982). However, very early winter depletion may be much greater than previously reported and initially fall in an exponential pattern. These findings are attributed to my earlier sampling - immediately following freeze up and particularly to the close proximity of sampling following the first snowfall. A similar spike in depletion rate was observed in relation to temporary thaw periods in late winter (Appendix A). Net photosynthetic oxygen production rapidly occurs (within one-two days) in the absence of snow. Yet, this bonus is eliminated just as rapidly following the next snowfall (if accumulation exceeds about 70 mm). The rapidity and magnitude of this photosynthetic DO loss can only be attributed to algal respiration (the dark reactions), of the these C-3 plants (see Appendix A). Following these post-snowfall exponential declines, a more typically linear or near-linear rate of decline begins. It was only the result of frequent sampling that allowed this discovery. This phenomenon is somewhat related to the often-observed several fold increase in oxygen depletion as a result of aeration startup (e.g. Bandow 1986, Smith et al. 1975, Patriarche 1961). These large increases are observed when aeration startup is delayed until after freeze up and lake DO has dropped to some predetermined critical value. In my study lakes this predetermined value was reached within a few days following the first snowfall. Hence, algal respiration had remained elevated as well as bacterial oxidation of myriad other compounds released by cell metabolism, cell death, or the advent of algal cells converting to a heterotrophic existence. In addition, the anoxia originating in sediments of eutrophic lakes rapidly migrates to the water column as soon as fall turnover ceases. This allows diffusion of reduced sulfides, metals and particularly CH_4 into the water column. In turn, artificial reaeration and mixing of the developing hypoxic layer readily consumes considerable amounts of oxygen. Further, incorporating methane oxidation into the mass balance model revealed that mixing greatly enhanced the rate of methane oxidation (by 2 to 3 fold and other oxidizable substrates by 3 to 4-fold (Table 5-2). This phenomenon was attributed to greater contact frequency of oxygen to substrates, similar to enhancing the rate of chemical reactions in a laboratory beaker by stirring.

These substrates are oxidized rapidly (in the range of a few days to maybe a few weeks, depending on the lake size and the actual rate of mixing). A greatly reduced and more linear depletion rate follows this initial startup period. This principle strongly supports aeration startup one to two weeks prior to ice cover. In this manner, oxygen depletion rates will have already entered this linear phase by the time freeze up occurs.

Methane production is a common occurrence in eutrophic lakes and is readily oxidized in nutrient-rich environments. Hence, it should be seriously considered in aeration design. Its presence at freeze up is unpredictable as it depends on the duration of fall turnover and accompanying wind energy. Normal turnover is effective in oxidizing or venting nearly all the CH_4 that has accumulated in the summer hypolimnion (Rudd and Hamilton 1978). Yet, where turnover has been incomplete, CH_4 may have a significant detrimental effect on the oxygen budget (Rudd and Hamilton 1978). Likewise, significant quantities of CH_4 in East Dollar lake greatly reduced the effectiveness of aeration. This became apparent in the experiment designed to evaluate the benefits of shallow vs whole lake aeration. The surface aerator was set over deep water for the 1995 to 1996 season (inducing whole-lake mixing), and set over 4 m of water during the 1996 to 1997 season, mixing only the top few m of the water column. During both years the aerator was started about three weeks after freeze up. The enhanced oxygen depletion during whole-lake aeration (approximately 4 fold) lasted only 24 hours, after which the DO began a sustained upward climb. Although CH_4 concentrations were not measured that year, the short duration of oxygen depletion following aeration startup suggests that turnover must have been effective in eliminating CH_4 and re-oxidizing the sediment surface. In contrast, during shallow aeration the following year, the lake continued losing oxygen at an average of 29 kg per day for two weeks following startup. At that time, a near-critical low DO of 3.4 mg L^{-1} had been reached in the mixed zone (top 5 m) and DO near the sediment surface was near zero. The prolonged loss of DO during shallow aeration was due to the oxidation of very high concentrations of CH_4 which remained in the water column after fall turnover. The high CH_4 concentration caused a rapid decline in DO in the stagnant layer and the large concentration gradient allowed continual diffusion of large amounts of CH_4 into the mixed zone. Oxidation of just the CH_4 consumed an estimated 45 kg·DO d^{-1} and this value alone was in excess of the oxygen supplied by the aeration process. Other substrates were also being oxidized (Table 5-3) and consequently, approximately three weeks of surface aeration were required before the lake began accumulating oxygen. It was fortunate that the surface aerator was started only two weeks after freeze up, when there was still an average of nearly 6 g DO m^3 throughout the lake. Otherwise, because the onset of aeration caused rapid and prolonged DO loss, even waiting an additional two weeks would have likely resulted in winterkill. Further, the switch to air injection in February immediately began mixing the stagnant, CH_4-rich benthic strata and caused another two-week period of sustained DO loss. Thus, both aeration systems required prolonged operation in order to overcome the substantial quantity of CH_4 that had remained trapped under the ice. Because insufficient turnover or otherwise entrapment of CH_4 under the ice is impossible to predict, the general rule of starting aeration equipment prior to freeze up should be followed.

The horizontal limit of elevated DO may also be influenced by CH_4 production and oxidation. Reduction in DO beyond approximately 800 m in Figure Eight Lake is likely due to the diffusion and oxidation of CH_4 into the mixed zone.

Traditional sizing of aeration equipment has generally been subjective and the result of trial and error or best professional judgement rather than scientific scrutiny. The only published recommendations have been for air injection. Wirth (1980) reported optimal air flow rates of 0.076-0.091 m^3 ha^{-1} (0.8-1.3 SCFM $acre^{-1}$) and Lorenzen and Fast (1977) suggested that a flow rate of 0.091 m^3 ha^{-1} (1.3 SCFM $acre^{-1}$) will provide good mixing. These values are reasonable if the goal is to create the largest polynya. For example, the largest polynya among my study lakes was achieved with air flow of 0.08 m^3 ha^{-1} (0.95 SCFM) per surface acre. This included a relatively low energy use of 0.15 kW ha^{-1}. This value allows greater heat conservation in the mixed layer which facilitates ice melting by the radial jet.

Here-to-fore, there are no known recommendations for sizing surface aeration equipment. In my study lakes, the largest polynya area was formed with similar energy use as for air injection (0.1 to 0.3 kW ha^{-1}). However, unlike air injection, this resulted in unnecessarily high lake DO values. Additional sizing experiments identified an optimal range of 0.05 to 0.15 kW ha^{-1}, depending upon the trophic state of the lake of concern. Interestingly, successful aeration of relatively large (153 ha) Swan Lake during the winter of 1997 to1998 required only 0.07 kW ha^{-1} (a total of seven 1-hp surface aerators) to maintain adequate oxygen (Dave Jackson, Alberta Conservation Association, personal communication). In addition, as with that observed in Figure Eight and Moonshine lakes, the zone of highest DO ranged to approximately 800 m, beyond which DO began to decrease. This information suggests that even larger lakes may be aerated successfully by surface aeration - resulting in a usable zone of at least an 800 m radius from where the aerators are set. However, there is one caveat to this principle, as experienced by the

Alberta Conservation Service in their attempt to aerate relatively large (215 ha) Cutbank Lake. This lake is shallow ($z_{average}$ = 1.4 m) which has allowed proliferation of large stands of macrophytes. Consequently, the radial jet flow is restricted, providing a zone of elevated DO of only about 300 m. This provides adequate DO for fish survival to only 1/4 to 1/3 of the lake surface area. Consequently, although overwinter survival has been documented, some winterkill is suspected (Daveid Jackson, Alberta Conservation Service, Peace River, personal communication).

Finally, the extent of these aerated zones is not the result of circulating cells of water as described by Baines (1961). Rather, the outgoing plume travels to the farthest shoreline (up to 1000 m in these study lakes). Further, although the vertically mixed zone contains both outgoing and return flow, as suggested by Baines (1961), near-field dye studies revealed that the outgoing plume leaves the aerator (or surface of the bubble plume) at a steep angle of about 45 degrees. The resultant mixed zone includes the entire lake volume if the aerator or diffuser is set in the deepest part of the basin. Otherwise, the mixed zone is restricted to the depth underlying the aeration device.

References

Babin, J., and E.E. Prepas. 1985. Modeling winter oxygen depletion rates in ice-covered temperate zone lakes in Canada. Can. J. Fish Aquat. Sci. 42:239-249.

Baines, W.D. 1961. The principles of operation of bubbling systems. In: Proc. symp. on air bubbling. pp. 12-22. Technical Memo. No. 70. Canadian National Research Council. Ottawa.

Bandow, F. 1986. Evaluation of winter lake aeration techniques in Minnesota. Minnesota Dept. Nat. Resources, Div. of Fish and Wildlife. Sect. Fish. Invest. Report No. 386. 48 pp.

Barica, J., and J.A. Mathias. 1979. Oxygen depletion and winterkill in small prairie lakes under extended ice cover. J. Fish. Res. Board Can. 36:980-986.

Fang, X. and H.G. Stefan. 1994. Modeling of dissolved oxygen stratification dynamics in Minnesota lakes under different climate scenarios. Project report No. 339. Prepared for Environ. Res. Lab. U.S. Environmental Protection Agency. Duluth, MN. 223 p.

Ellis, C.R. and H.G. Stefan. 1989. Oxygen demand in ice covered lakes as it pertains to winter aeration. Water Resources Bulletin 25(6) 1169-1176.

Jackson, M.B. and D.C. Lasenby. 1982. A method for predicting winter oxygen profiles in ice-covered Ontario lakes. Can. J. Fish. Aquat. Sci. 39:1267-1272.

Lorenzen, M.W. and A.W. Fast. 1977. A guide to aeration/circulation techniques for lake management. Ecological Res. Series, EPA-600/3-77-004. (Jan.) Washington, D.C.: U.S. Environmental Protection Agency.

Patriarche, M.H. 1961. Air-induced circulation of two shallow Michigan lakes. J. Wildl. Manage. 25(3):282-289.

Rudd, J.W.M. and R.D. Hamilton. 1978. Methane cycling in a eutrophic shield lake and its effects on whole lake metabolism. Limnol. Oceanogr. 23(2): 337-348.

Smith, D.W. 1986. Aeration system design protocols: a North American perspective. pp. 85-100. IN: boyle W.C. (ed.) Aeration systems. Design, testing, operation and control. Pollution technical review No. 127. Noyes Publications. Par Ridge, NJ.

Smith, S.A., D.R. Knauer and T.L. Wirst. 1975. Aeration as a lake management technique. Wisc. Dept. Nat. res. Tech. Bull. 87. 39 pp.

Wirth, T. 1980. Lake aeration in Wisconsin lakes. Wisconsin Dept. of Nat. Res. Publ-WR-196. 76 p.

Appendix A

Relationship of Snow Depth, Ice Thickness, Light Penetration and Chlorophyll *a* to Dissolved Oxygen

Introduction

Several workers have reported elevated dissolved oxygen (DO) values immediately following freeze-up and before substantial quantities of light-reflecting snow accumulate on the ice surface (Greenbank 1935, Schindler 1971, Barica et al. 1983, Babin and Prepas 1985). Although this has been associated with under ice photosynthesis (Schindler 1971, Barica et al. 1983), little data exists which correlate the period and intensity of Photosynthetically active radiation (PAR) to phytoplankton biomass and subsequent elevation in DO.

Freeze-out of oxygen during ice formation may contribute to this increase with values ranging from 32 to 97% (Mortimer 1941, Welch 1974). However, the magnitude of this contribution to the oxygen budget is relatively minor and is most significant in shallow lakes. For example, Schindler (1971) estimated that for a freeze-out of 50% the ice cover of shallow (Z_{max} = 2.5 m) Lake 303 of the ELA may cause an underestimation of the depletion rate by slightly less than 10%.

DO values have been known to greatly exceed that contributed by freeze-out alone (Schindler 1971, Barica et al. 1983). In one instance, Barica et al. (1983) found DO to be in excess of 300% saturation for nearly all of a snow-free winter. Although sampling was terminated at the end of January, chlorophyll *a* (Chl *a)* was also quite high at that time (circa 5 mg m^{-3}). Babin and Prepas (1985) measured DO and Chl *a* in several lakes in central Alberta. In one case, high Chl *a* concentrations (32 mg m^{-3}) was recorded for

Halfmoon Lake on December 14 at 1 m. This bloom could have introduced DO to the lake but DO was not measured prior to December 14 and by December 24 DO had fallen from 6.6 to 4.8 mg L^{-1}. Under snow cover DO and Chl *a* decline with Chl *a* concentration often falling below 1 mg m^{-3} (Barica et al. 1983, Babin and Prepas 1985).

Despite the understanding of this relationship, most workers have addressed only individual components such as snow and ice extinction coefficients (Bolsenga 1981, Prowse and Stephenson 1986, Maguire 1975a), under-ice light intensity (Maguire 1975b), or under-ice DO and Chl *a* (Babin and Prepas 1985). For example, Prowse and Stephenson (1986) used the multilayered model of Bolsenga (1981) to estimate radiation receipts at the ice water interface. They correlated periods of oxygen depletion to periods when light attenuation by snow and ice cover fell below the compensation point. The model pointed out the sensitivity of light penetration to particularly snow cover and to a lesser extent to opaque ice and then to clear ice.

Despite this evidence for the presence of under ice photosynthesis, the relationship between light penetration and various regimes of ice and snow cover has never been empirically determined and particularly in association with measured Chl *a* and DO concentrations. In this study, I provide several examples of the synchronous occurrence of elevated DO, substantial Chl *a* concentrations and the availability of sufficient light to exceed the compensation point beneath the snow and ice cover.

Materials and Methods

Study lakes

In order to understand the variability in lake cover, Chl *a* and DO samples were collected from all nine lakes used in this study (see Figs. 2-2 to 2-9 for bathymetric descriptions). All of these lakes are shallow (mean depth = 1.75 to 4.1 m) and are classified as hypereutrophic (mean summer Chl $a > 50$ mg m^{-3}) and would experience complete fish winterkill if they were not aerated. The control lakes were devoid of fish because of extreme oxygen depletion during winter. The greatest frequency of measurements were concentrated on two aerated lakes (East Dollar and Moonshine Lakes) and two unaerated lakes (West Dollar and Swan Lakes).

Field measurements and sample collection

This study was conducted during the 1995-1996 aeration season. Each lake was visited 5 to 17 times for DO measurements. Incident radiation (IR), under ice light photosynthetically active radiation (PAR), and Chl *a* sampling were performed at least monthly during these visits. Two to five stations (depending on lake size and morphometric features), were sampled for DO, snow depth and opaque and clear ice thickness. Dissolved oxygen was measured at one m intervals and approximately 100 mm above the bottom. Under ice light measurements and Chl *a* concentrations were measured 3 to 6 times in each lake from just prior to freeze-up to early April.

PAR (μmols m^{-2} s^{-1}) was measured using a Licor submarine photometer. Various depths of snow cover were occasionally removed to determine its impact on light penetration. In this process, a patch of snow, approximately 2 m x 2 m was cleared or reduced to the designated depth. The photometer was attached to the end of a 2 m length of 25.4 mm diam. (1-in.) PVC which was attached to a 3 m length of PVC with a 90° elbow. This apparatus was fitted through an enlarged auger hole and extended 2 m to the measuring location, located in the center of the cleared area. The auger hole was then filled with snow or ice shavings to prevent interference with light measurements. Early measurements made prior to opaque ice formation allowed visual confirmation of the sensor location.

Chlorophyll *a* samples were collected on the same days that light was measured by integrating samples from near the ice-water interface and at 1 m intervals throughout the euphotic zone. Approximate equal proportions were collected from each sampling depth using a 1.2 L Kemmerer bottle to acquire a total sample of 1 L. These samples were filtered onto Whatman GFC glass fiber filters that evening and immediately frozen. Concentrations were measured using Ostrofsky's ethanol extraction procedure described by Bergman and Peters (1980).

Samples for DO were collected from the same Kemmerer grab used to collect Chl *a* samples and additional samples were collected at 1 m intervals throughout the remainder of the water column. These samples were fixed in the field and transported to the lab for analysis using Carpenter's (1965) modification of the Winkler method.

Results

Various data from each of the study lakes provided some insight into the relationship between light penetration, Chl *a* and oxygen production. Moonshine Lake provided perhaps the most useful data set. A late fall algal bloom became apparent before freeze-up. The greatest concentration of Chl *a* occurred on the leeward side of the lake where prevailing western winds had concentrated buoyant blooms of *Aphanizomenon flos-aqua*. Chlorophyll *a* concentrations were @ 70 mg m^{-3} and DO concentrations were near saturation at 10.9 g m^{-3} (Fig. A-1B. The first snowfall (180 mm) occurred on November 9, seven days after freeze-up. Yet DO had increased to 13.0 g m^{-3} under the ice and 11.7 g m^{-3} at 1 m. The ice was only 80 mm thick and, although Chl *a* had fallen by 50%, it remained very high at 33 mg m^{-3}. This substantial snowfall immediately submersed the ice and measurements on November 19 indicated that 9 cm of cloudy ice had formed. A slush thickness 30 mm remained and there were 20 mm of snow. The slush was considered as cloudy ice for light transmittance measurements (Fig. A-1A). There was only ten additional mm of clear ice (90 mm total). Yet, DO at Station B had increased to 14.7 g m^{-3} at the surface and 11 g m^{-3} at 1 m. A notable increase in Chl *a* (to 63 mg m^{-3}) at 1 m was also measured and was associated with the ability of sufficient light [> compensation point, here defined as 10 μmol m^{-2} sec^{-1} (Moss 1988)] to reach a depth of 0.75 m. Following the second major snowfall on about November 25, Chl *a* concentrations began a sustained decline. The rate of this decline could not be accurately determined during this time because of the length of time between sampling visits. However, values obtained in late

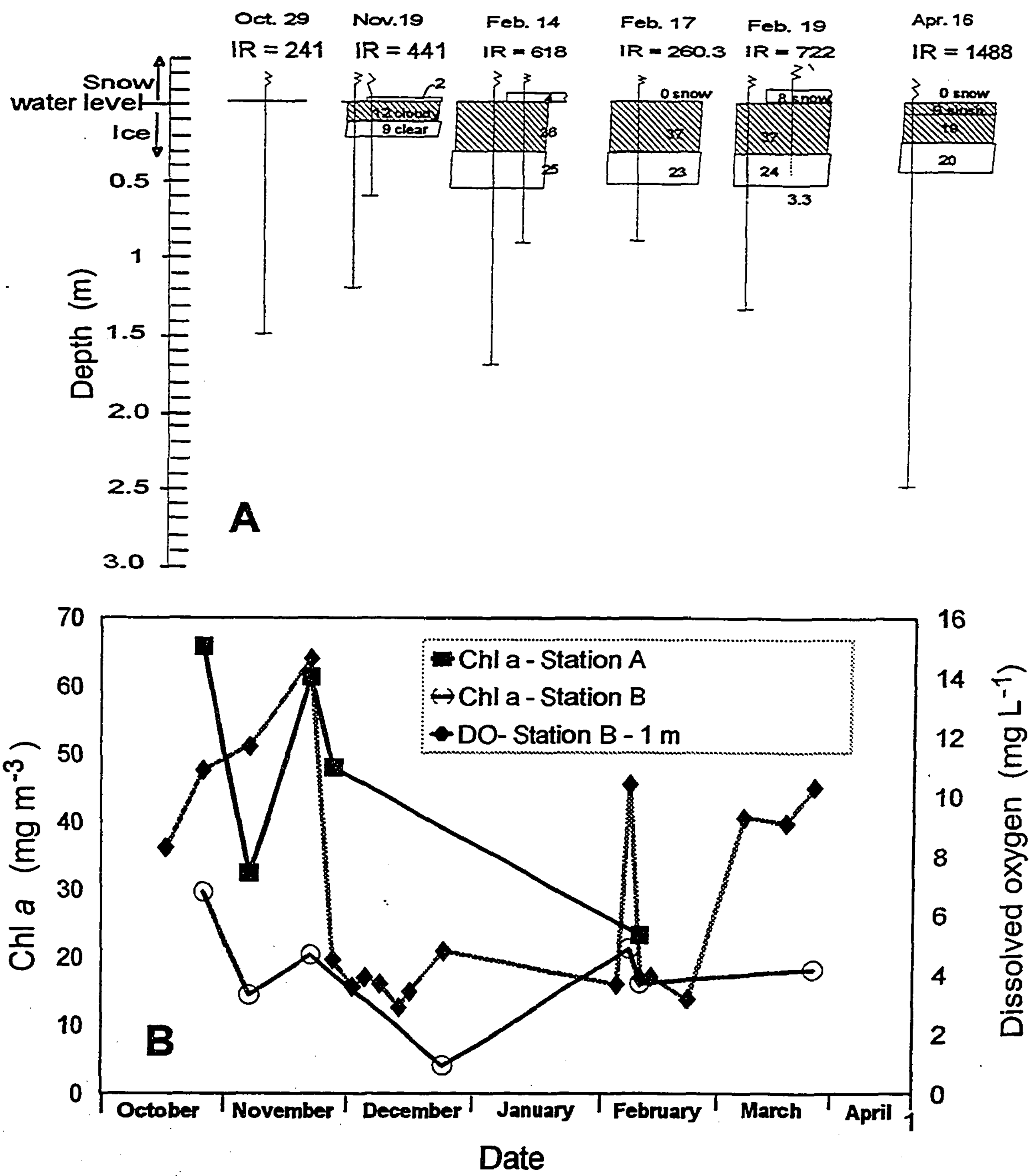

Figure A-1 (A) Snow depth, ice thickness and light penetration in Moonshine Lake. The vertical bars indicate the depth at which light was attenuated to 10 umols m^{-2} s^{-1} (the approximate compensation point). Measurements were made under snow and after the snow was artificially removed. IR = incident radiation with a water droplet on the sensor. Values located under the ice layer were measured at the ice-water interface; (B) Chlorophyll *a* and dissolved oxygen concentration. Station A was located approximately 20 m from the eastern (leeward) shoreline. Station B was located 150 m west of stastion A. The rapid decline in Chl *a* during November occured during a periood of 120 to 280 mm of snow accumulation. Note how frequent sampling reveals rapid response of Chl *a* to the presence or absence of light.

December from Station B indicate values had declined considerably (Fig. A-1B).

A mid-February thaw eliminated all the snow from Moonshine Lake (Fig. A-1A). During the time snow cover had declined to ≤ 40 mm (February. 13 - February 17), light could penetrate at least 1 m into the water column. Chlorophyll *a* concentrations experienced a resurgence at Station B and DO at 1 m spiked from 3.65 g m^{-3} on February 12 to 12.4 g m^{-3} on February 14. This February bloom occurred despite the continual operation of aeration equipment. Heavy cloud cover and rain greatly reduced incident radiation from February 15 to 17 and this caused an equally rapid decline in both Chl a and DO to pre-thaw values. This storm event ended after an 8o mm snowfall on February 18 and considerable snow cover (>80 mm) persisted until mid April. At this time snow melt once again allowed adequate light to penetrate through the ice and induce photosynthetic oxygen production (Fig. A-1).

East Dollar Lake behaved somewhat different from Moonshine Lake. Although the heavy snowfall of early November caused some cloudy ice formation considerable (> 100 mm) of snow remained on the ice (Figure A-2). As a result, DO at 1 m increased only slightly, probably due to freeze-out and Chl *a* steadily decreased after freeze-up to only about 1 mg m^{-3}. As with Moonshine Lake, aeration caused an immediate decrease in surface DO and the lake became homogeneous within 24 hours. The lake was aerated continuously until mid January at which time aeration was discontinued for about 30 days. Also similar to Moonshine Lake, the mid-February thaw melted all the snow on East Dollar Lake. From February 9 to 17, the lake had ≤ 20 mm of snow. On a cloud-free day (February 15) the compensation point reached approximately 3 m. During these few days,

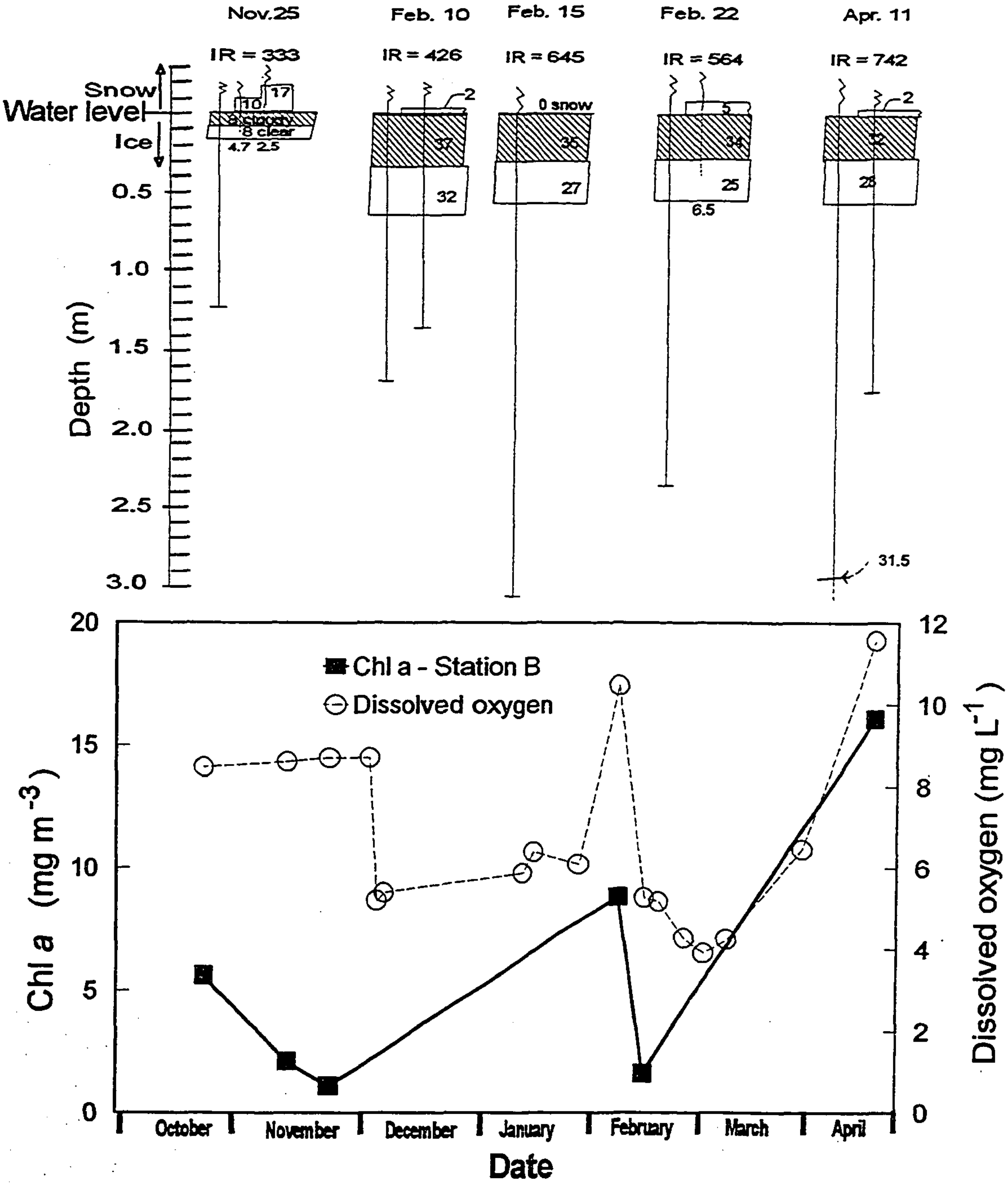

Figure A-2. (A) Snow depth, ice thickness and light penetration in East Dollar Lake, 1995-1996. Vertical bars indicate the depth at which light was attenuated to 10 umols m^{-2} s^{-1} (the approximate compensation intensity for phytoplankton). Measurements were made under snow and after snow was artificially removed. IR = incident radiation with a water droplet on the sensor. Values located under the layer were measured at the ice-water interface. Note that even 50 mm of snow over cloudy ice (February 22) was enough to reduce light in the water column to below the compensation intensity. (B) Chlorophyll *a* and dissolved oxygen concentrations. Chlorophyll *a* was measured in integrated samples from the euphotic zone or at 1 m below the hydrostatic surface. Values for dissolved oxygen are from 1 m below the hydrostatic surface.

Chl *a* had increased several fold (from 1 to 8 mg m^{-3}) and DO surged from 5.8 to 10.5 g m^{-3}. Fifty mm of snow fell on February 18 and measurements made on February 22 indicated that this was sufficient to reduce light to below the compensation point in the water column - even though it was a near-cloudless day. In addition, the DO had fallen to below the pre-bloom concentration. The lake actually appeared to resume the depletion rate that it was experiencing prior to the thaw event. During this same time interval, Chl *a* also dropped dramatically to the approximate pre-bloom value of 1 mg m^{-3}. Surface aeration was resumed on March 3 which immediately began adding oxygen to the water column. Most of the snow was again eliminated by the end of March (snow depth = 40 mm on March 29). Measurements on April 11 confirmed that considerable light was penetrating the water column with 20 mm of wet snow and Chl *a* had again increased to very high levels under the ice.

Figure Eight Lake exhibited a similar trend. There was an increase in dissolved oxygen immediately after freeze-up which was most likely associated with photosynthesis during this early snow-free period (Fig. A-3). A major snowfall (120 mm) occurred on November 8. However, this was rapidly converted to opaque ice at Stations A and C which resulted in $\leq$ 30 mm of snow cover from November 10 to 25. Notably, even under cloudy skies on November 21, yielding low incident radiation, light in excess of the compensation point penetrated nearly 1.5 m under ice and 10 mm of snow (Fig. A-3A). Aeration startup on November 21 began to decrease DO at Station A (closest to the aerator) but the next major snowfall of 130 mm on November 25 was also associated with the decline in both DO and Chl *a* at that time. Chlorophyll *a* remained low (circa 1.5 mg m^{-3}) for the remainder of the

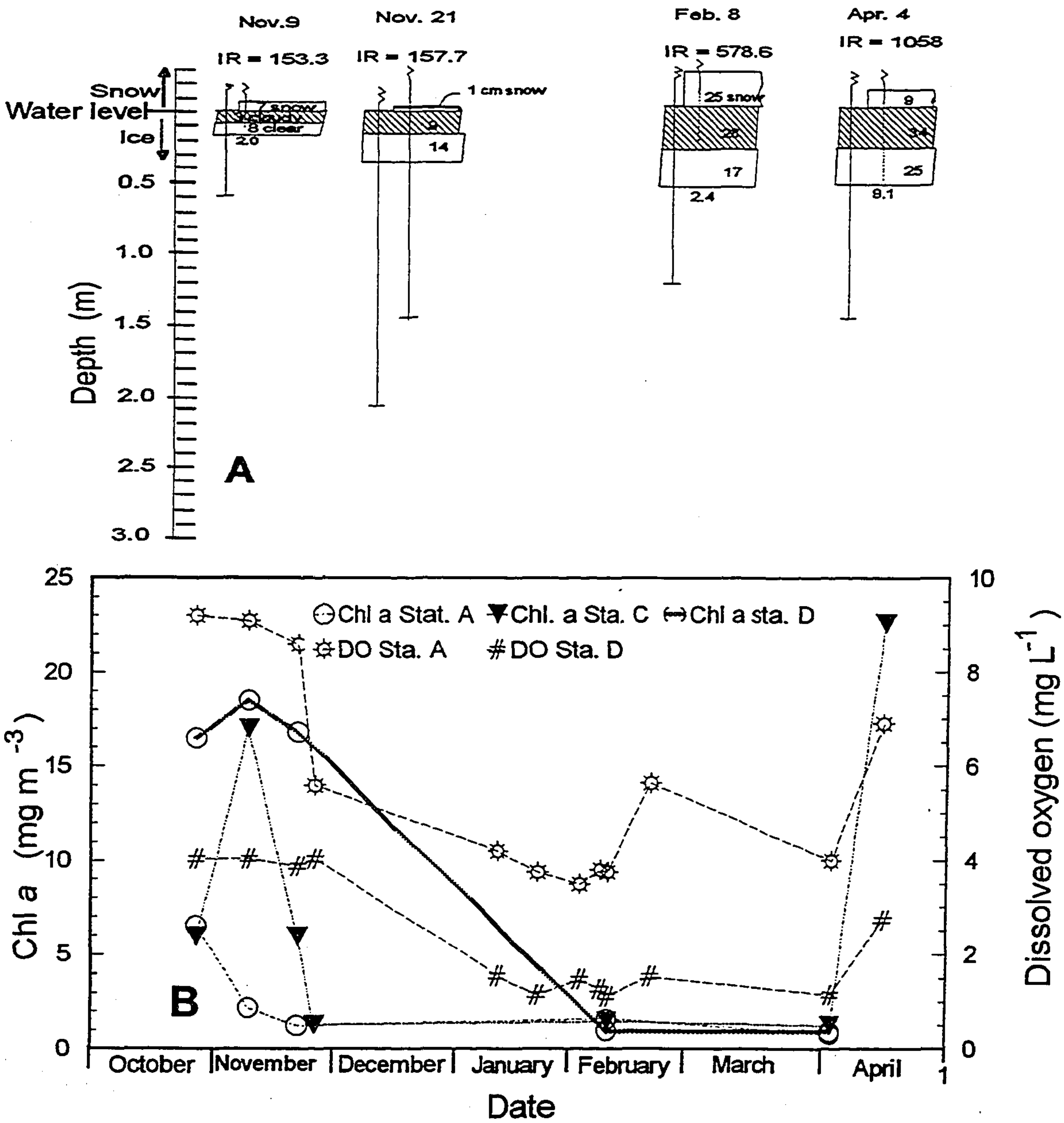

Figure A-3. (A) Snow depth, ice thickness and light penetration in Figure Eight Lake, 1995-1996. Station A was located 100 m from the aeration site, Station B was located approximately 600 m away and Station D was 900 m away. Vertical bars indicate the depth at which light was attenuated to 10 umols m^{-2} s^{-1} (the approximate compensation intensity for phytoplankton). Measurements were made under snow and after snow was artificially removed. IR = incident radiation with a water droplet on the sensor. (B) Chlorophyll *a* in integrated samples from the euphotic zone or at 1 m under the ice and dissolved oxygen at 1 m. Sampling stations were located in each of the three basins (See Figure 2-5). The first major snowfall occurred November 7, but this snow was rapidly converted to opaque ice. Aeration was started November 21 and the second major snowfall occurred on November 25. Values located under the ice were measured at the ice-water interface. The increase in DO during February was due to the temporary operation of 2 surface aerators to boost concentrations.

winter at all three stations as there were no observed snow-free periods. The temporary increase in DO at Station A occurred as a result of temporarily (two weeks) operating two surface aerators to boost concentrations. These aerators were installed near the diffusers and hence had little effect on DO concentrations at Station D - 600 m away. By the middle of April the lake was snow-free and DO and Chl *a* increased substantially (Fig. A-3).

Chlorophyll *a* and DO were also measured in two unaerated control lakes. Fall and early winter characteristics were similar to those of aerated lakes. In Swan Lake, freeze up occurred on about November 1. As with the other lakes, most of the substantial snowfall that occurred on November 8 rapidly converted to opaque ice and considerable light was able to penetrate the water column for several more weeks (Fig. A-4A). Although Chl *a* had decreased from pre-freeze up concentrations it had remained relatively high (9.1 mg m^{-3}) until the second visit on November 16. This was concurrent with an increase in DO of nearly a full mg L^{-1} from pre-freeze up values. The mid-winter sample also revealed a substantial decline in Chl *a* under prolonged periods of snow cover. Although Chl *a* was not measured there was also a brief snow-free period in February that likely had boosted DO values to near the December values.

West Dollar Lake was apparently the most eutrophic of all the study lakes. The pre-freeze up Chl *a* was at 76.2 mg m^{-3} (Fig. A-5). Yet, the first sample after freeze-up yielded a value of 191.5 mg m^{-3}. The standard deviation among the lab triplicates was 1.24 indicating that there was little analytical error. Dissolved oxygen at that time was very near saturation. However, the depletion rate following the November 23 snowfall was extraordinarily high (0.89 g m^{-2} day^{-1}) and by December 27, the DO at 1 m was 0.32 g m^{-3}

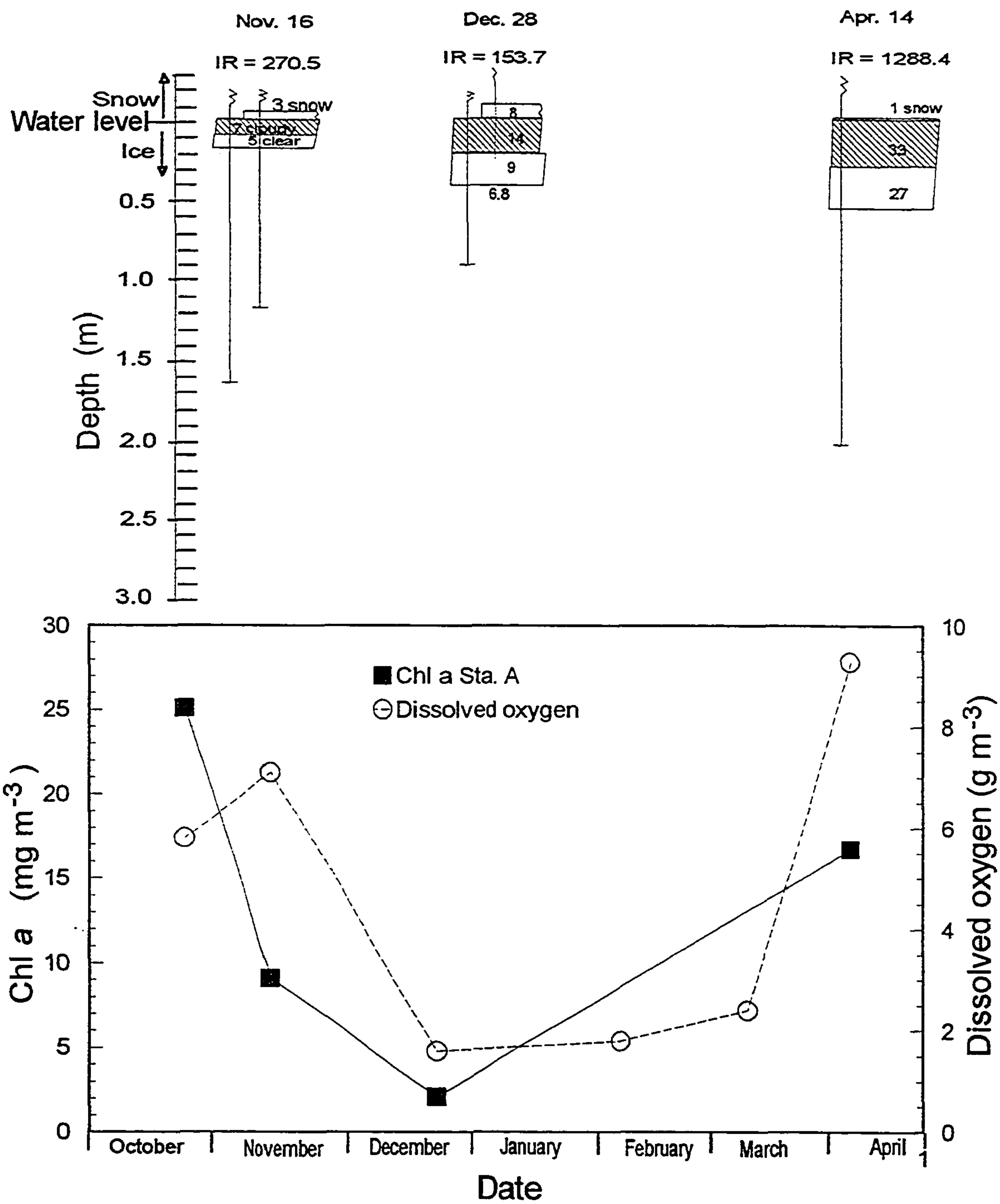

Figure A-4. (A) Snow depth, ice thickness and light penetration in Swan Lake, 1995-1996. Vertical bars indicate the depth at which light was attenuated to 10 umols m^{-2} s^{-1} (the compensation intensity for phytoplankton). Measurements were made under snow and after snow was artificially removed. IR = incident radiation with a water droplet on the sensor. (B) Chlorophyll *a* and dissolved oxygen at Station A. Chlorophyll *a* was measured in integrated samples from the euphotic zone or at 1m depth. The first major snowfall occurred November 26. Values located under the ice layer were measured at the ice-water interface. Note that 80 mm of snow reduced light intensity to below the compensation point, IR was also low at this time of year.

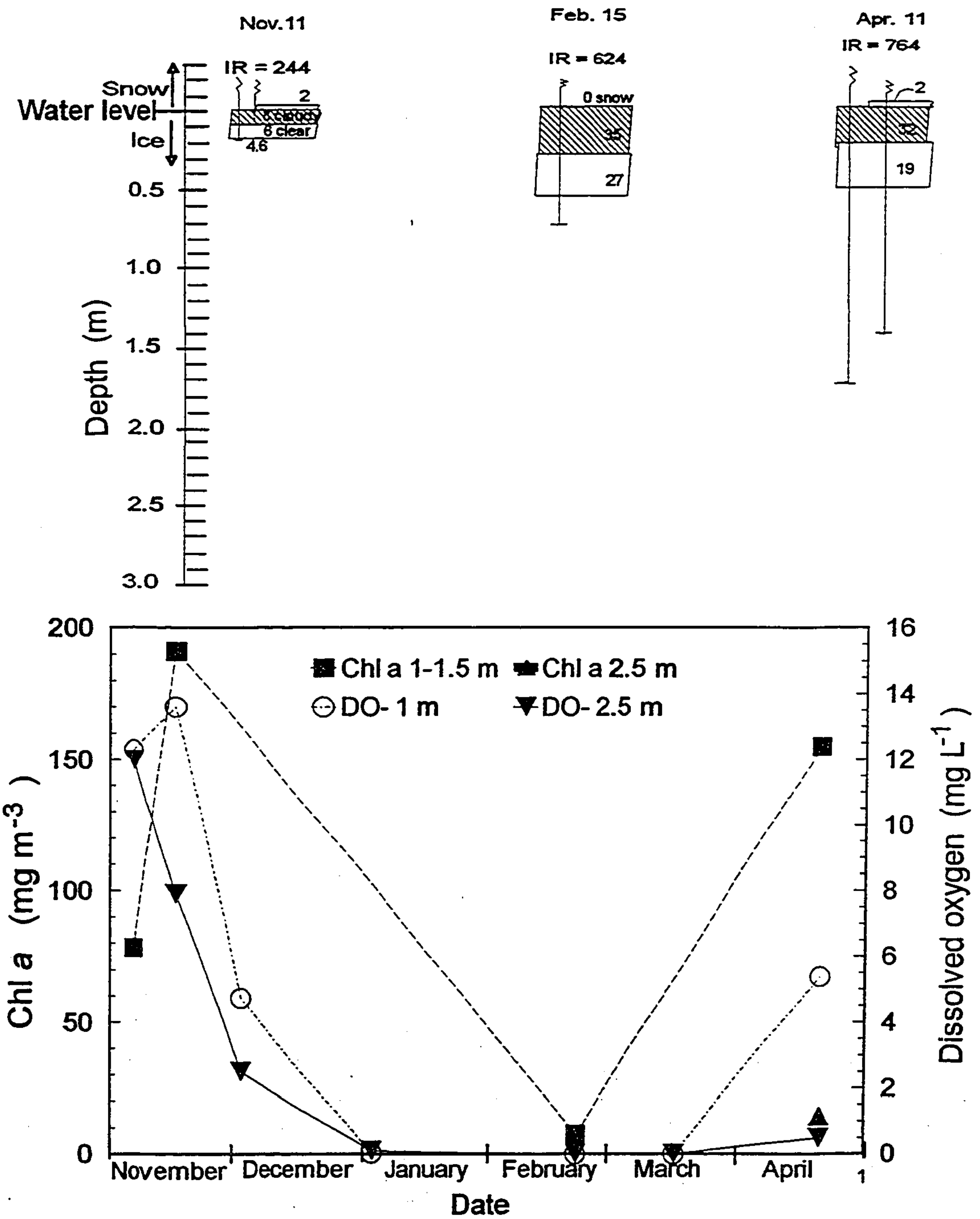

Figure A-5. (A) Snow depth, ice thickness and light penetration in West Dollar Lake, 1995-1996. Vertical bars indicate the depth at which light was attenuated to 10 umols m^{-2} s^{-1} (the compensation intensity for phytoplankton). Measurements were made under snow and after snow was artificially removed. IR = incident radiation with a water droplet on the sensor. (B) Mean of triplicate Chl *a* samples in integrated samples from the euphotic zone or at 1 m depth and dissolved oxygen at 1 and 2 m. The first major snowfall occurred November 26. Values located under the ice layer were measured at the ice-water interface. Note extremely high Chl *a* concentrations immediately after freeze up.

while the bottom 3 m had reached anoxia. Chlorophyll *a* had also fallen dramatically to 7.25 mg m^{-3} by February 15. On April 15 samples were collected from two depths. The 0.5 to1.0 m integrated sample indicated a dramatic recovery in Chl *a* to 155 mg m^{-3} while that at 2.5 m was only 14.25 mg m^{-3} (Fig. A-5B). Similarly, DO had recovered to 5.39 g m^{-3} at 1 m and 0.13 g m^{-3} at 2 m.

Discussion

Although evidence for under-ice photosynthesis has primarily been obtained immediately following freeze up (i.e. Greenbank 1945, Schindler, 1971, Barica et al. 1983, Chapter 2), this study provides evidence that under-ice photosynthesis can occur at any time snow cover is less than 50 to 70 mm and can provide substantial quantities of DO. Dissolved oxygen exceeded saturation with no or very little growth of clear ice.

The ability to add net primary production is dependant upon light intensity to exceed the compensation point in the water column. In freshwater systems this value has been as low as 2.8 μmol m^{-2} s^{-1} (0.445 W m^{-2} s^{-1}) for individual cultured species such as *Chlorella pyrenoidosa* (Gibbs 1962) and 6.25 μmol m^{-2} s^{-1} in cultures of multiple species (Steeman-Nielsen and Hansen 1959) The in situ compensation point is generally considered to approximate 10 μmol m^{-1} s^{-1} (1.6 W m^{-2} s^{-1}) (Moss 1988). In the present study, in all cases where increased DO were observed, light intensities $\geq$ 10 μmol m^{-2} sec^{-1} penetrated to depths > 1 m.

Chlorophyll *a* has been found to fall to near 1 mg m^{-3} under heavy snow cover in Alberta lakes (Babin and Prepas 1985). This was also the case in this study (Figs. A-1 to A-5). However, Chl *a* concentrations were very responsive to periods of very little or no snow, including temporary late-winter thaws. For example, following persistent snow cover from mid-November until February, Chl *a* fell to approximately 2 mg m^{-3}. Yet, during the very short (4 days) February thaw, Chl *a* concentrations increased to 8 mg m^{-3} in East Dollar Lake and to 20 mg m^{-3} in Moonshine Lake (Fig. A-1, A-2). Equally notable, however, Chl *a* concentrations rapidly declined to near pre-bloom concentrations just 5 days after the ensuing snowfall at East Dollar Lake (Fig. A-2) and after just three days of new snow cover at Moonshine Lake (Fig. A-1).

The February thaw also eliminated the snow cover in West Dollar Lake and light intensities exceeding the compensation point entered the water column (Fig. A-5). Greater that 10 μmol m^{-2} sec^{-1} reached 200 mm beneath the ice into this turbid lake. Yet, no increases in Chl *a* or DO were observed. This suggests that the estimate of 10 μmol m^{-2} s^{-1} by Moss (1988) may overestimate the compensation point in West Dollar Lake. However, it is also possible that the shallow zone which exceeded 10 μmol m^{-2} sec^{-1} may not have been sufficient to provide discernable differences in Chl *a* or DO. Also, the highly reducing conditions, as indicated by a heavy H_2S odour and high concentrations of CH_4, as measured the following year, may have readily consumed photosynthetically produced oxygen.

Interestingly, the algal bloom and subsequent spike in DO in Moonshine Lake occurred during aeration by air injection. This was particularly unexpected in that air injection was found to cause greater velocity and hence turbulence that surface aeration (See Chapter 2). One explanation for this observation is that, in this case, the diffusers were anchored over only 1.75 m. This caused the mixed layer to penetrate to only about 2 m (see Chapter 2; Fig. 2-25). Because light intensity exceeding the compensation point could easily penetrate this layer it is understandable that Chl *a* and subsequent oxygen production could experience a sharp increase in this mixed layer. Had the diffuser been anchored at a deeper location, creating a mixed layer which exceded the compensation point, it would be unlikely that such a bloom and associated oxygen production to the observed magnitude would develop.

The reduction in light penetration by snow and ice cover has been studied previously. Maguire (1975a) measured extinction coefficients for fresh powder snow, hard powder snow, cloudy ice and clear ice. He then tested these values against field measurements and found, for example, that under 100 mm of soft new snow, 50 mm cloudy ice and 300 mm cleart ice that predicted and observed PAR intensities were 2.8 and 2.7 μmol m^{-2} s^{-1}, respectively. Even though IR was not reported, his measurements of radiation receipts to the water are similar to those measured in this study. For example, reducing snow depth to 100 mm on East Dollar Lake on November 25 allowed 4.7 μmol m^{-2} s^{-1} to penetrate 80 mm of cloudy ice and 80 mm of clear ice (Fig. A-2). Similarly, under relatively high IR (1058 μmol m^{-2} s^{-1}) on February 22 at Figure Eight Lake 9.35 μmol $m^{-2}s^{-1}$ penetrated 70 mm of fresh snow, 350 mm of cloudy ice and 140 mm of clear ice (Fig. A-3). Even just 80 mm of fresh snow over 100 mm of clear ice at Cummings Lake (Fig 3-25) was able to reduce 461 μmol $m^{-2} s^{-1}$ of IR (on cloud-free November 11, 1995) to 11.1 μmol $m^{-2} s^{-1}$ at the ice-water interface. These data strongly emphasize the importance of snow in eliminating light penetration into the water body. This threshold is further diminished as the thickness of cloudy ice increases. For example, on February 22 East Dollar Lake had 340 mm of cloudy ice over 25 mm of clear ice. Just 50 mm of snow reduced light to below the compensation point (6.5 μmol $m^{-2} s^{-1}$) at the ice-water interface. Similarly, at Moonshine Lake on February 14, there were 350 mm of cloudy ice, 250 mm of clear ice and 40 mm of snow. This slightly less amount of snow on Moonshine Lake allowed the compensation point to penetrate approximate 300 mm into the water column. Because IR was very similar and measured on cloudless days these values might be considered to encompass the threshold of net primary production under these various conditions of northern Alberta lakes.

All of these study lakes experienced a recovery in both Chl *a* and DO by early to mid-April. In each case, increased light penetration was possible as snow cover was eliminated. West Dollar Lake proved to be an exceptional case. An extremely large increase in Chl *a* (158 mg m^{-3}) was measured at the 1 m depth on April 15. Even though this value was > 10 fold higher that all other study lakes except Figure Eight Lake, DO remained relatively very low at only 5.7 mg L^{-1}. The reason for this discrepancy is unknown. However, as mentioned above, the entire water column had experience prolonged anoxia, which was accompanied by a substantial buildup of H_2S and likely CH_4 as well. For example, CH_4 ranged from 100 μmol at 1 m to about 500 μmol at the sediment surface by December 19 of the 1996 to1997 season. Although CH_4 was not measured during the 1995-1996 season, oxygen depletion rates were similar among all study years (See Chapter 3). Hence, it is likely that this large inventory of biochemical oxygen demand was consuming photosynthetic oxygen nearly as quickly as it was being produced.

In addition, although respiration is a measurable quantity in primary production studies, individual values vary substantially among populations. Platt and Jasby (1976) incubated natural marine populations of phytoplankton and estimated a R^B/P_m^B of ~4%, where P_m^B = the specific production rate at optimal light intensity (mg C[mg Chl a]$^{-1}$ h^{-1}) and R^B = the respiration rate normalized to Chl a (also in mg C[mg Chl a]$^{-1}$ h^{-1}). However, other workers have found R^B/P_m^B to vary from 8 to 100% in isolated cultures (Subba Rao 1969, Humphrey and Subba Rao 1967). Higher values were generally associated with older populations. Hence, it is possible that such low DO values with respect to the high Chl a concentration could be due to either the presence of high oxygen-consuming compounds and/or high re spiration rates of phytoplankton populations themselves.

References

Babin, J., and E.E. Prepas. 1985. Modeling winter oxygen depletion rates in ice covered temperate zone lakes in Canada. Can. J. Fish Aquat. Sci. 42:239-249.

Barica, J., J. Gibson, and W. Howard. 1983. Feasibility of snow clearing to improve dissolved oxygen conditions in a winterkill lake. Can. J. Fish. Aquat. Sci. 40:1526-1531.

Bergmann, M., and R.H. Peters. 1980. A simple reflectance method for the measurement of particulate pigment in lake water and its application to phosphorus-chlorophyll-seston relationships. Can. J. Fish. Aquat. Sci. 37: 111-114.

Bolsenga, S.J. 1981. Radiation transmittance through lake ice in the 400-700 nm range. J. Glaciol. 29:57-66.

Carpenter, J.H. The Chesapeake Bay Institute technique for the Winkler dissolved oxygen method. Limnol. Oceanogr. 10:141-143.

Gibbs, M. 1962. Respiration. p. 62-94. In: Physiology and biochemistry of algae. R.A. Lewin (Ed.). Academic Press, New York.

Greenbank, J. 1945. Limnological conditions in ice-covered lakes, especially as related to winter-kill of fish. Ecol. Mon. 15(04):343-392.

Humphrey, G.F. And Subba Rao, D.V. 1967. Photosynthetic rate of the marine diatom *Cylindrotheca closterium*. Aust. J. Ecol. 18: 111-119.

Maguire, R.J. 1975a. Light transmission through snow and ice. Can. Sci. Ser. No. 91. Inland Water Directorate, C.C.I.W. Branch.

Maguire, R.J. 1975b. Effects of ice and snow cover on transmission of light in lakes. Environ. Can. Sci. Ser. No. 54. Ibid.

Moss, B.1988. Ecology of fresh waters, man and medium. Second Edition. Blackwell Scientific Publications. Oxford. 417 p.

Mortimer, C.H. 1941. The exchange of dissolved substances between mud and water in lakes. I and II. J. Ecol. 29: 280-329.

Platt, T. and A.D. Jassby. 1976. The relationship between photosynthesis and light for natural assemblages of coastal marine phytoplankton. J. Phycol. 12: 421-430.

Prowse, T.D. and R.L. Stephenson. 1986. The relationship between winter lake cover radiation receipts and the oxygen deficit in temperate lakes. Atmosphere-Ocean 24(4):386-403.

Schindler D.W. 1971. Light, temperature, and oxygen regimes of selected lakes in the Experimental Lakes Area, Northwestern Ontario. J. Fish. Res. Bd. Canada 28:157-169.

Steemann-Nielsen, E. and V.K. Hansen. 1959. Measurements with the Carbon-14 technique of the respiration rates in natural populations of phytoplankton. J. Cons. Int. Explor. Mer. 29: 19-24.

Subba Rao, D.V. 1969. *Asterionella japonica* bloom and discoloration off Waltair, Bay of Bengal. Limnol. Oceanogr. 14: 632-634.

Welch, H.E. 1974. Metabolic rates of arctic lakes. Limnol. Oceanogr. 19: 65-73.

Appendix B

Convective Circulation Patterns in an Unaerated Lake

and a Destratified, Post-Aerated Lake

Introduction

One of the primary goals of this thesis was to describe aeration-induced circulation patterns and test the hypothesis that winter lake aeration involves large-scale convective flow patterns rather than discrete cells of circulating water. Dye was used to determine far field velocity, thickness of the detrainment plume and horizontal extent of the circulation process.

I wanted to compare these aeration-induced circulation patterns with natural under-ice convective flow. To accomplish this, I injected dye into unaerated West Dollar Lake and in East Dollar Lake after the aeration system had been shut down for about three weeks but yet when the lake was still nearly isothermal.

Methods and Materials

Study lakes

The size and morphometric details of East and West Dollar lakes are presented in Fig. 2-6. Lake temperature in East Dollar Lake when this test was done ranged from 0.4 °C at 1 m to 0.6 °C at 8 m and was 1.1 °C at the sediment surface (8.5 m). West Dollar Lake ranged from 4.6 °C at the bottom to 0.9 °C at 1 m.

Dye Injections

Dye injections in West Dollar Lake were performed at midway between the center and shoreline at both the east and west sides of the lake. Dye was injected at the 2 and 3 m depths to determine if the slight variation in depth and temperature were associated with different flow patterns A sampling grid was established with north-south and east-west orientation with sampling points at 5 m intervals to facilitate tracking and mapping of dye movement. Hence, 20 - 30 holes were drilled each day to track dye movement.

Dye was injected in East Dollar Lake approximately three weeks after aeration was shut down. Injections were made very near the centre of the lake at 3 m and later at 6 m deep. Holes were drilled along three axes that intersected at the lake's center to trace the direction and rate of movement. Additional sampling was performed at 5 m intervals at sites perpendicular to some of the axes to better trace zones containing particularly high dye concentrations. Dye was traced for four days in these tests.

Rhodamine WT (Ben Meadows Catalogue) was the chosen dye. Approximately 100 mL was used for each injection. Dye release was accomplished by pouring through various lengths of PVC tubing. The bottom of the tube was fitted with a cap which was drilled in four directions to allow equal lateral dispersal. Several litres of lake water were poured into the tubing following the dye to insure complete injection of dye.

Samples were collected with a 1.2 L Kemmerer bottle and dye concentrations were measured using a Turner model 53A Fluourometer. Serial dilutions in tap water indicated that the detection limit was between 1 and 2 $\eta g\ L^{-1}$. However, similar dilutions in lake water reduced sensitivity to approximately 5 ηg L^{-1}.

Results

At both injections points in West Dollar Lake dye movement traveled about 20 m per day in anticyclonic (clockwise) fashion (Fig. B-1). Most of this dye was found at the 3.5 m depth after 24 hours and near the bottom (4 to 4.5 m) on subsequent days. This movement was easily traced throughout the four-day period.

The first injection at East Dollar Lake was at the 3 m depth. Traces of dye were detected in all directions (Fig. B-2). However, a bolus of particularly high concentration was found to emanate from the centre and followed an anticyclonic path.

A second injection was performed at 6 m deep to determine water movements in deeper strata (Fig. B-3). Traces of dye were again found to radiate in all directions from the center of the lake. However, unlike the earlier, shallow injection, a concentrated mass was found that traveled in a cyclonic pattern and descended to a depth of 7 m.

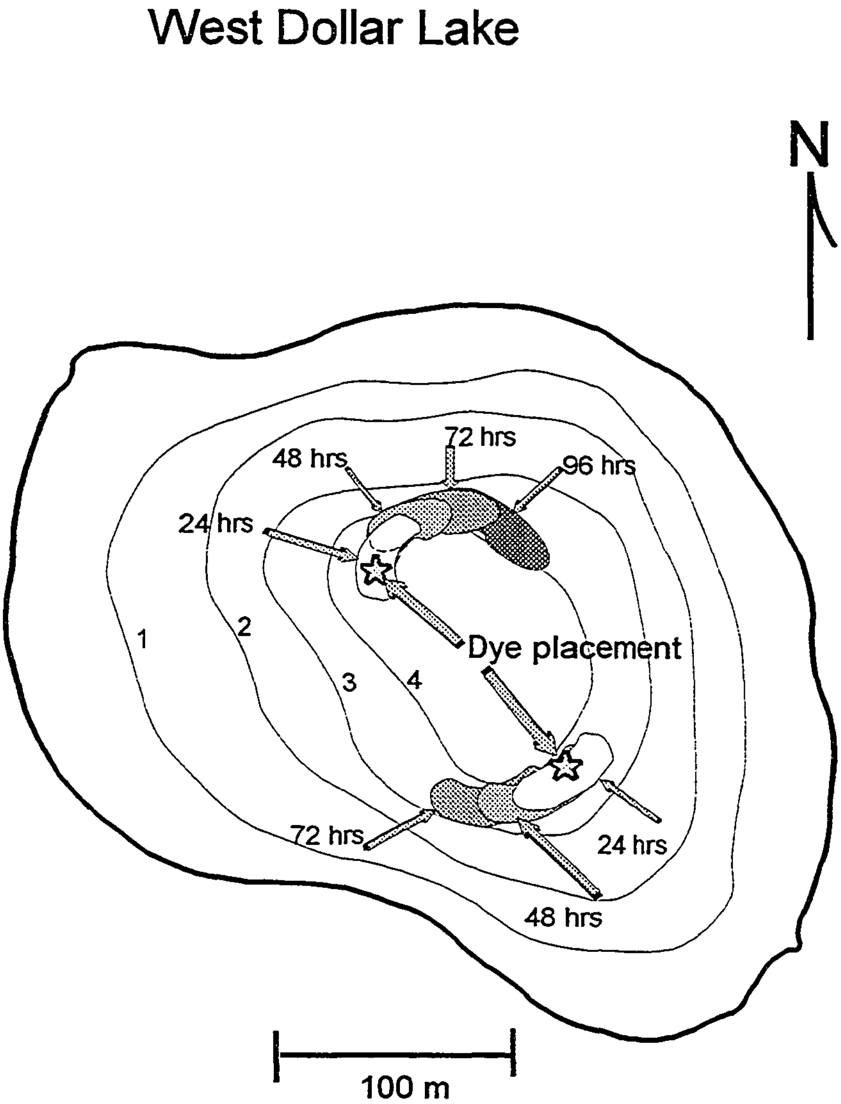

Figure B-1. Dye movement in non-aerated West Dollar Lake. Dye was injected at two points approximately 50 m from the center of the lake and at a depth of 3 m. Most dye was found at 3.5 m after 24 hours and near the bottom (4.5 m) on subsequent days.

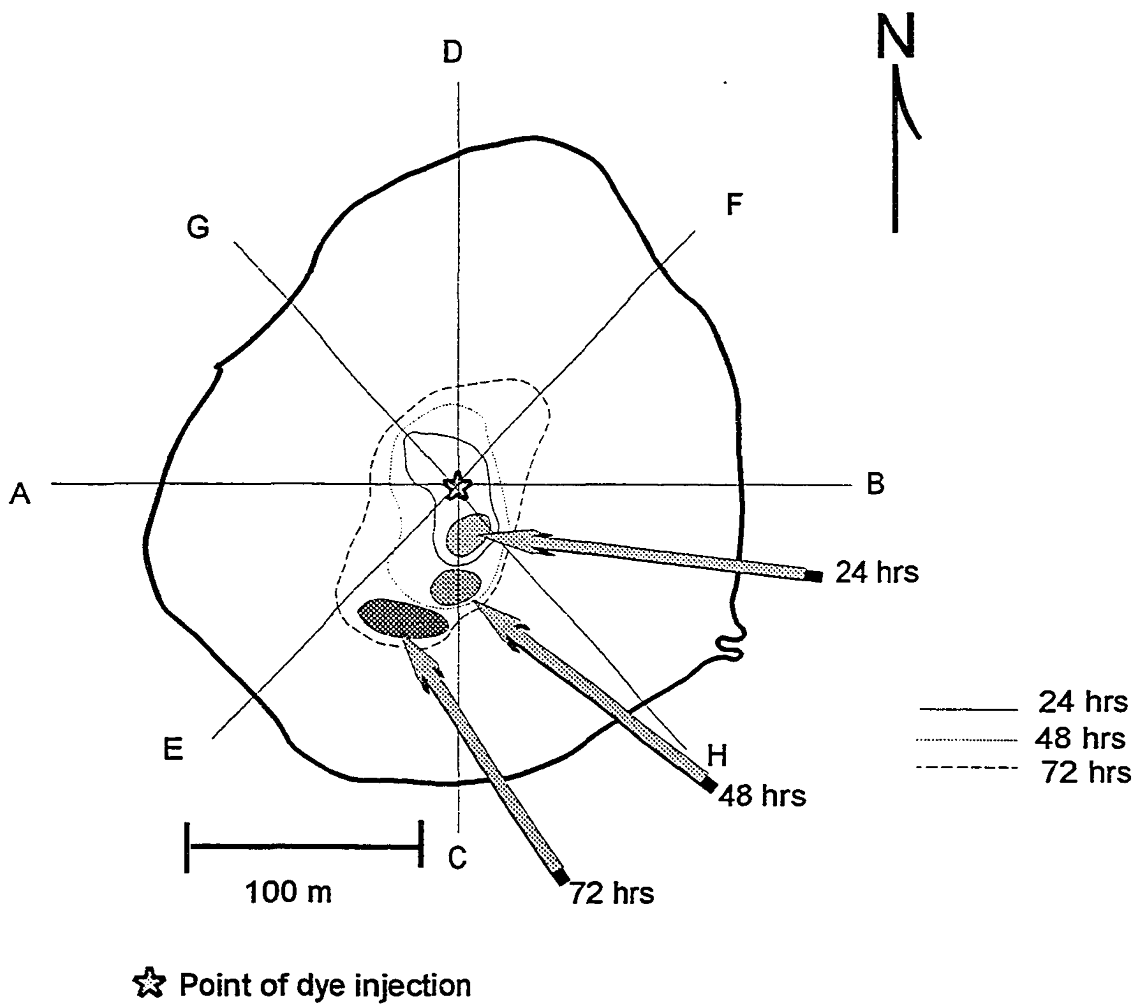

Figure B-2. Dye dispersal following injection at the geographic center of East Dollar lake. Artificial aeration had been termined three weeks previously but the lake had remained thermally destrafied. Rhodamine wt dye was injected at 3 m deep. The shaded area indicates a distinctly identifiable bolus of relatively high dye concentration that was traced at the 4 to 5 m depth. The dashed line represents the limit at which traces of dye were found.

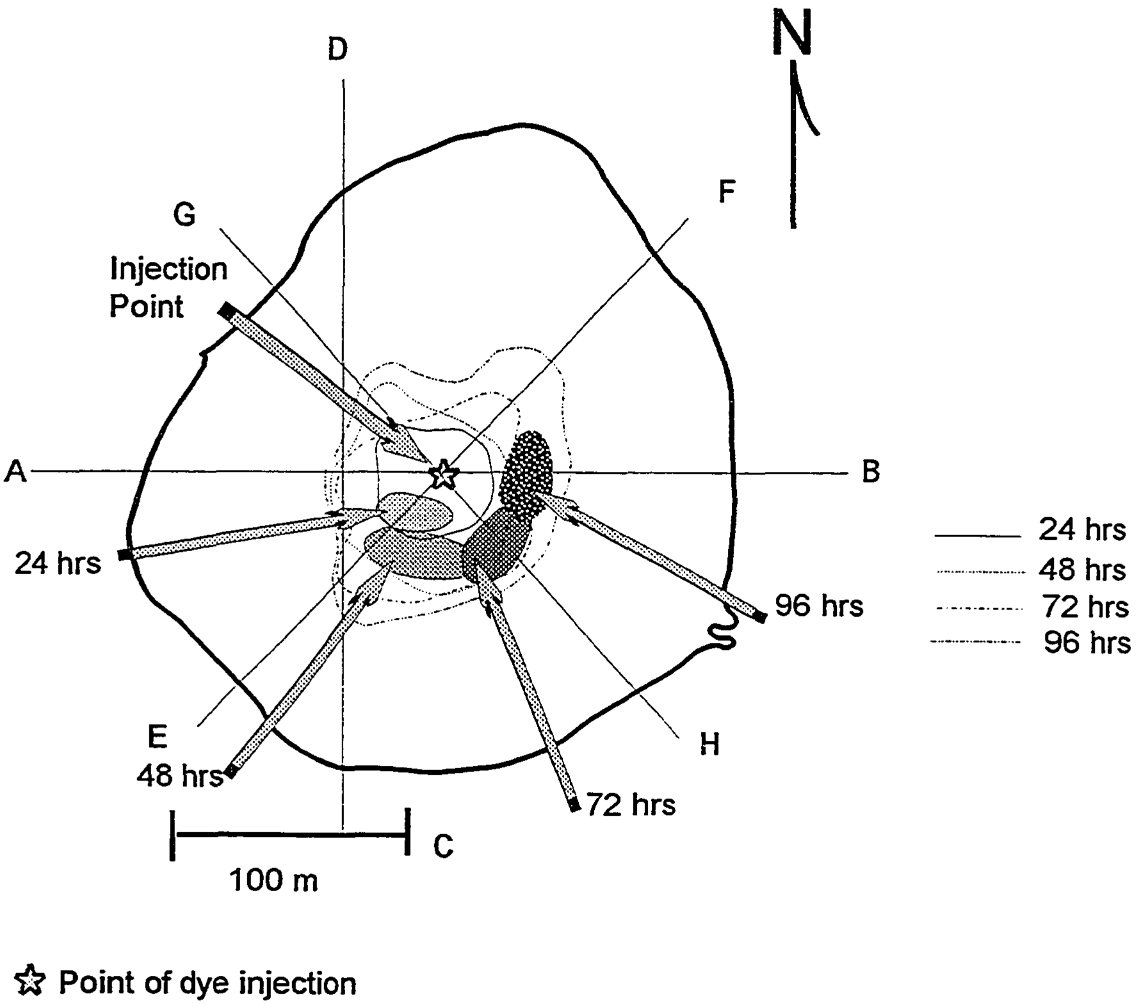

Figure B-3. Dye tracings in East Dollar Lake initiated approximately four weeks after cessation of aeration. Dye was injected at approximately 6 m deep. Lines represeent lateral movement found between 5 and 7 m. Shaded areas represent a concentrated bolus that occurred at the 7-8 m depth.

Discussion

Dye movement in both West Dollar and East Dollar lakes were quite similar to the large-scale movements reported by Likens and Ragotzkie (1966). They reported anticyclonic movement at the 5 m depth in the perimeter of Tub Lake, Wisconsin. The Dye injected at 3 m in West Dollar Lake slowly sank to the 4 m depth (very near the bottom) and also underwent anticyclonic motion.

Conversely, dye injected at the 2 and 5 m depth near the center of Tub Lake exhibited cyclonic movement. These movements were attributed to large-scale convective flow induced by relatively greater heating of water from litoral sediments than from deeper sediments and by cooling at the surface with relatively greater cooling near the center relative to the perimeter. This would result in ascending water near the edges and descending water near the center of the Lake. Resultant velocities in Tub Lake were 30 m day^{-1} near the perimeter and 35 m Day^{-1} near the center. They related these experiments to the lab experiments of Fultz (1951, 1960) and Fultz et al. (1959) where heating of the perimeter of a bowl resulted in anticyclonic motion near the rim and cyclonic motion near the center.

Injections of dye near the center of East Dollar Lake exhibited both cyclonic and anticyclonic movement. Dye injected at the 6 m depth followed a cyclonic path. However, the greatest concentration of this dye descended to the 7 to 8 m depth, a patterin that is consistent with Fultz et al. (1959). However, dye injected at the 3 m depth exhibited anticyclonic movement, a pattern similar to movement at the perimeter of Tub Lake and

West Dollar Lake. The reason for this discrepancy is unclear. However, it may lie in the temperature regime of East Dollar Lake at the time of the experiment (mid-April). Tub Lake was near 4°C throughout most of the water column while temperature in East Dollar ranged from 0.6°C at 1 m, 0.5°C from 2 to 7 m and 1.1 °C at the sediment surface (8.5 m). Although Tub Lake was warmer, the Δ density with depth would be quite similar between the two lakes. Hence, there was slightly warmer water near the surface of East Dollar Lake relative to lower strata. This increase was due to solar heating resulting firm the absence of snow cover. Therefore, unlike midwinter conditions, when the ice surface is typically a source of cooling, the entire lake surface was a source of mild heating. Hence, it can be hypothesized that the mild warming of the upper strata would disrupt the typical midwinter circulation observed by Likens and Ragotskie (1966), and perhaps allow the anticyclonic motion to encompass the entirety of the upper strata. Tracing of movement prior to this warming trend would be necessary to confirm this hypothesis.

References

Fultz, D. 1951. Experimental analogies to atmospheric motions. pp. 1235-1248. In: T.F. Malone. (ed.) Compendium of Meteorology. Amer. Meteor. Soc., Boston.

Fultz. D. 1960. Experimental models of rotating fluids and possible avenues for future research. pp. 71-77. in: R.L. Pfeffer (ed.) Dynamics of Climate. Pergamon Press. New York.

Fultz, D., R.R. Long, G.V. Owens, W. Bohan, R. Kaylor and J. Weil. 1959. Studies of thermal convection in a rotating cylinder with some implications for largescale atmospheric motions. Meteor. Monogr. 4(21):1-104.

Likens, G.E. and A.D. Hasler. 1962. Movements of radiosodium (Na^{+2}) within an ice-covered lake. Limnol. Oceanogr. 7:48-56.

Likens, G.E. and R.A. Ragotzkie. 1966. Rotary circulation of water in an ice-covered lake. Verh. Internat. Verein. Limnol. 16: 126-133.

Appendix C

Additional Methane Profiles in Aerated and Control Lakes

Results and Discussion

Results and Discussion

Methane profiles were measured once in Sulphur, Moonshine, Swan and West Dollar lakes during the 1996 to 1997 season. In Sulphur Lake, the CH_4, temperature and DO gradients were not as sharp as those in East Dollar or Figure Eight lakes (Figs. C-1A and 5-4A). However, the effect of shallow aeration in Sulphur Lake was similar to that in East Dollar Lake and the middle basin of Figure Eight Lake.

Moonshine Lake contained substantially less CH_4 (Fig. C-!B). The surface aerator in Moonshine Lake was anchored over 1.5 m which mixed only the top 2 m. Although near-normal temperature stratification was retained, both DO and CH_4 varied little throughout the water column. DO near the sediment surface remained relatively high (> 4 g m^{-3}) while CH_4 concentrations remained very low (< 0.4 mmol m^{-3}). Using the median of all calculated K values from Table 5-2 (21.9 x 10^{-3} m^2 d^{-1}), the, low CH_4 concentration and weak gradient and high DO near the sediment surface resulted in a flux of only 0.09 mM m^{-2} day^{-1}. The fact that only one 1.8 kW surface aerator maintained these satisfactory conditions, including low levels of CH_4 in a lake nearly 5 times larger than East Dollar Lake, indicates that Moonshine Lake was less eutrophic than East Dollar Lake.

Sulphur Lake was likely intermediate in trophic status. Using the same K value (21.9 x 10^{-3} m^2 d^{-1}) and the CH_4 gradient in the deepest part of the lake, a flux of 3.31 mM m^{-2} day^{-1} was estimated. Even though the bottom 1 m was anaerobic, the CH_4 concentration was only about 90 mmol m^{-3} at the sediment surface at the end of the winter. Appropriately, the aeration system was sized intermediate between that of Moonshine and East Dollar lakes (See Chapter 3).

West Dollar Lake (a control lake) was clearly the most eutrophic of all the study lakes. The entire water column was nearly anoxic by December 19, six weeks after freeze up (Fig. C-1C). In turn, CH_4 concentrations were quite high throughout the water column, ranging from about 500 mmol m^{-3} at the sediment surface (4.5 m) to 120 mmol m^{-3} at 1 m. This suggests that CH_4 oxidation in the water column had been minimal for a considerable amount of time prior to sampling, allowing large quantities to diffuse upward throughout the water column. However, with this duration of anoxia, it might be expected that an even greater amount of CH_4 would have entered the water column. Indeed, benthic concentrations were not as high as those in East Dollar Lake at that time even though East Dollar Lake had measurable DO at the sediment surface. The exact reason for this discrepancy is unknown. However, it may be related to H_2 limitation in this environment. Winfrey and Zeikus (1977) and Jones et al. (1982) reported that additions of H_2 greatly increased CH_4 production. Further, where SO_4^{2-} was very low, additions as low as 0.5 mmol SO_4^{2-} inhibited CH_4 production and enhanced sulphate reduction to H_2S. Hence, sulphate-reducing bacteria may be competing with methanogenic bacteria for the terminal electron accepter (Kelly and Chynoweth 1979).

The less-eutrophic Swan Lake did not reach anoxia near the sediment surface (5 m) until late winter (February 11). At that time, DO at 1 m was 2.64 g m^{-3}. When the CH_4 profile was measured on March 19, DO near the surface had fallen to 0.18 g m^{-3}. Although CH_4 concentrations were relatively low in Swan Lake there was a steep gradient in the 3 to 5 m range resulting in a relatively high estimated flux of 39.5 mmol m^{-2} day^{-1}. This Indicates that Swan lake would also lie in the low to intermediate trophic state between all of the study lakes. Indeed this relatively large (153 ha) lake was aerated

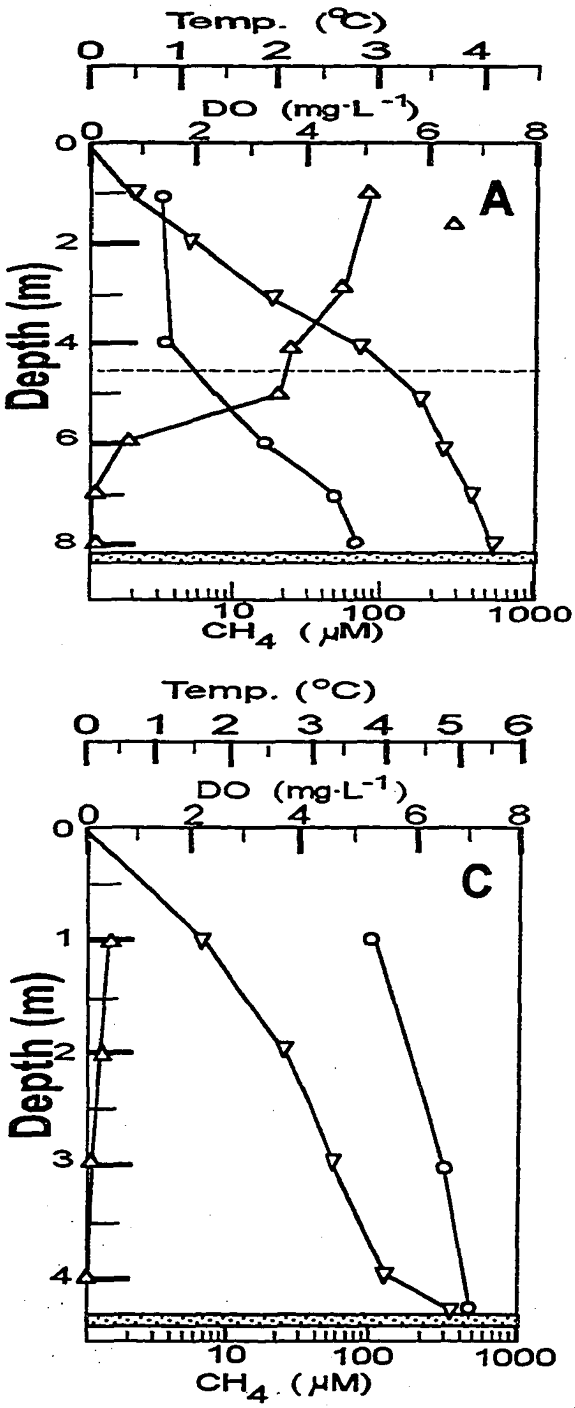

Figure C-1. Methane (o), temperature (▽) and dissolved oxygen (△) profiles of two aerated lakes (Sulphur [A] and Moonshine [B] lakes) and two unaerated control lakes (West Dollar [C] and Swan [D] lakes). Profiles of Sulphur and Moonshine Lake were measured April 2 and 3, 1997, while that of West Dollar Lake and Swan Lake were measured December 19, 1996 and March 19, 1977, respectively. Benthic DO values in Moonshine Lake had remained above 4.0 mg L^{-1} for the entire winter. Benthic DO values in Sulphur had been near 0.1 mg L^{-1} since February 3 and at 0 mg L^{-1} since about March 4. Those for West Dollar and Swan lakes reached 0 mg L^{-1} by December 19, 1996 and March 19, 1997, respectively. Note variation in CH_4 scale.

successfully during the 1997 to 1998 winter using seven 1.8 kW aerators (0.08 kW ha^{-1}) (Dave Jackson, Alberta Conservation Service, Peace River, AB, personal communication). This value was slightly greater than that used when one 1.8 kW aerator was used in Moonshine Lake (0.06 kW ha^{-1}).

References

Jones, J.G., B.M. Simon and S Gardener. 1982. Factors affecting methanogenesis and associated anaerobic processes in the sediments of stratified eutrophic lake. J Gen Microbiol. 128:1-11.

Kelly, C.A. and D.P. Chynoweth. 1979. Methanogenesis: A measure of chemoorganotrophic (heterotrophic) activity in anaerobic lake sediments. in: Costerton, J.W. and R.R. Colwell (eds). Native aquatic bacteria: Enumeration activity and ecology. ASTM STP 695. pp. 164-179.

Winfrey, M.R. and J.G. Zeikus. 1977. Effects of sulphate on carbon and electron flow during microbial methanogenesis in freshwater sediments. Applied and Environ. Microbiol. 37: 244-253.