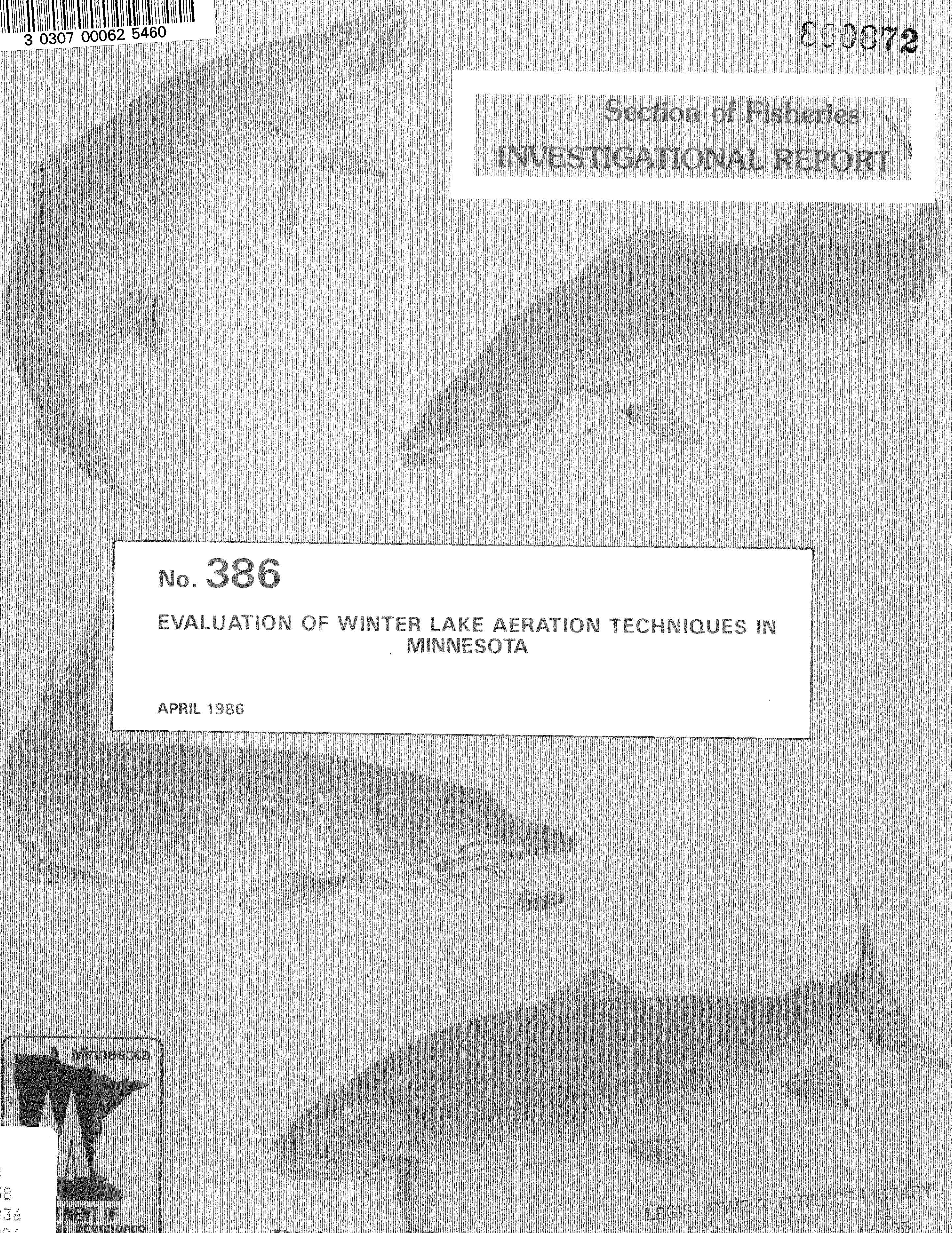

Section of Fisheries

INVESTIGATIONAL REPORT

No. 386

EVALUATION OF WINTER LAKE AERATION TECHNIQUES IN MINNESOTA

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Division of Fish and Wildlife

EVALUATION OF WINTER LAKE AERATION TECHNIQUES IN MINNESOTA[1]

by

Farrell Bandow
Fisheries Biologist

ABSTRACT

Subsurface bubbler aeration systems provided game fish refuge in two shallow southern Minnesota winterkill lakes during a winter characterized by dense snow cover from mid-November to mid-March. Stabilized oxygen concentrations were alarmingly low but adequate. The shallower lake had less heat storage and the aeration system maintained a relatively small ice free area. Accordingly, less active circulation favorably influenced a relatively small but adequate portion of the lake implying that diffuser placement to create as large an open water area as possible need not be an overriding goal in bubbler aeration. Costs and site availability may be weighed against size of desired refuge area. Lowest oxygen concentrations in both lakes at onset of sampling in early winter were near the aeration sites in areas favorably influenced later suggesting that initially the aeration equipment might have caused increased oxygen consumption. Subsequent investigation of the impact of subsurface bubblers early in winter when oxygen concentrations were high revealed a brief oxygen depletion rate increase at onset of aeration in one of three study lakes. Low near-sediment oxygen concentrations in areas of the lake suggested potential for increased consumption by intrinsic processes but air lines detached from diffusers may have caused increased oxygen demand in

[1] This project was funded in part by Federal Aid Fish Restoration (Dingell-Johnson) Program. Completion Report, Study 305, Project D-J F-26-R Minnesota.

the water column by suspending sediments. Oxygen input from bubbler aeration balanced oxygen consumption only after concentrations declined to threshold levels where consumption rates declined. Thus, rationale for the common practice of starting bubbler equipment at time of ice formation is questionable. Results from a recirculating and a groundwater pump and baffle aeration system indicated that shore-based equipment can fill the need for safer operation on small lakes (arbitrarily <40 ha) but cost-effectiveness on large lakes has not been established.

INTRODUCTION

Shallow fertile lakes in many areas of the midwestern United States offer high potential for fish production if winterkill can be controlled. Winterkill resistant species that are undesirable to most anglers usually dominate fish communities in these lakes and while rapid growth between winterkills occasionally produces fishable game populations, the sport fishing potential is largely unrealized.

Causes of winterkill, associated problems and various early efforts to alleviate it have been described by Greenbank (1945) and Patriarche and Merna (1970). A few early artificial aeration attempts with compressed air yielded encouraging results but widescale interest in the procedure was not generated until the 1970's after successful efforts with wastewater treatment equipment were reported from Wisconsin (Wirth 1970).

The first successful large-scale aeration attempt in Minnesota was in 1,356 ha Shetek Lake during the winter of 1974-75 (Johnson and Skrypek 1975). Since then, compounding enthusiasm for artificial aeration in Minnesota has resulted in substantial equipment and operational expenditures by private and civic organizations with minimal knowledge of performance and proper use of various types of equipment.

Aeration equipment used in Minnesota can be categorized into four general types: 1) subsurface bubbler systems that utilize shore-housed blowers or compressors to deliver air via submerged lines to offshore diffusers; 2) surface bubblers that inject air directly at the lake surface; 3) floating agitators and spray pumps; and 4) pump and baffle systems that aerate recirculated lake water or groundwater before discharge into lakes. Bubbler systems are most popular in Minnesota and were given the most attention during this investigation. Evaluations of some equipment are incomplete or entirely lacking (agitators and spray pumps) because mild winters failed to develop winterkill conditions.

Some early experiences indicated that bubbler aeration delayed until dissolved oxygen concentrations had approached threatening levels tended to hasten winterkill by mixing the water column. That led to the conventional practice of starting bubbler systems at or shortly after ice formation and operating them continuously until ice-out. Some investigators (Halsey 1968; Lackey and Holmes 1972; Smith et al. 1975) have reported short-term increase in oxygen depletion rates when aeration was initiated. Efforts were made in this investigation to better define operational characteristics of lake aeration equipment and determine most efficient operational procedures.

AERATION EQUIPMENT AND STUDY SITE DESCRIPTIONS

LARGE SUBSURFACE BUBBLER AERATION

Two large lakes with Helixor[2] aeration systems were studied during the 1978-79 winter. Helixor systems consist of shore-housed blowers or compressors that deliver air via 38 mm I.D. weighted polyethylene tubing to diffusers (Helixors) spaced offshore on the lake bottom. The Helixor, a 457 mm diameter polyethylene cylinder that is partitioned longitudinally into two helical chambers, is a product of the Polcon Corporation of Montreal, Canada. Wirth (1970) describes the system in detail.

Upwelling of relatively warm benthic water by rising air bubbles maintains an open-water area and facilitates oxygenation of water through wind agitation and photosynthesis. Disruption of thermal stability in the water column generates convection that circulates large portions of a lake or an entire basin depending upon lake morphology and diffuser placement.

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[2] Use of trade name does not imply endorsement of product.

Lura Lake

Lura Lake occupies portions of Blue Earth and Faribault Counties in the south-central agricultural region of Minnesota. It has a surface area of 496 ha and during winter 1978-79 maximum and mean depths approximated 2.6 and 1.5 m, respectively. Historically, Lura Lake had a mean winterkill frequency of 2.5 yr and received minimal attention from fisheries managers. Although occasional stocking created temporary angling for panfish, the fishery was comprised primarily of winterkill resistant black bullhead (*Ictalurus melas*).

The aeration system, installed in 1976, consisted of two blowers powered by two 10 hp, three-phase electric motors that delivered 8.5 m^3 of air/min (vendor's claim) to 12 diffusers spaced 40-50 m apart in a 4x3 rectangle at a mean depth near 2 m. Operation began at time of freeze-up in mid-November and continued through ice out.

Elysian Lake

Elysian Lake, in south-central Minnesota, occupies portions of Waseca and Le Sueur Counties. It encompasses an area of 780 ha and has maximum and mean depths approximating 3.7 and 2.1 m, respectively. The lake historically had a mean winterkill frequency of 3.8 yr. Fisheries managers frequently established walleye (*Stizostedion vitreum vitreum*), northern pike (*Esox lucius*) and panfish populations which provided some angling between winterkills. Carp (*Cyprinus carpio*) and black bullhead dominated the fish community and provided extensive commercial harvest.

The aeration system was operated at full capacity for the first time during winter 1978-79. It was comprised of three blowers powered by three 7.5 hp, single-phase motors which delivered 10.6 m^3 of air/min (vendor's claim) to 15 diffusers spaced 40-50 m apart in a 5x3 configuration at a mean depth near 3.2 m. Operation began at freeze-up in mid-November and continued until ice-out.

SURFACE BUBBLER AND SMALL SUBSURFACE BUBBLER AERATION

Performance of surface bubbler systems and a small subsurface bubbler system was monitored during the 1980-81 and 1981-82 winters. In addition, three unaerated winterkill lakes were sampled during each of those winters (Table 1). One of the surface bubbler systems was also monitored in 1983-84.

Table 1. Characteristics of study lakes during winters of 1980-81, 1981-82 and 1983-84.

Lake	County	Area (ha)	Mean depth (m)	Winters sampled	No. of sample stations	Aeration equipment[a]
Cedar	Scott	268	2.6	1981-82	6	Aire-O_2
Eagle	Carver	95	1.7	1980-81	7	Aire-O_2
				1981-82	3	Aire-O_2
				1983-84	5	Aire-O_2
Crystal	Hennepin	32	3.5	1980-81	5	Fish-Air
				1981-82	5	Fish-Air
Clear	Le Sueur	108	3.0	1980-81	3	None
Steele	Le Sueur	29	2.7	1981-82	2	None
Sabre	Le Sueur	106	2.6	1980-81	3	None
				1981-82	2	None
Sunfish	Le Sueur	48	3.6	1980-81	2	None
				1981-82	2	None

[a] Use of trade names does not imply endorsement of product.

Surface Bubblers: Eagle and Cedar Lakes

The surface bubbler investigated, Aire-O_2[3], is a product of Aeration Industries of Chaska, MN and consists of a floating, directional aspirator powered by a self-contained 2 hp electric motor. A submerged propeller at the end of a hollow tube draws air into the water at high velocity and creates substantial turbulence in the water column.

Four units operated in Eagle Lake were spaced approximately 50 m apart 50-75 m offshore where lake depths approximated 1.5-2 m. Operation began at or shortly after freeze-up in 1980 and 1981 and was delayed until 22 December in 1983.

Cedar Lake had six units spaced 100-200 m apart about 50 m offshore over water approximately 2.5 m deep. Difficulty was experienced with two units and one or the other was inoperable at the time of most sampling visits to the lake. Operation began on Cedar Lake on 19 December 1981.

Small Subsurface Bubbler System: Crystal Lake

The subsurface bubbler system in Crystal Lake, Fish-Air[3], is a product of Clean-Flo Laboratories, Inc. of Hopkins, MN. Three onshore 0.5 hp electric compressors delivered air through 13 mm I.D. polyethylene tubing to three ceramic, microporous diffusers set close together offshore at depths near 11 m. The system operates year-round in Crystal Lake, but operational difficulties were experienced in both 1981 and 1982 and frequently the system was functioning at reduced capacity or not at all.

DELAYED BUBBLER OPERATIONS

Operation of Helixor aeration systems was delayed on three lakes in 1983-84 to allow establishment of pre-aeration oxygen depletion rates and

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[3] Use of trade name does not imply endorsement of product.

assessment of the impact of bubbler aeration when oxygen concentrations were well above levels lethal to game fish.

Greenleaf Lake in Le Sueur County of south-central Minnesota encompasses 119 ha. Maximum and mean depths are 5.5 and 2.4 m, respectively. The aeration system consisted of a single 5 hp blower and three diffusers spaced in a line 40-50 m apart at depths of 3-4 m.

Shetek Lake in Murray County of southwestern Minnesota encompasses 1,356 ha and is comprised of two major basins connected by a series of shallow narrows and channels. For analysis in this study the lake was arbitrarily divided into a 650 ha north basin and a 340 ha south basin. Maximum depths of the basins were 3.4 and 2.8 m, respectively. Mean depths were 2.6 and 2.0 m, respectively. The aeration system, located in the north basin, consisted of three 7.5 hp blowers and 12 diffusers set approximately 60 m apart at depths of 2.5-3 m. The system is described in greater detail by Johnson and Skrypek (1975). Air lines became detached from some of the diffusers, leaving only six diffusers functioning in 1983-84.

Only 10 of 15 diffusers previously described in Elysian Lake were functioning because of an inoperable blower unit. The Elysian Lake and Greenleaf Lake systems were started on 14 January and the Shetek Lake system on 6 January. Six sampling stations were monitored on Elysian Lake, four on Greenleaf Lake, and five on the north basin and two on the south basin of Shetek Lake.

PUMP AND BAFFLE AERATION

Lily Lake

A short pump and baffle operation was conducted on 24 ha Lily Lake, Waseca County, in March 1980. Aeration equipment included a 30.5 cm

Crisafuli[4] regular lift trailer pump powered by a diesel engine with a continuous duty rating of 80 hp at 2,000 rpm. A baffled discharge chute made from a hay loader was connected to the pump by 76 m of butyl hose. The chute had four 5x15 cm planks spaced on the 3.1 m long by 1.8 m wide loader bed. Outflow was 1.5 m above the ice surface. Intake and discharge sites were 74 m apart. The pump was installed just offshore at a depth of approximately 1 m. Only the end of the discharge chute was offshore.

The pump was operated at 400 rpm and the flow rate, estimated from horizontal measurement of the outflow, was 7.6-8.3 m^3/min. Pumping commenced on 12 March and had progressed 43.7-48.5 h during a 47.2-52.0 h period when the final series of lake samples were recorded. Spring recovery began the following day and pumping was discontinued.

Penn Lake

Performance of a low-volume groundwater pump and baffle aeration system was monitored on Penn Lake in Hennepin County in 1981-82. Penn Lake had a surface area of 12.5 ha and a maximum depth of about 1.6 m. The pump, installed to maintain basin water level, is operated year-round. Groundwater is discharged from a 10.2 cm I.D. vertical pipe and tumbles down a concrete staircase before entering the lake. The flow rate, estimated on four occasions from measurements of the height of the pipe discharge, was 0.79-0.91 m^3/min. The 1.2 m wide staircase consists of 14 steps on a 3:1 slope. Vertical drop is 2.1 m.

[4] Use of trade name does not imply endorsement of product.

METHODS

Dissolved oxygen concentration and temperature were measured in situ with a combination temperature compensated polarographic sensor (±0.1 mg/L) and thermistor (±0.5C) probe. Measurements were recorded at sampling stations at various depth intervals ranging from 0.25 to 1.0 m to within 10 to 20 cm of the bottom. Ice thickness at each station was measured to the nearest cm from underside the ice to the surface of the water in the sampling hole.

Volume-weighted mean lake oxygen concentration, volume-weighted mean lake temperature and oxygen mass per unit surface area were calculated from mean station values recorded at 1 m depth intervals. Depth contour areas at 5 ft intervals were determined by planimetry on bathymetric maps. Contour areas at 1 m intervals were estimated by interpolation involving mean basin slope between map contours bracketing metric depths. Lake volumes were similarly corrected for ice formation. Ice volume was not corrected for expansion.

Oxygen mass/m^2 of surface area unadjusted for ice formation was used to compare depletion rates in 1983-84 because ice formation rates during pre-aeration periods were about twice those during post-aeration periods. Ice formation acts to increase oxygen concentration in the water column without a net change in oxygen mass because nearly all dissolved oxygen is excluded from clear ice (Welch 1974; Welch and Bergmann 1985). The oxygen mass/m^2 ratios (unadjusted) ignore freezeout of oxidation substrate but when compared with ratios using adjusted surface areas differences were small and final analyses unchanged.

RESULTS AND DISCUSSION

LARGE SUBSURFACE BUBBLER AERATION

Lura Lake - Dissolved Oxygen

The highest oxygen concentrations in Lura Lake in December were not near the aeration system but in the south basin, a great distance from the aeration site (Figs. 1 and 2). The mean water column concentration at the aeration site (near Station 1) on 16 November as the lake surface was freezing was 11.0 mg/L. By 14 December the mean concentration at Station 1 had declined to 3.3 mg/L, a mean depletion rate of 0.275 mg/L/d. For the remainder of the critical winter period (through 15 March), the oxygen concentration at Station 1 was essentially stable with the mean fluctuating between 2.5 and 3.3 mg/L. Maximum concentrations in the water column during that period fluctuated between 2.9 and 4.0 mg/L.

Oxygen concentrations at other stations in the north basin of Lura Lake also tended to stabilize but at progressively lower levels at greater distances from the aeration site. The mean concentration at Station 2, approximately 100 m from open water, reached a low of 1.9 mg/L on 18 January then stabilized in the range of 2.0 to 2.3 mg/L through 15 March. The maximum concentration at Station 2 reached a low of 2.7 mg/L on 18 January and then fluctuated between 3.2 and 3.5 mg/L.

At Station 3, approximately 500 m from the aeration site, the mean oxygen concentration declined to around 1.0 mg/L in late January then increased and fluctuated between 1.0 and 1.8 mg/L. Maximum concentration reached a low of 2.0 mg/L on 18 January then steadily increased to 3.4 mg/L by 15 March.
An oxygen concentration of 2.0 mg/L is considered critical for winter survival of most game fish. A concentration of 1.0 mg/L is usually lethal to many species.

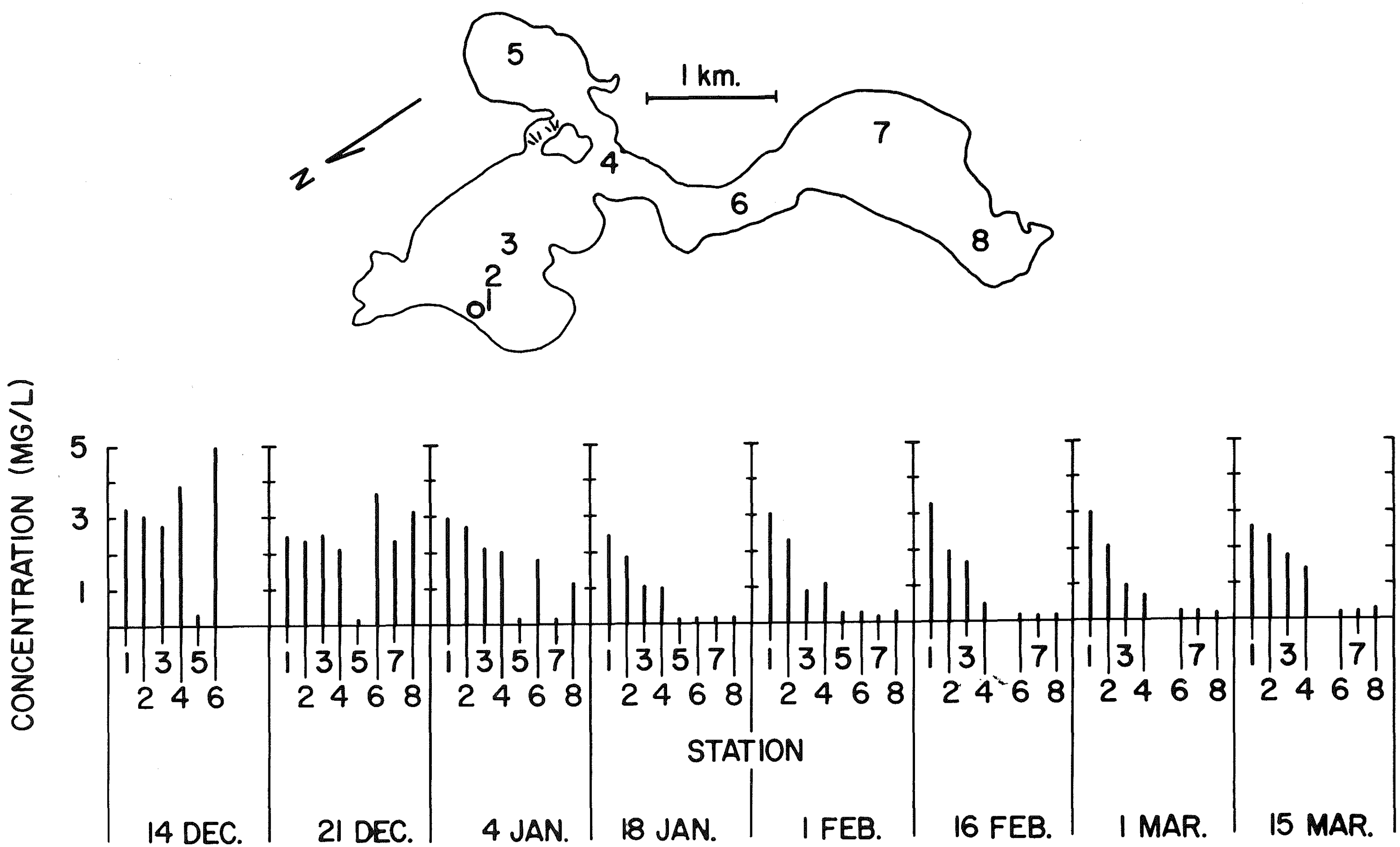

Figure 1. Lura Lake sampling stations, and mean water column dissolved oxygen concentrations (mg/l), winter 1978-79. Station 0 is the aeration site; Station 1 is 2-10 m from open water; Station 2 is 100 m from Station 1; others are to scale.

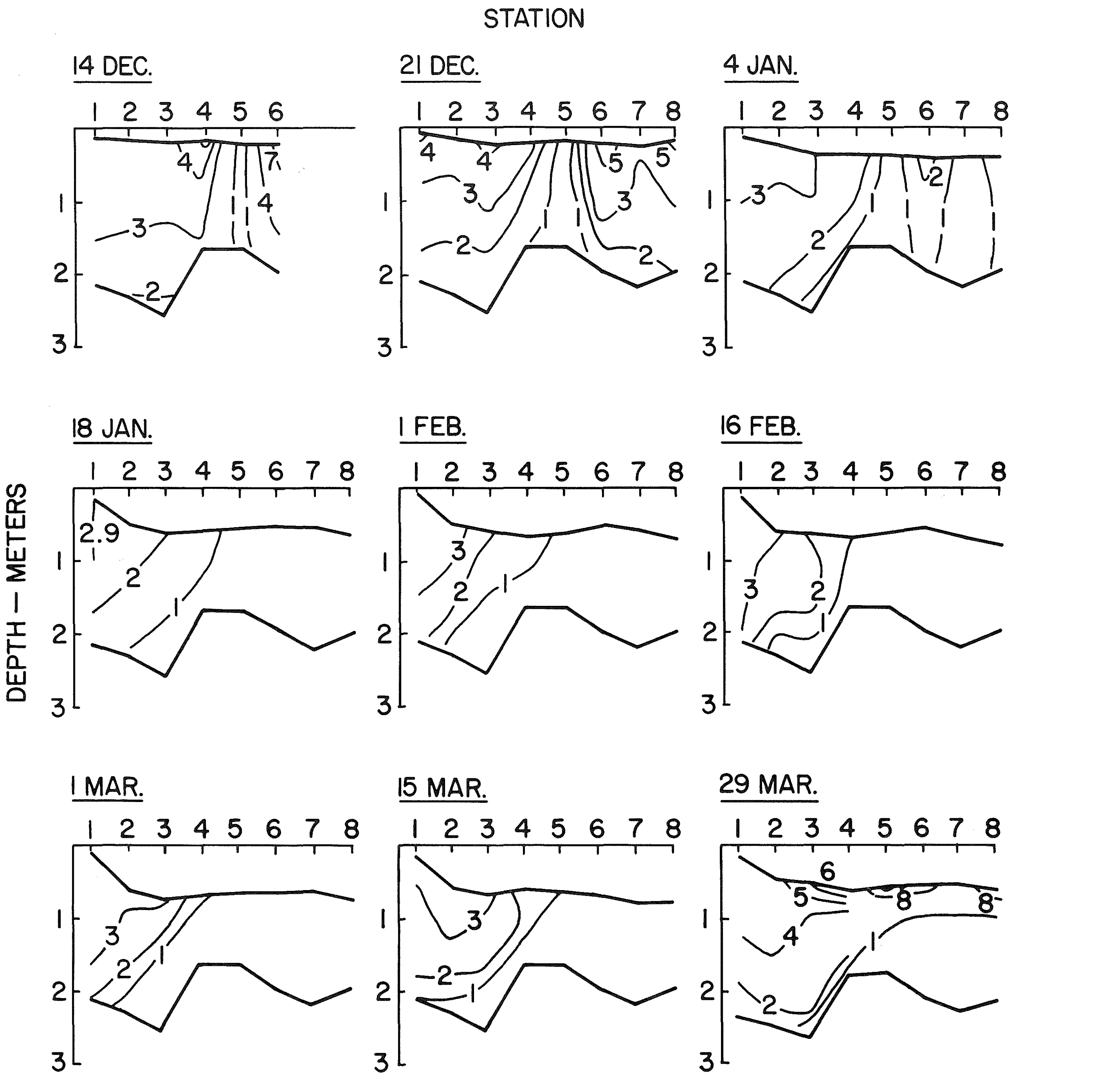

Figure 2. Isopleths of dissolved oxygen (mg/l) in the Lura Lake water column, winter 1978-79. Bold lines represent the undersurface of the ice layer and lake bottom.

Mean and maximum oxygen concentrations at Station 4, 1,600 m from the aeration site, declined to lows of 0.5 and 1.0 mg/L, respectively, by 16 February. Meanwhile, Station 5, in the east basin of Lura Lake, was near anoxia in December while Stations 6-8 in the south basin declined to lethal levels in January.

Oxygen conditions measured at the north basin sampling stations indicate that the aeration system favorably influenced 60 to 65 ha (12 to 13%) of Lura Lake.

Lura Lake - Temperature

The aeration system substantially cooled the water column in the north basin of Lura Lake (Fig. 3). By mid-January, the only temperatures above 2 C in the north basin were found at Stations 2 and 3 in stagnant water at depths below bottom contours at the aeration site.

Meanwhile, the water column was much warmer in the shallower south basin where temperatures approached 4 C in some areas. Heat in the south basin was mostly unavailable to the aeration system because a shallow narrows between basins restricted convection. By February, the mean temperature at Station 1, at the aeration site, was less than 1 C and remained so until spring recovery in late March (Table 2). Consequently, open water at the aeration site declined from a single area estimated to encompass 4-6 ha on 21 December to single areas above each of the 12 diffusers totaling <0.5 ha by early January.

Lura Lake - Fish Populations

Examination of the entire shoreline of Lura Lake after ice-out revealed no evidence of appreciable winterkill in any basin of the lake. The only dead game fish found were three yellow perch (*Perca flavescens*) in the east basin. A few dead black bullhead were seen in the east basin and a few hundred were washed ashore in the south basin but it is believed they were from a

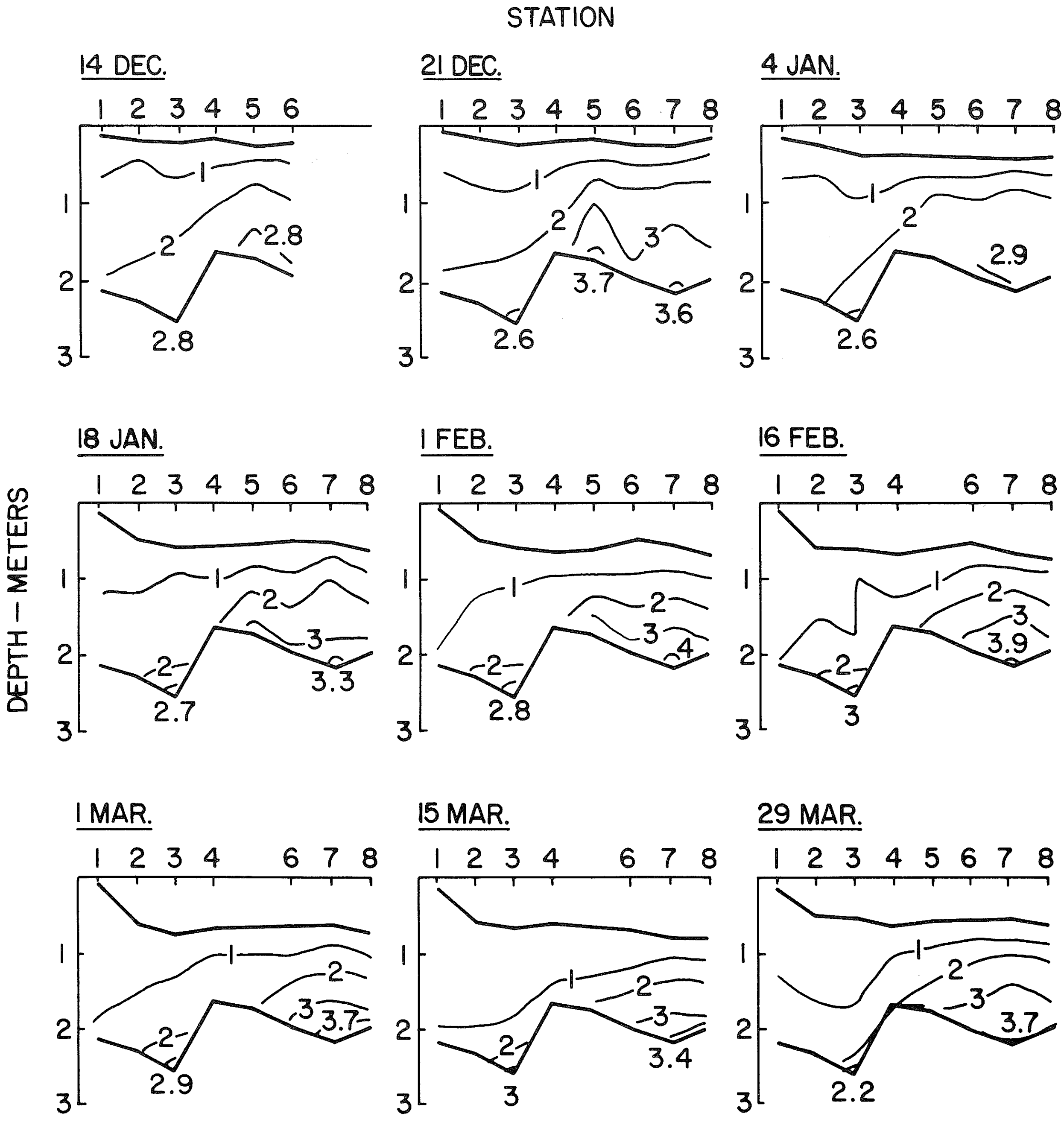

Figure 3. Isotherms (^{o}C) in the Lura Lake water column, winter 1978-79, Bold lines represent the undersurface of the ice layer and lake bottom.

Table 2. Mean and maximum water column temperatures at Station 1 on Lura Lake, winter 1978-79.

Date		Temperature (C)	
		Mean	Maximum
December	14	1.3	2.1
	21	1.5	2.1
January	4	1.1	1.3
	18	1.0	1.6
February	1	0.8	1.0
	16	0.8	0.8
March	1	0.8	1.2
	15	0.5	1.3
	29	1.1	1.7

commercial fishing catch which suffocated in a holding crib in January. The black bullhead is one of the most winterkill resistant species in Minnesota. No dead fish were found in the north basin.

Walleye are considered quite sensitive to low winter oxygen concentrations (Moyle and Clothier 1959). Test netting conducted in September 1978 and repeated in September 1979 indicated high walleye survival during the intervening winter (Table 3). Although the yellow perch catch declined substantially between sampling periods, the presence of an expanding walleye population likely influenced their abundance. The previous winterkill in Lura Lake occurred in 1975 before the aeration system was installed, and was followed by walleye fry stocking in 1975 and fingerling stocking in 1976 and 1978.

Table 3. Catches of age 1+ and older fish in Lura Lake, September 1978 and 1979. Number of lifts in parenthesis.

Species	Mean number/lift Trap net (8) 1978	1979	Gill net (2) 1978	1979
Northern pike *Esox lucius*	0.1	0.1	--	--
Black bullhead *Ictalurus melas*	58.6	43.6	60.0	62.0
Pumpkinseed *Lepomis gibbosus*	0.1	--	--	--
Black crappie *Pomoxis nigromaculatus*	1.1	0.6	0.5	--
Yellow perch *Perca flavescens*	14.1	6.4	109.5	19.0
Walleye *Stizostedion vitreum vitreum*	0.3	1.6	14.5	34.0

Elysian Lake - Dissolved Oxygen

The highest oxygen concentrations in Elysian Lake in early winter were at stations farthest from the aeration system (Figs. 4 and 5). Mean water column oxygen concentrations at the vicinities of Stations 1, 6 and 8 on 15 November, as the lake surface was freezing, were 12.7, 12.0 and 12.1 mg/L, respectively. An inverse relationship between rate of decline and distance from the aeration site ensued. Between 15 November and 22 December, Stations 1, 6 and 8 exhibited mean depletion rates of 0.114, 0.205 and 0.186 mg/L/d, respectively.

Stations in the middle basins of Elysian Lake subsequently exhibited low rates of oxygen decline and concentrations at Stations 3-7 eventually stabilized. Oxygen concentrations at remote Stations 1 and 9 declined to serious levels before winter's end.

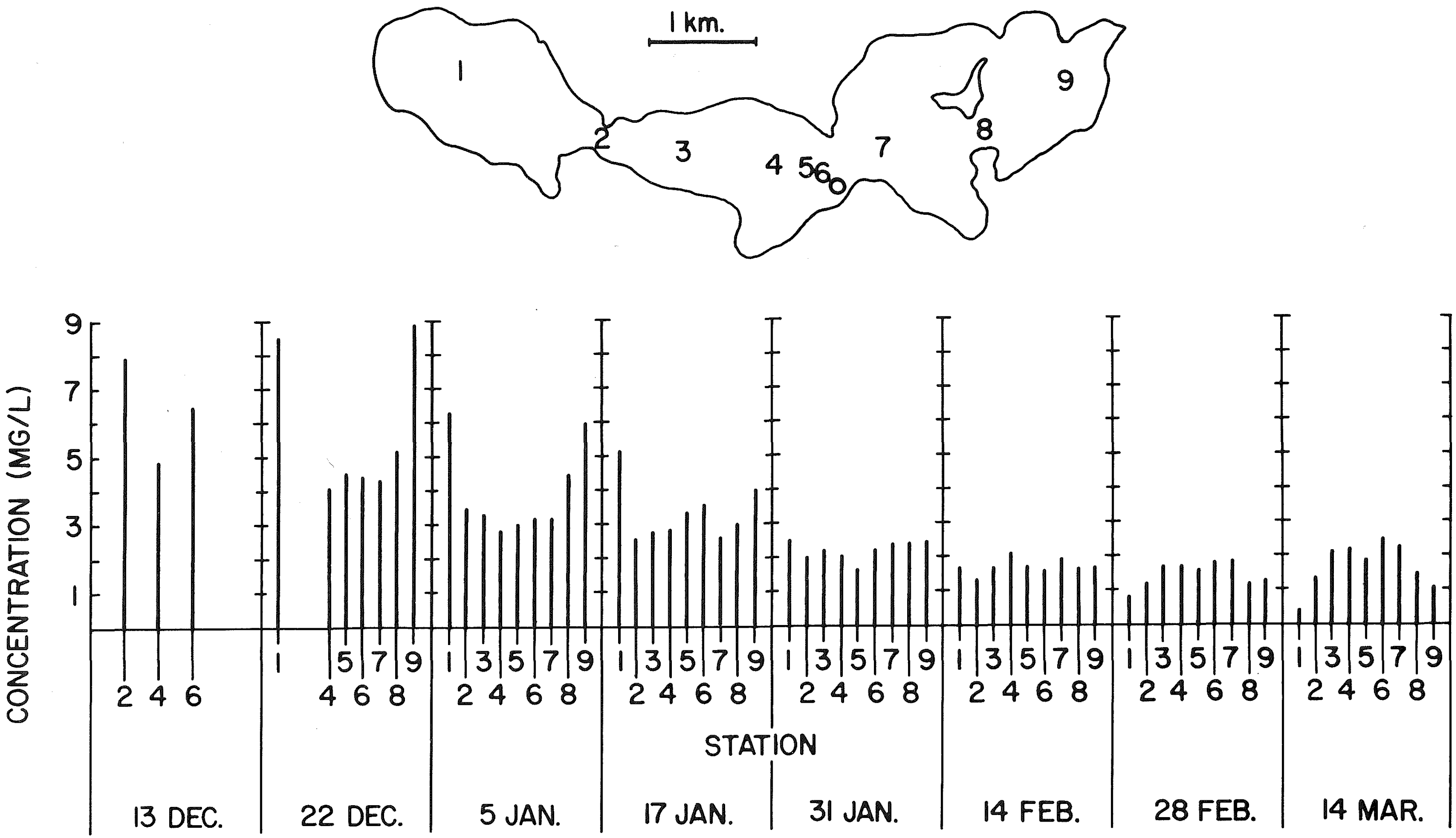

Figure 4. Elysian Lake sampling stations and mean water column dissolved oxygen concentrations (mg/1), winter 1978-79. Station 0 is the aeration site; Station 6 is 5-15 m from open water; Station 5 is 100 m from Station 6; others are to scale.

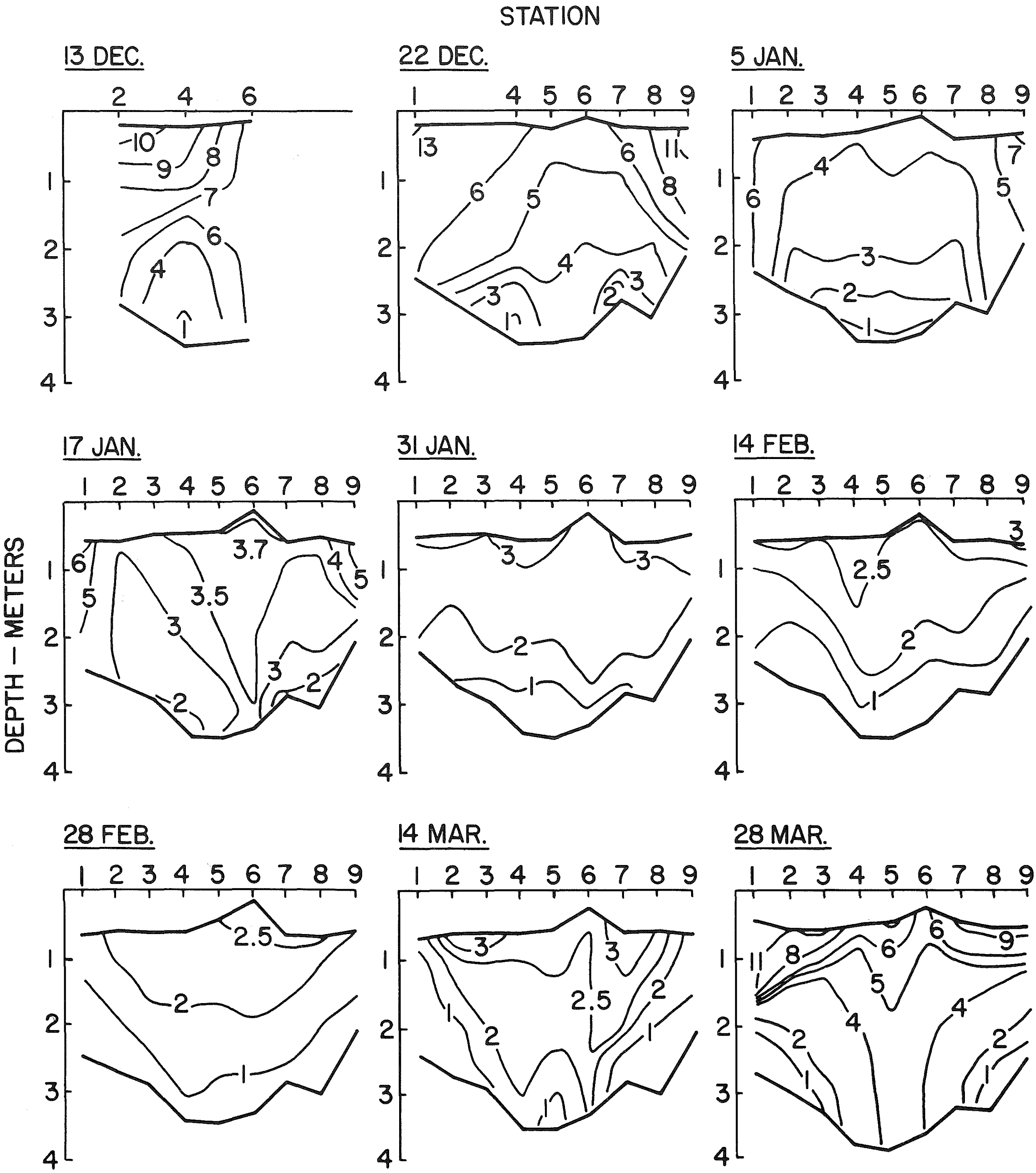

Figure 5. Isopleths of dissolved oxygen (mg/l) in the Elysian Lake water column, winter 1978-79. Bold lines represent the undersurface of the ice layer and lake bottom.

Mean concentrations at Stations 3-7 generally stabilized near 3.0 mg/L between 5 and 17 January. Thereafter, they declined to near 2.0 mg/L where they were generally stable for the remainder of the critical winter period. Maximum concentrations at Stations 3-7 stabilized in February at 2.5-3.0 mg/L. Concentrations at all stations but 1 and 9 increased slightly in March probably as a result of milder weather and near doubling of open water area at the aeration site.

The aeration system had a strong influence on a large portion of Elysian Lake. Mean oxygen concentrations at Stations 3-7 remained essentially indistinguishable throughout most of the winter. Station 3 was about 1,400 m from the aeration site. It appears the aeration system strongly influenced approximately 175 ha (20-25%) of the lake and had lesser but favorable influence on much more.

Elysian Lake - Temperature

Because of its greater depth and relatively large basin area sloping toward the aeration site, Elysian Lake had a considerably larger reservoir of heat available to the aeration system than did Lura Lake. Temperatures of 2-3 C existed in the water column at the aeration site throughout winter and more often than not the surface temperature at Station 6 exceeded 1C (Fig. 6). Mean temperatures at Station 6 declined slowly through winter but remained about 1 C above temperatures at the Lura Lake aeration site (Table 4).

Open water at the Elysian Lake aeration site in January and early February encompassed an estimated 2 ha, at least five times that at Lura Lake. Accordingly, the Elysian Lake aeration system influenced a much larger lake area than did the Lura Lake system.

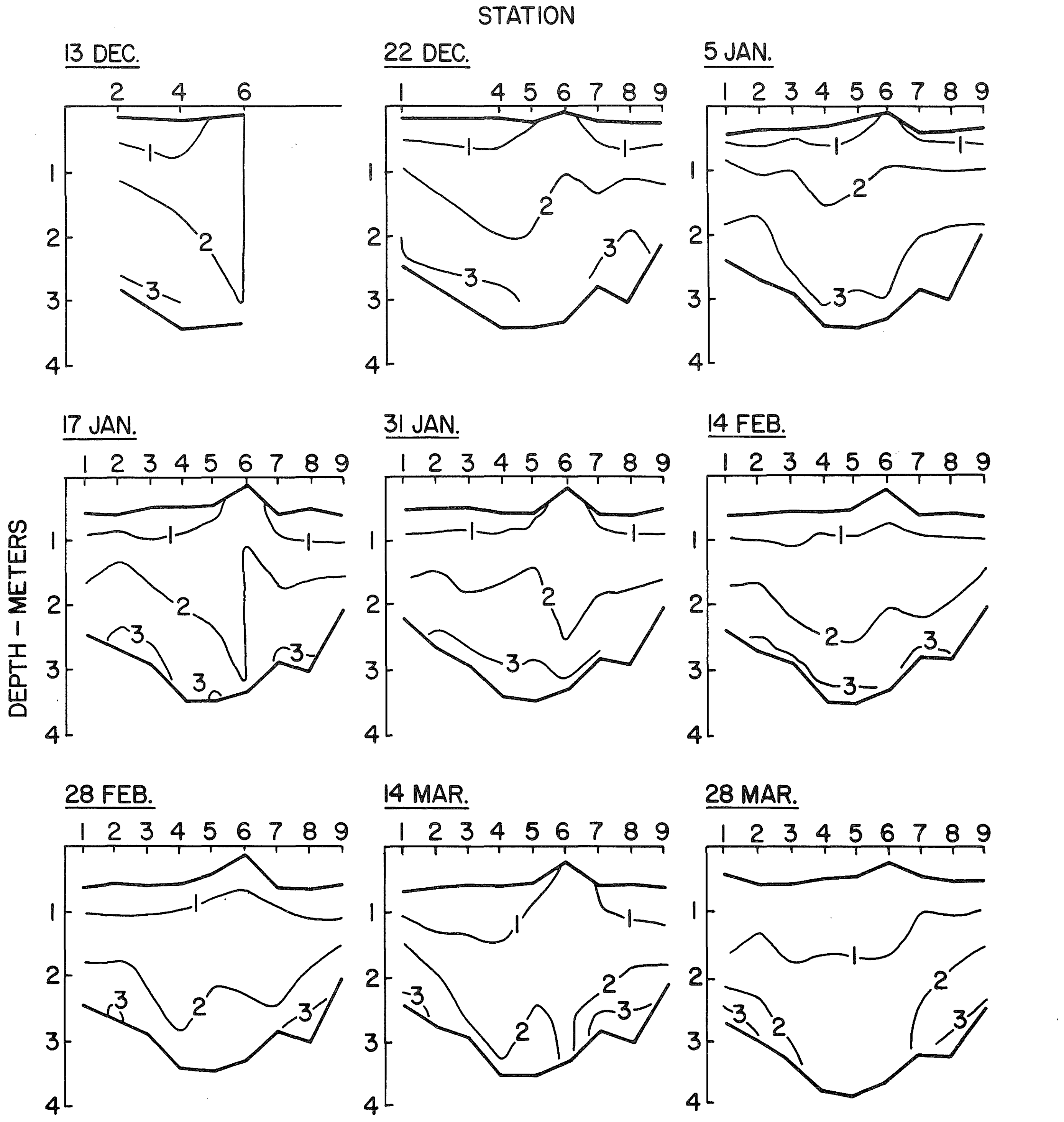

Figure 6. Isotherms (^{o}C) in the Elysian Lake water column, winter 1978-79. Bold lines represent the undersurface of the ice layer and lake bottom.

Table 4. Mean and maximum water column temperatures at Station 6 on Elysian Lake, winter 1978-79.

Date		Temperature (C) Mean	Maximum
December	13	2.0	2.0
	22	2.2	2.6
January	5	2.2	3.2
	17	2.0	2.0
	31	2.0	3.0
February	14	1.9	2.9
	28	1.8	2.8
March	14	1.6	1.7
	28	1.0	1.2

Elysian Lake - Fish Populations

No apparent winterkill of fish occurred in Elysian Lake. The entire shoreline was examined following ice-out and no dead fish were found. Test netting in September 1978 and September 1979 indicated high game fish survival (Table 5). Catches of walleye and northern pike were markedly higher in 1979. Although low both years, catches of most other game fish species were slightly higher in 1979.

Elysian Lake had suffered a partial fish-kill during the 1977-78 winter and game fish populations were recovering in 1978 and 1979. Northern pike appear to have been least affected by the winterkill. Most walleye captured in 1979 were yearlings stocked the previous summer. The sharp decline of the black bullhead catch between years might be attributed to intensive commercial harvest (84 kg/ha) between sampling periods.

Table 5. Catches of age 1+ and older fish in Elysian Lake, September 1978 and 1979. Number of lifts in parenthesis.

Species	Mean number/lift			
	Trap net (8)		Gill net (3)	
	1978	1979	1978	1979
Northern pike *Esox lucius*	2.0	0.8	6.3	16.7
Carp *Cyprinus carpio*	0.3	2.0	6.0	3.7
White sucker *Catostomus commersoni*	0.8	0.8	2.3	20.3
Bigmouth buffalo *Ictiobus cyprinellus*	-	-	1.0	1.3
Black bullhead *Ictalurus melus*	7.1	10.9	271.7	46.0
Green sunfish *Lepomis cyanellus*	0.1	-	-	-
Bluegill *Lepomis macrochirus*	0.1	0.3	-	-
White crappie *Pomoxis annularis*	-	0.3	-	0.3
Black crappie *Pomoxis nigromaculatus*	0.9	2.4	1.0	0.7
Yellow perch *Perca flavescens*	-	-	-	1.7
Walleye *Stizostedion vitreum vitreum*	-	-	-	16.0

SURFACE BUBBLER AND SMALL SUBSURFACE BUBBLER AERATION

The winters of 1980-81 and 1981-82 did not produce the severe oxygen depletion needed for complete evaluations of the effectiveness of aeration equipment. Sparse snow cover in January 1981 allowed oxygen concentrations to increase to uncommonly high levels in both aerated and unaerated lakes. The impact of aeration equipment on oxygen concentrations was imponderable. Although the following winter was initially severe, a late February thaw clouded analysis of the impact of artificial aeration on oxygen levels.

Surface Bubbler Systems: Eagle and Cedar Lakes - Dissolved Oxygen

The oxygen curve of Cedar Lake differed from those of subsurface aerated and unaerated lakes (Fig. 7). The oxygen depletion rate in Cedar Lake slowed considerably in February 1982 and by 9 March the mean lake oxygen concentration had nearly stabilized between 4.0 and 5.0 mg/L. Meanwhile. oxygen concentrations in Crystal Lake, with the subsurface bubbler, and the three unaerated lakes continued to decline at relatively high rates. Some of the other lakes exhibited late season trends similar to that in Cedar Lake but they were minor in comparison. A warming trend which began 20 February caused a marked decline in snow depth on all lakes and possibly influenced oxygen concentrations. With the exception of Sabre Lake, Cedar Lake appeared to have the most extensive snow cover remaining in early March.

The depletion rate in Eagle Lake slowed in the latter half of January 1984 when the mean lake oxygen concentration was near 4.0 mg/L (Fig. 8). After declining to near 3.0 mg/L on 31 January, the concentration remained nearly stable in early February before an extended thaw intervened.

Maximum oxygen concentrations at all sampling stations on Cedar and Eagle Lakes far exceeded critical levels. At Cedar Lake they ranged from 4.8 to 6.8 mg/L on 23 February 1982 and from 5.3 to 6.1 mg/L on 9 March. Maximum concentrations at Eagle Lake ranged from 4.0 to 4.8 mg/L on 31 January 1984 and from 3.9 to 4.1 on 7 February. Only three of the four aeration units were operating on 7 February.

Small Subsurface Bubbler System: Crystal Lake - Dissolved Oxygen

Results of 1982 sampling of Crystal Lake are not indicative of aeration equipment ineffectiveness (Fig. 7). Based on 1979 results from large subsurface bubbler systems, the oxygen concentration in Crystal Lake on 10 March was just nearing the stabilization point when sampling ceased. In

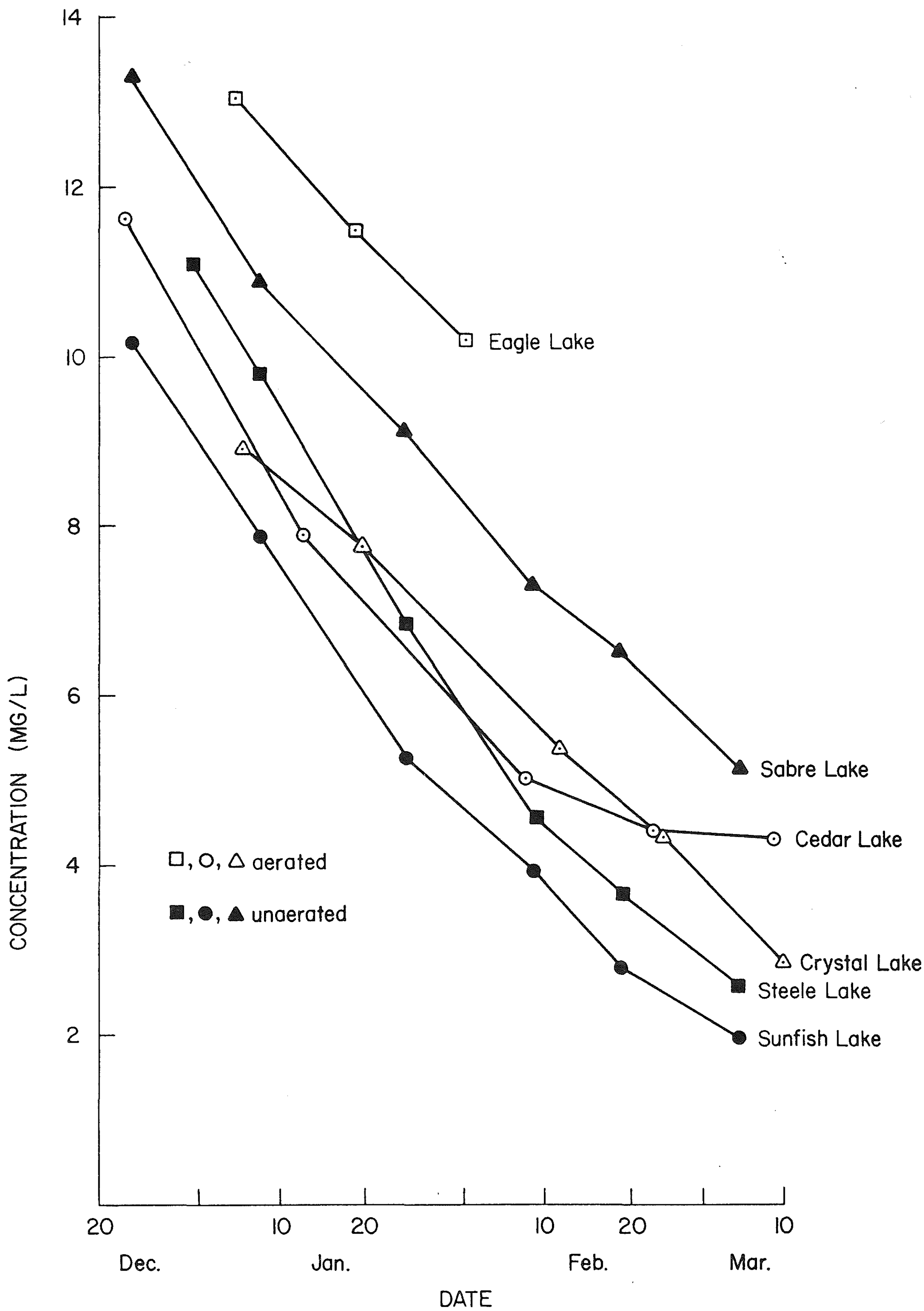

Figure 7. Volume-weighted mean lake oxygen concentrations of aerated and unaerated lakes, winter 1981-82.

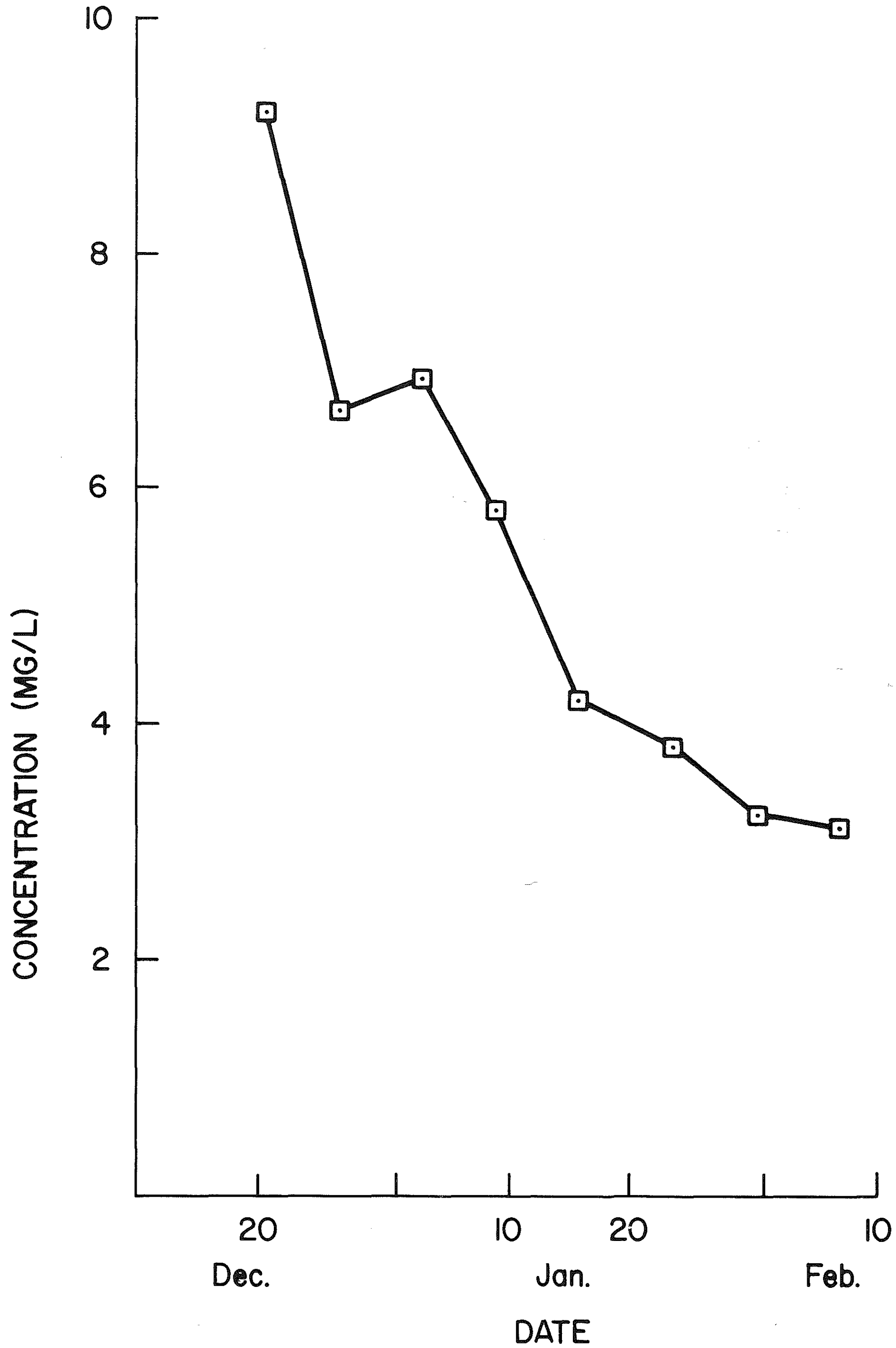

Figure 8. Volume-weighted mean oxygen concentration of Eagle Lake, winter 1983-84.

addition, the aeration system was not operating at full capacity. On 20 January and 10 March, only one of the three diffusers was functioning and on 24 February, none were. The operators indicated that the small diameter air delivery lines repeatedly froze shut, particularly where the water column froze to lake bottom.

Surface and Small Subsurface Bubbler Systems: Water Temperature

Both surface and small subsurface bubblers substantially influenced water temperature (Figs. 9 and 10). Volume-weighted mean temperatures in aerated lakes were generally in the order of 1.0-1.5 C lower than in unaerated lakes. Similarity of depth-temperature profiles at various sampling stations indicated that aerated lakes were well mixed horizontally.

Temperature differences between aerated and unaerated lakes were somewhat greater in 1980-81 than in 1981-82. Sparse snow cover in 1980-81 allowed atmospheric conditions to exert greater influence at the lake surface. All lakes were warmer during the earlier season and temperatures fluctuated. Temperatures in unaerated lakes rose to 3 C within a few cm of the ice.

Estimates of total area of open water created by the aerators on Cedar Lake in January and February 1982 ranged from 0.4 to 1.2 ha. Eagle Lake open water estimates ranged from 0.4 to 0.6 ha in January 1981 and 0.09-0.13 in January 1982 and 1984. The size of the open-water area on Crystal Lake varied considerably because of malfunctioning equipment. Estimates ranged from 0.003 ha on 22 January 1981 to 0.30 ha on 6 January 1982. Most commonly they were 0.27 ha in 1981 and 0.1-0.2 ha in 1982.

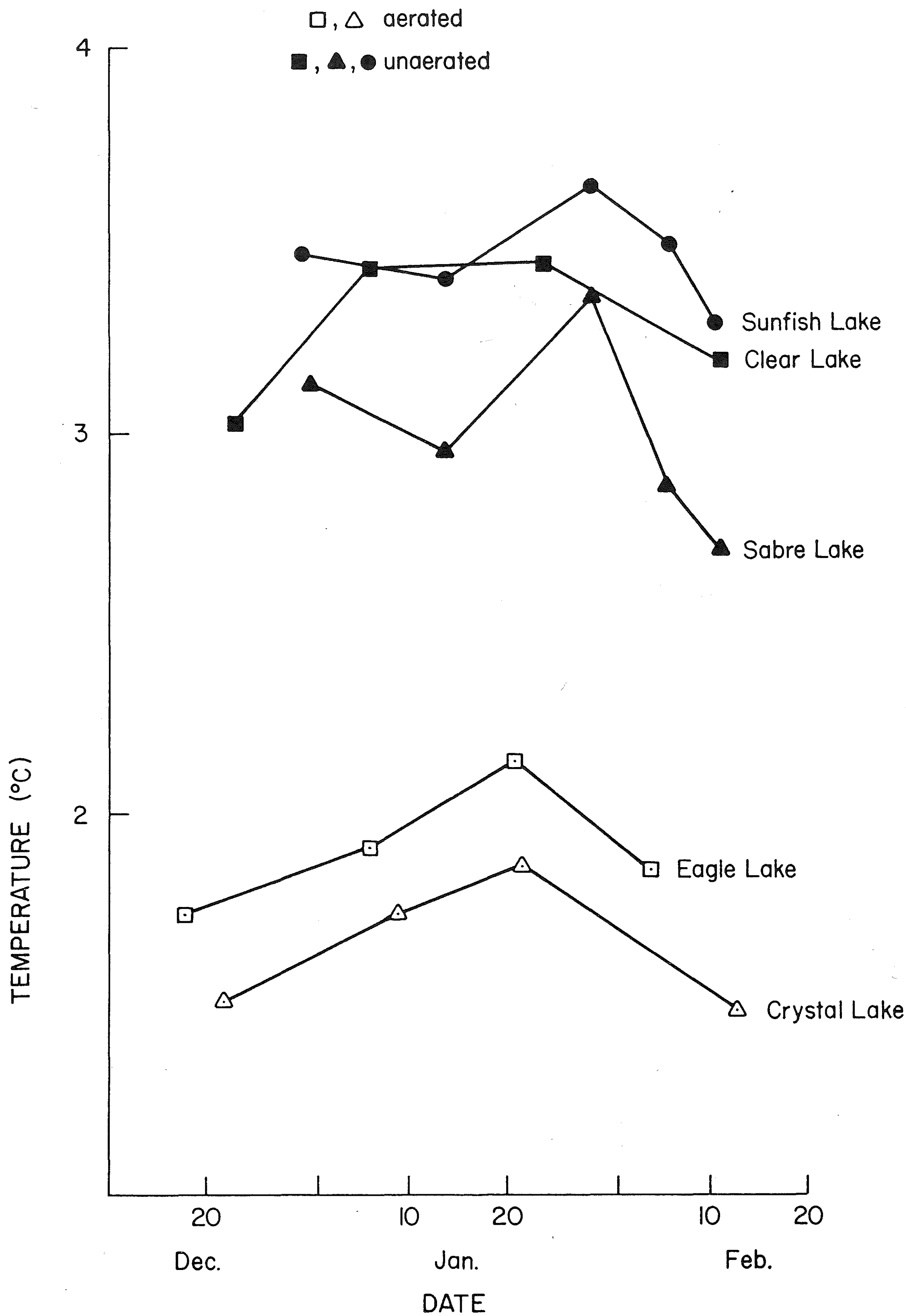

Figure 9. Volume-weighted mean lake temperatures (°C) of aerated and unaerated lakes, winter 1980-81.

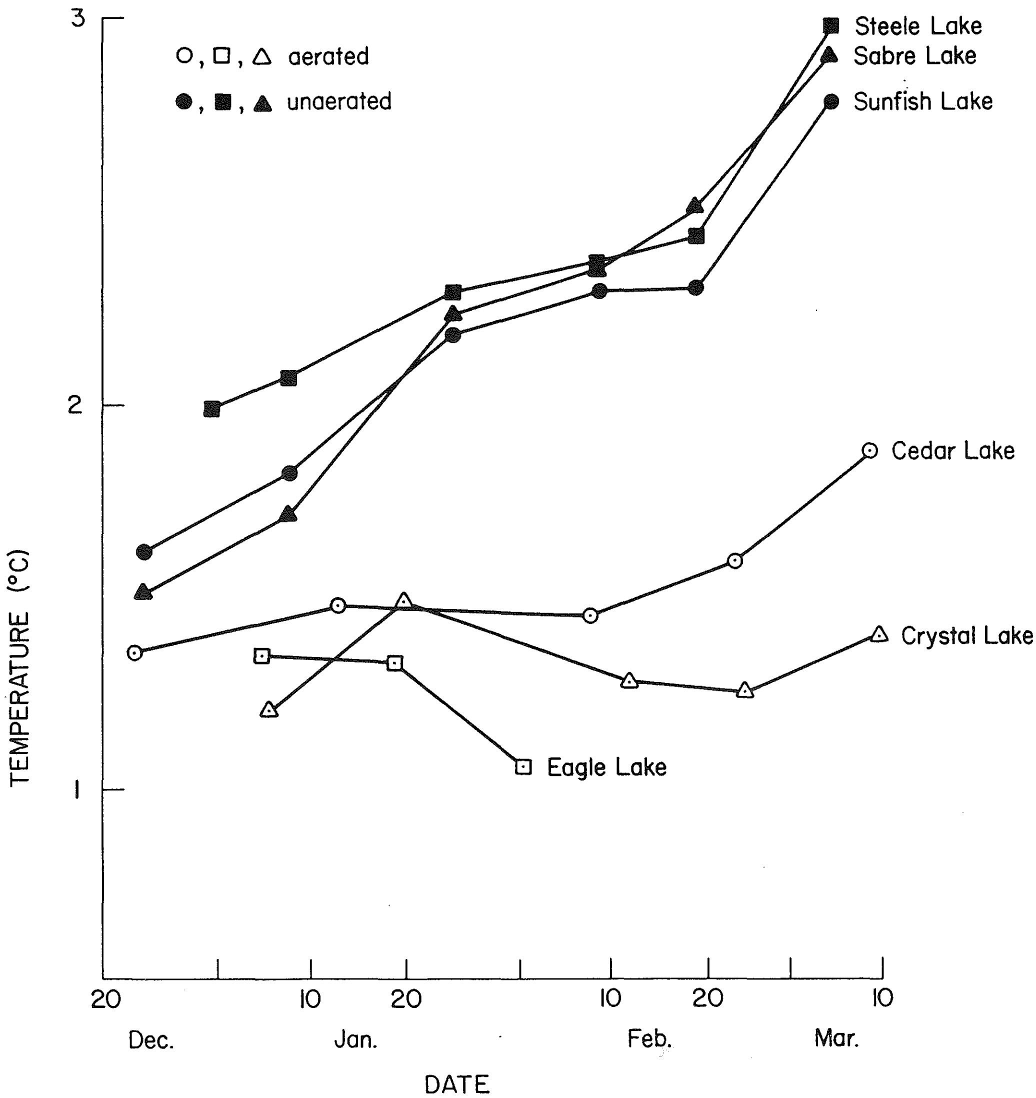

Figure 10. Volume-weighted mean lake temperatures (^{o}C) of aerated and unaerated lakes, winter 1981-82.

DELAYED BUBBLER OPERATION, 1983-84

Oxygen depletion rates in Elysian and Greenleaf Lakes significantly declined following onset of aeration (Fig. 11; Table 6). Overall, the post-aeration depletion rate in Shetek Lake did not differ significantly from the pre-aeration rate (Fig. 12; Table 6). However, a pulse of increased oxygen consumption at onset of aeration in Shetek Lake is indicated by an abrupt decline of the oxygen concentration in the north basin during the

Table 6. Slopes of regressions of dissolved oxygen on days (Figs. 11 and 12) and results of tests for homogeneity between pre- and post-aeration periods.

Lake	(b) Mean oxygen depletion rate ($g/m^2/d$)	H_0: $b_1 = b_2$	
		t	p
Shetek, N. basin			
(1) Pre-aeration	0.424	0.192	>0.5
(2) Post-aeration	0.438		
Shetek, S. basin			
(1) Pre-aeration	0.263	0.857	>0.4
(2) Post-aeration	0.212		
Elysian			
(1) Pre-aeration	0.365	5.627	<0.01
(2) Post-aeration	0.152		
Greenleaf			
(1) Pre-aeration	0.335	2.786	<0.05
(2) Post-aeration	0.249		

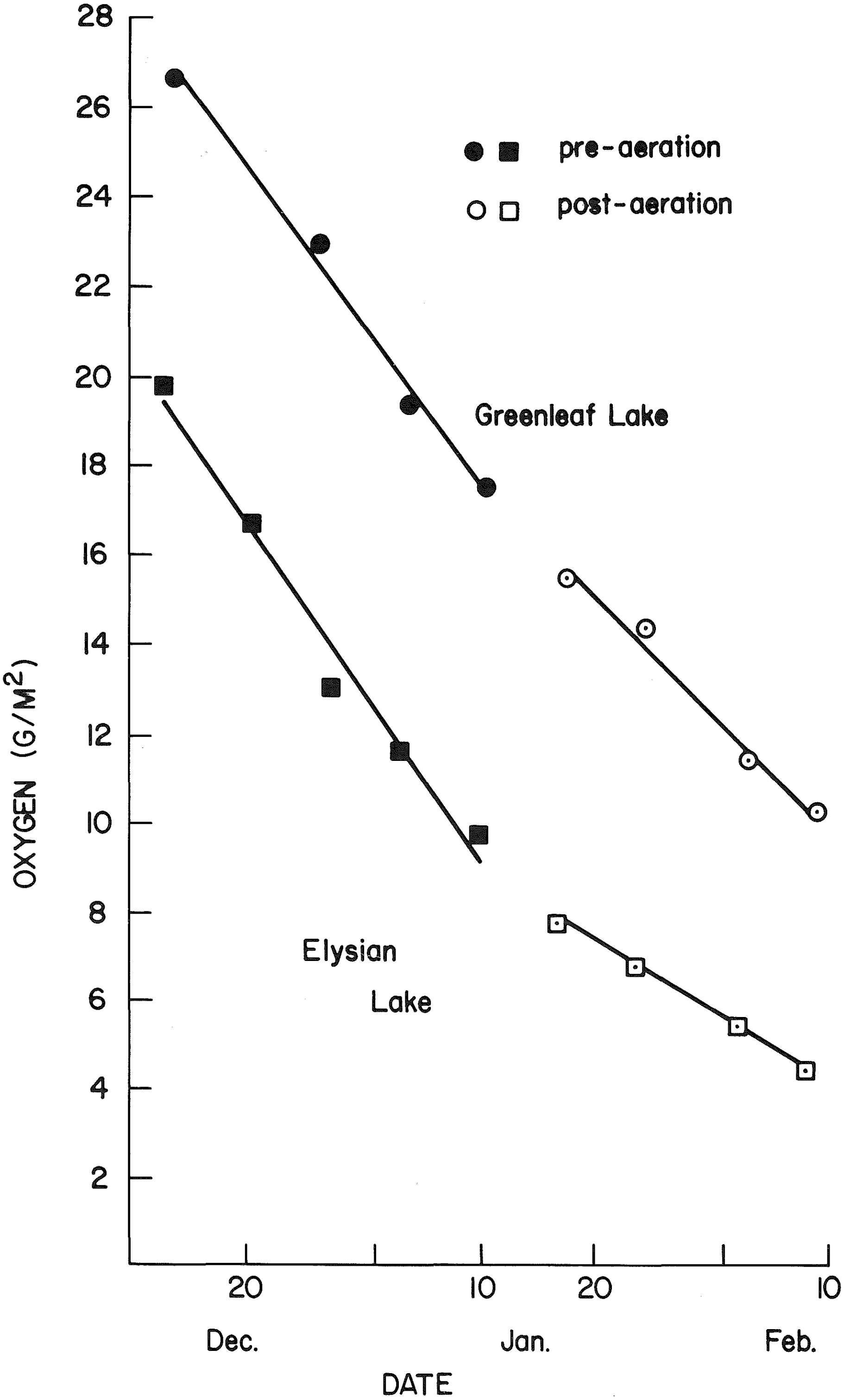

Figure 11. Oxygen mass (g/m^2 of surface area) before and after aeration began in Greenleaf and Elysian Lakes, winter 1983-84.

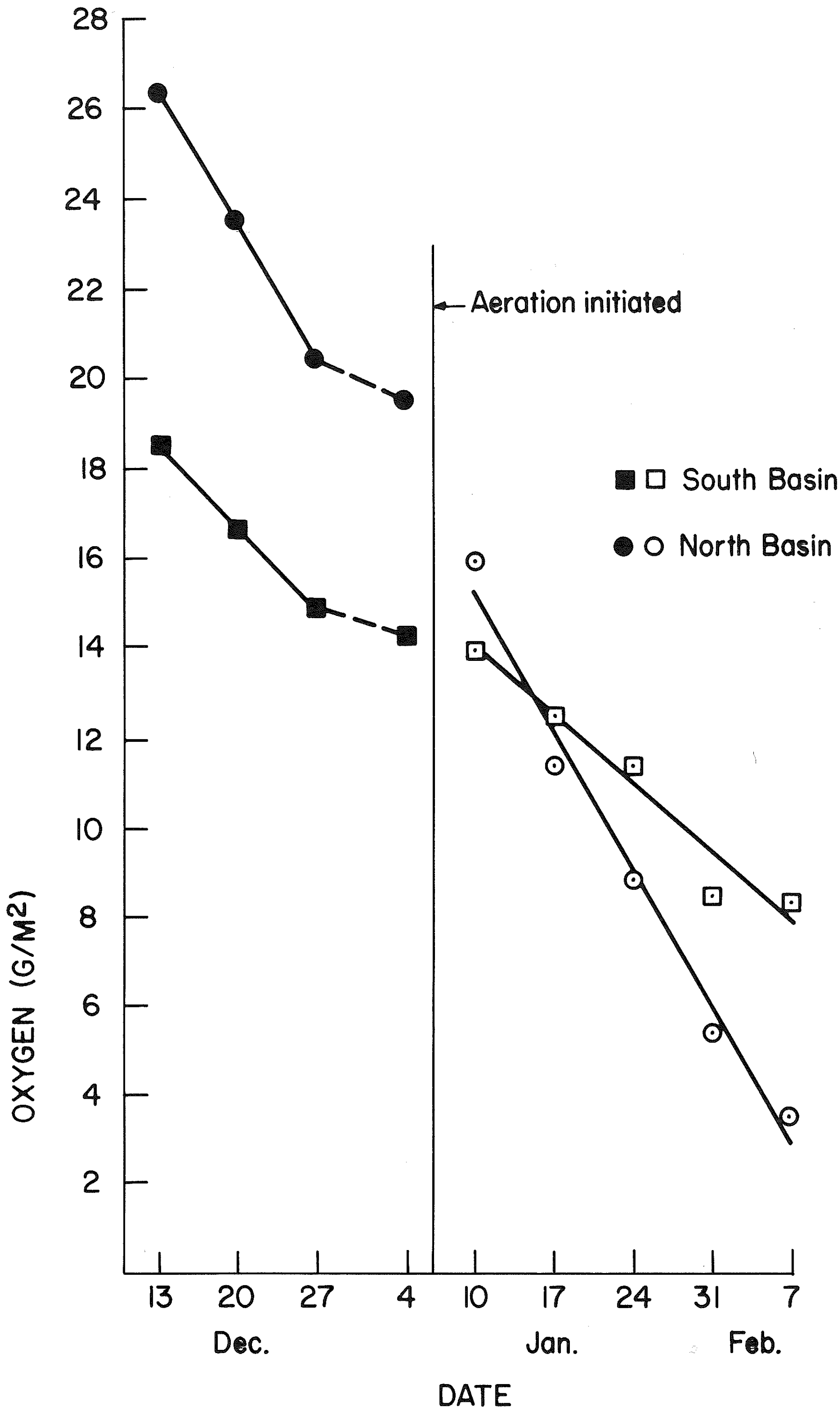

Figure 12. Oxygen mass (g/m^2 of surface area) before and after aeration began in Shetek Lake, winter 1983-84. Broken lines indicate intervals not included in regression analysis.

interval 4-10 January while a mild decline in the south basin continued to reflect an interlude of diminished snow cover. When the assessment period is separated into three intervals, a brief and significant increase in oxygen depletion is detected in the north basin (Fig. 13; Table 7). After 11 d of aeration the depletion rate reverted to a level similar to the pre-aeration rate.

Table 7. Slopes of regressions of dissolved oxygen on days (Fig. 13) and results of tests for homogeneity between three time intervals in north basin Shetek Lake, winter 1983-84.

Interval	(b) Mean oxygen depletion rate ($g/m^2/d$)	H_0: $b_1 = b_2$ t	p
(1) 13-27 December	0.424	15.884	<0.01
(2) 4-17 January	0.623		
(1) 4-17 January	0.623	4.978	<0.02
(2) 17 January-7 February	0.386		
(1) 13-27 December	0.424	0.883	>0.4
(2) 17 January-7 February	0.386		

This increased oxygen consumption in the aerated basin of Shetek Lake may have resulted from oxygen demand of sediment particles suspended by turbulence from detached air lines. In experiments with lake sediment cores, Hargrave (1969) found that agitating overlying water enough to suspend sediment particles markedly increased oxygen consumption.

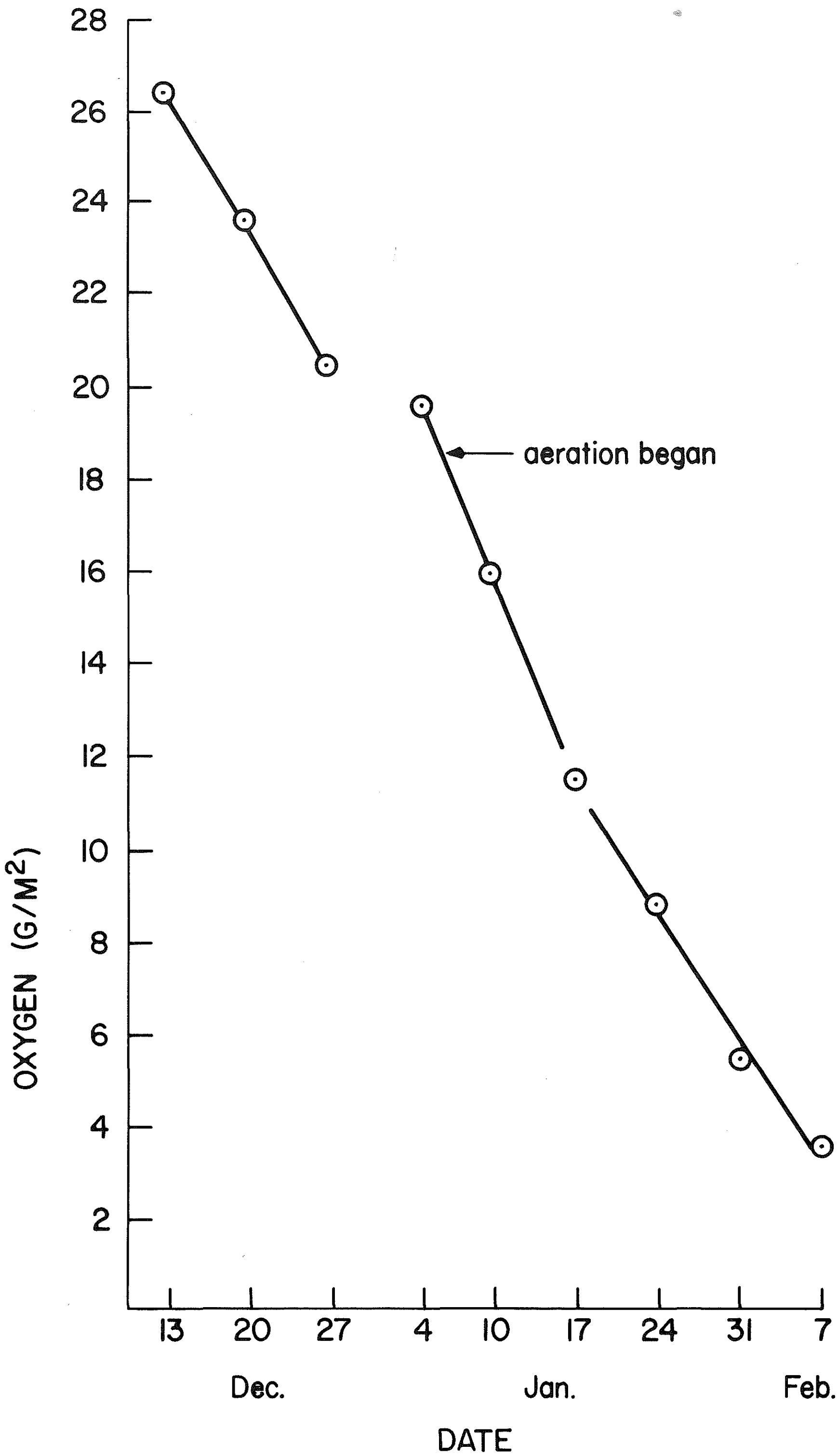

Figure 13. Oxygen mass (g/m^2 of surface area) in the north basin of Shetek Lake before and after aeration began, winter 1983-84.

Circumstances in Shetek Lake differed from those in Elysian and Greenleaf Lakes in another respect. Although there were variations from station to station, there was considerably less oxygen near the sediment in Shetek Lake prior to aeration (Fig. 14). In parts of the lake, near-sediment water was nearly anoxic. Hargrave (1969) reported that gentle stirring of water overlying sediment cores significantly increased oxygen consumption only after concentrations fell below a threshold level. Lowered consumption in Canadian prairie lakes occurred when near-sediment concentrations were near 2.0 mg/L (Mathias and Barica 1980). Perhaps near-sediment threshold levels had been reached in Shetek Lake and oxygen consumption was limited. Under these conditions, oxygen movement across sediment as a result of circulation generated by aeration equipment should elicit a response. If this occurred, however, it is unclear why the response was only temporary as long as high oxygen concentrations existed in the upper water column unless reduced gases had accumulated near anoxic sediments and influenced oxygen consumption until they were exhausted.

PUMP AND BAFFLE AERATION

Lily Lake

Rather than following a direct route back toward the intake and producing sharp increases in local oxygen concentrations, convection apparently moved much of the oxygen differently and favorably influenced a large area of the lake. Increased oxygen concentrations at Stations 12 and 13 between 10-14 March indicate that discharged water moved southeasterly away from the aeration site (Fig. 15; Table 8). Oxygen concentrations were influenced to a depth of 1.5 m. Allowing for 55-60 cm of ice at the surface, approximately 1 m of the water column was affected. Oxygen dissipated quite rapidly at the discharge site. The concentration of discharged water on 14 March was

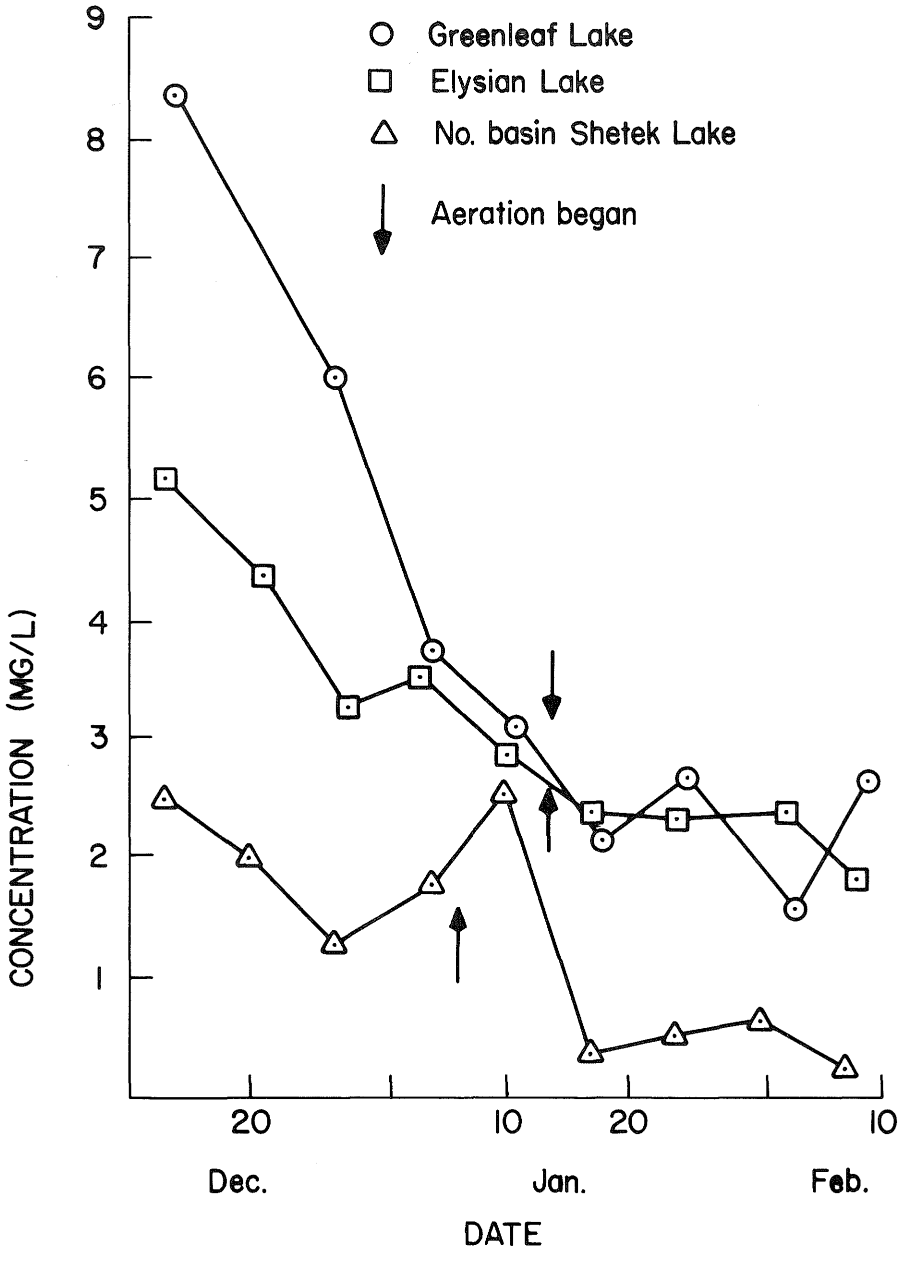

Figure 14. Mean station oxygen concentrations (mg/1) 20 cm above the bottom sediments in three lakes before and after aeration began, winter 1983-84.

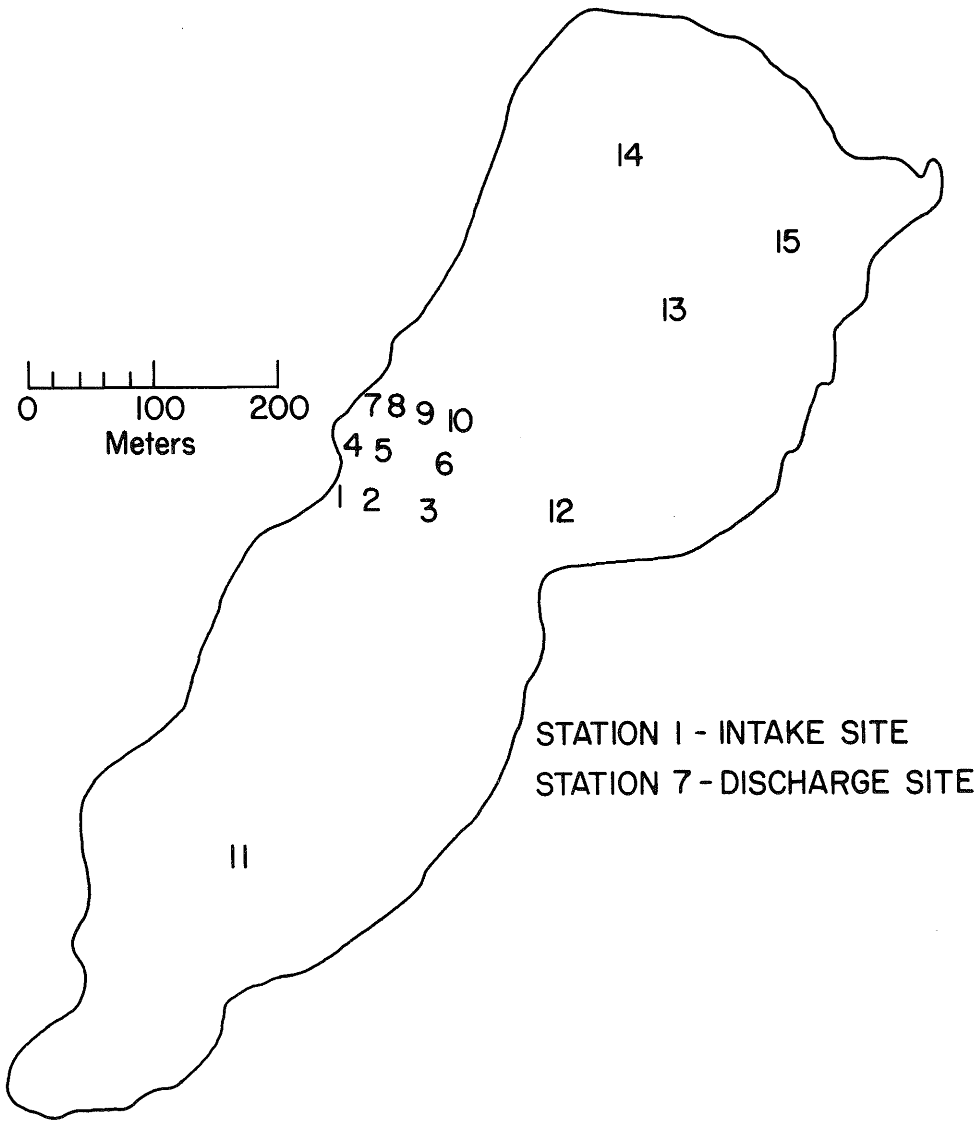

Figure 15. Aeration intake and discharge sites, and sample station locations on Lily Lake, March 1980.

Table 8. Summary of results of pump and baffle aeration including discharge water oxygen concentration, saturation and temperature, and sample station oxygen and temperature measurements at Lily Lake, March 1980.

		March 10		March 12		March 13		March 14	
Hours pumped (cumulative)		0		0.3		20.8		43.7-48.4	
Baffle discharge:									
D.O. (mg/L)				7.5		7.9		8.6	
Temp. (C)				1.5		2.1		2.1	
Percentage saturation				56		60		65	
Sampling station	Parameter	D.O. (mg/L)	Temp (C)	D.O. (mg/L)	Temp (C)	D.O. (mg/L)	Temp (C)	D.O. (mg/L)	Temp (C)
1	a			0.7	1.1	1.7	1.3	2.3	1.8
	b			1.4	1.6	2.4	2.2	2.5	2.5
2	a	1.5	2.0					1.8	2.5
	b	2.8	3.0					2.6	3.0
3	a							1.0	2.4
	b							1.7	3.4
4	a							2.7	1.8
	b							2.9	2.2
5	a	1.2	2.4					1.8	2.5
	b	2.7	3.1					2.8	3.1
6	a							2.6	2.3
	b							3.7	3.3
7	a							2.8	2.3
	b							3.2	2.5
8	a							2.3	2.5
	b							4.4	2.9
9	a							2.3	2.6
	b							3.7	3.2
10	a							2.4	2.5
	b							3.8	3.3
11	a	1.0	2.2					0.5	2.0
	b	2.7	2.9					0.9	2.6
12	a	1.3	2.6					2.2	2.3
	b	2.4	3.3					3.1	3.2
13	a	1.3	2.7					2.5	2.4
	b	2.0	3.2					3.6	3.1
14	a	1.3	2.5					1.0	2.4
	b	2.1	3.5					2.2	3.4
15	a	1.2	2.7					1.0	2.5
	b	2.3	3.4					2.0	3.3

[a] Mean concentrations and temperatures in the upper 2 m of the water column.
[b] Maximum concentrations and temperatures.

8.6 mg/L while the maximum lake concentration next to the discharge hole was only 2.5 mg/L.

The 2.1 C discharge influenced temperature in the first 1 m of the water column beneath the ice at Stations 12 and 13 between 10-14 March (Table 9).

Table 9. Temperature profiles (C) at sampling stations on Lily Lake before and after pump and baffle aeration, March 1980.

	Sampling station and date													
	2		5		11		12		13		14		15	
Depth	Mar.		Mar.		Mar.		Mar.		Mar.		Mar.		Mar.	
(m)	10	14	10	14	10	14	10	14	10	14	10	14	10	14
0.75	0.9	1.7	0.9	2.1	1.1	1.3	0.8	1.1	1.2	1.6	1.0	0.9	1.2	1.1
1.00	2.2	2.6	2.7	2.8	2.2	2.2	2.8	2.3	2.9	2.3	2.5	2.4	2.8	2.7
1.50	3.0	2.8	3.1	2.8	2.8	2.4	3.2	2.8	3.2	2.8	3.2	2.9	3.2	3.0
2.00	-	-	-	-	-	-	3.3	3.2	3.2	3.1	3.5	3.4	3.4	3.3

There was a warming at depths that were initially cooler than 2.1 C and a cooling at depths that were warmer than 2.1 C. The same pattern was also evident at Station 11 where the oxygen concentration was poorly influenced. The overall pattern was warming of the water column at stations near the aeration site and cooling at stations further from the discharge site (Table 8).

Spring recovery occurred shortly after 14 March and pumping was discontinued. Fuel consumption rate of the diesel engine was 4.2 L/h. The baffle chute, with a 1.5 m vertical drop, yielded 56 to 65% oxygen saturation that was substantially below the desired 85-90%.

Penn Lake

The relatively low-flow groundwater discharge into Penn Lake appeared to influence oxygen concentrations throughout the lake. Concentrations at Stations 6 and 8 remained quite stable during the 43 d period 30 December-11 February (Fig. 16; Table 10). Station 8 was 250 m from the discharge.

Table 10. Mean and maximum dissolved oxygen concentrations (mg/L) in Penn Lake, winter 1981-82. Depth (m) of sample station in parentheses.

Date and Parameter	Sampling station									
	1 (0.5)	2 (1.3)	3 (1.3)	4 (1.5)	5 (1.6)	6 (1.3)	7 (0.7)	8 (0.8)	9 (0.6)	10 (0.7)
30 December										
Mean	5.7					5.4		5.4		
Max.	6.4					6.6		5.9		
21 January										
Mean	5.9					4.8		3.1		
Max.	7.0					6.7		4.9		
11 February										
Mean	8.6	1.5	3.3	4.8	2.4	4.8	3.0	4.1	3.3	2.6
Max.	8.6	2.6	4.0	5.2	3.0	5.5	3.1	4.2	3.6	2.8

Discharged water appeared to have strongest influence along a line from the discharge site to Station 10. Snow depth was such that early anoxia was otherwise probable in such a shallow lake. Oxygen concentrations in nearby Crystal Lake steadily declined during the same period (Fig. 7).

Estimates of open-water area created by the 12 C discharge ranged from 0.06 ha on 30 December to 0.11 ha on 21 January when open water extended 45 m from shore.

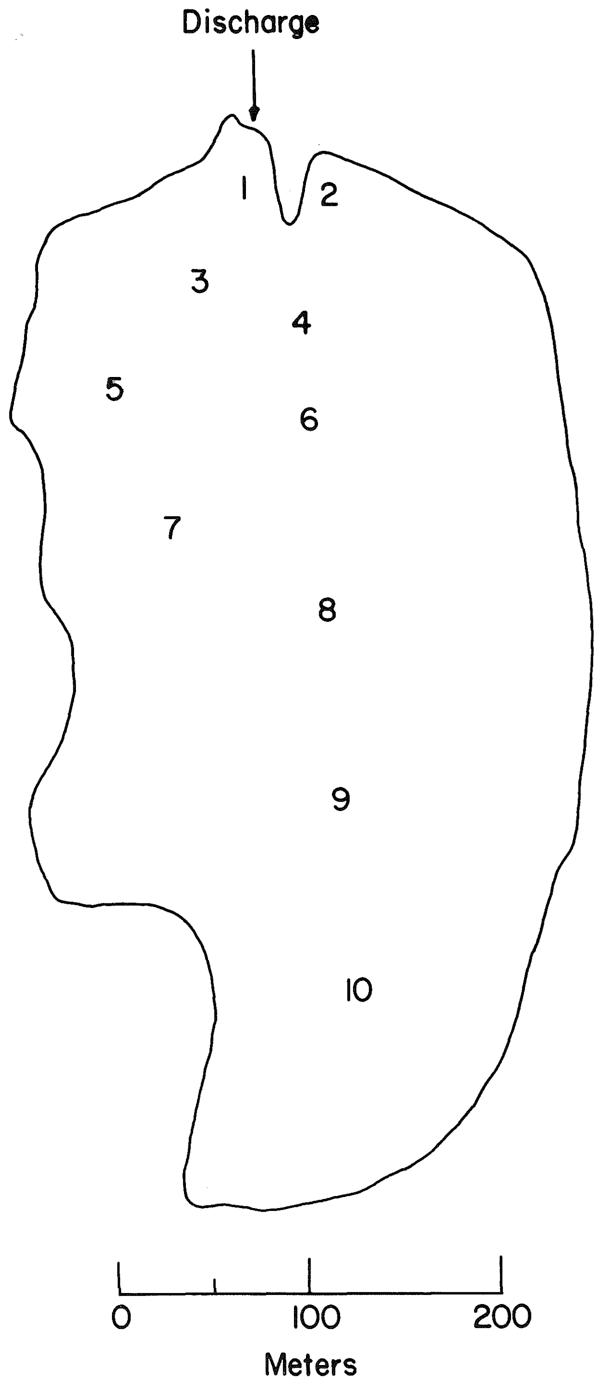

Figure 16. Discharge site and sample station locations on Penn Lake, winter 1981-82.

SUMMARY AND MANAGEMENT IMPLICATIONS

Large subsurface bubbler systems on Lura and Elysian lakes were highly successful in preventing winterkill during the severe 1978-79 winter. Stable oxygen concentrations were maintained in sufficiently large areas of both lakes for long periods of winter. Although concentrations were alarmingly low, they were adequate to prevent suffocation of sensitive game fish during a winter of dense snow cover from mid-November to mid-March. In terms of the number of winterkill lakes reported in Minnesota, the 1978-79 winter was the fourth severest in a 27 yr. span (Pederson 1982). Surface bubblers will likely produce similar results although investigation of the persistence of oxygen stability over a several week period was prevented by early intervention of warm weather.

Morphological characteristics of lakes influence performance of aeration systems. Shallow Lura Lake had less heat storage than Elysian Lake and the Lura Lake aeration system maintained a relatively small area of open water. Accordingly, a small but adequate sized lake area was favorably influenced.

Fish will apparently locate the most favorable areas as anoxia approaches. Johnson and Moyle (1969) and Flick (1968) reported concentrations of northern pike and trout, respectively, at artificially created refuge areas. Anglers at the Lura Lake aeration site indicated that walleye and yellow perch were concentrated there and were quite active in spite of near freezing temperatures throughout the water column.

Relatively low oxygen concentrations near the large subsurface bubbler aeration sites in early winter suggest that the aeration equipment might have caused increased oxygen consumption. Immediate, short-term increases in oxygen depletion rate with onset of aeration with compressed air have been reported by Halsey (1968), Lackey and Holmes (1972) and Smith et al. (1975). Investigation of this possibility in 1983-84 revealed a brief depletion rate increase at onset of aeration in one of three study lakes, but the exact cause could not be identified. Low near-sediment oxygen concentrations in areas of Shetek Lake before aeration began suggested potential for increased oxygen consumption by intrinsic processes but the cause of the rate increase could have been that detached air lines in the diffuser field caused substantial oxygen demand in the water column by suspending sediments.

Bubbler aeration equipment did not offset high oxygen consumption early in winter but did become manifest when oxygen concentrations were still above levels lethal to game fish. Several investigators have reported declining lake oxygen consumption after concentrations drop to threshold levels (Hargrave 1972; Welch 1974; Welch and Bergmann 1985). Mathias and Barica (1980) reported threshold levels in Canadian prairie lakes when near-sediment concentrations were near 2.0 mg/L and mean lake concentrations were near 4.0 mg/L. In Lura and Elysian lakes, declining consumption was balanced when mean station concentrations were generally near 2.0 mg/L or less and maximum concentrations were usually 0.5-1.5 mg/L higher.

Reduced lake temperature caused by bubbler aeration probably aids stabilization at desirable levels. Oxygen uptake by lake sediments is strongly influenced by temperature and increasingly so toward the low end of the scale where a 1 C increment makes a substantial difference (Hargrave 1969).

Operating early in winter when the oxygen concentration is near saturation is extremely inefficient, particularly if it causes increased oxygen consumption. Annual savings in operating costs and equipment depreciation can be derived by operating only after the concentration has declined to some predetermined point above stabilization level. Savings will be substantial during winters with sparse snow cover or early intervention of thawing temperatures.

Optimum start-up time for bubbler equipment will vary depending upon depletion rate and heat storage. Consideration must be given to the time required for creation of sufficient open water area and adherence to state or local laws requiring public notification within a specified time frame prior to operation. It generally takes about 2-3 wk for removal of about 50 cm of ice in an adequate area. Heat storage should not be a problem in lakes blanketed with snow because heat from sediments tends to gradually accumulate in the water column as winter progresses.

In most cases, optimum start-up time will probably be when the mean oxygen concentration is between 5-7 mg/L. Initially, a wide margin of safety is advisable until operators become familiar with their situation, then the operation can be fine tuned to achieve maximum performance. A sampling station near the aeration site and one near maximum depth are probably adequate for monitoring depletion rates and projecting oxygen concentrations. Station mean water column oxygen concentrations are adequate indicators since they underestimate whole lake means and provide a safety margin. This avoids resorting to the laborious task of determining whole lake mean concentrations.

Precautions should prevent ice build up within the air delivery lines and plugging. Air lines should be adequately buried near shore to avoid running the system continuously after freezeup. Check valves to prevent water from filling air lines when equipment is idle and a brief start-up period before freezeup to clear any water from the lines are also recommended.

Size of ice-free area is less critical than previously thought and considerable flexibility can be exercised in choosing bubbler aeration sites.

Diffusers should be placed to utilize as much stored heat as is practical but site availability and costs should be weighed against size of refuge area needed. Two meter diffuser depth should be considered minimum. Diffuser sites exposed to prevailing winds should be selected whenever possible.

Area/equipment ratios for Lura Lake were 25 ha/hp and 41 ha/diffuser. Elysian Lake ratios were 35 ha/hp and 52 ha/diffuser. Lura Lake values should probably be considered maximum for shallow lakes less than 400 ha. Small additions in equipment capacity and diffuser numbers in small lakes will greatly change area ratios without much additional cost. Pederson (1982) reports that smaller lakes have generally larger sized aeration systems relative to surface area.

Pump and baffle aeration has not been used extensively in Minnesota but it offers a less hazardous alternative to offshore bubbler systems. Pump and baffle systems investigated were shore-based operations that created open water in shallow areas adjoining shore. Recirculated lake water made a small hole in the ice while groundwater removed ice from a considerably larger area. Hyland Lake, a 38 ha lake in Hennepin County (not included in this investigation), has a recirculating system with an underground baffled culvert and an offshore discharge that leaves ice cover intact.

Pump and baffle systems should compare favorably in performance with bubblers on small lakes and are probably the best choice for extremely shallow lakes because heat storage is not a consideration. Delayed or intermittent operation is more readily accomplished with pump and baffle systems and may put cost-efficiency in line with bubbler systems. However, cost effectiveness on large lakes is not established and pump and baffle aeration on lakes larger than about 40 ha should yet be considered experimental. Baffle design criteria that yield optimum performance at various flow rates are needed.

Wheaton (1977) points out that transfer of a unit of oxygen from air to water requires increased energy as saturation is approached. There is little economic justification for attempting to aerate beyond 90% saturation.

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