Lake aeration in British Columbia: Applications and experiences

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Keywords: artificial circulation, lake aeration, hypolimnetic aeration, winterkill, eutrophication

1. Introduction

The complex geology, extensive glacial history and diversity of climatic conditions in British Columbia have resulted in a wide range of lake typology and productivity. In recognition of these climatic and geological variations, Northcote and Larkin (1956, 1966) distinguished 12 distinct limnological regions (Fig. 1). Additional studies in the Northern Interior Plateau, Columbia Mountains and Insular and Coast Mountains will undoubtedly reveal further subdivisions, and a review of the limnological regions is currently underway (pers. comm., T. Northcote, Summerland, B.C.). Two limnological zones in particular, the Southern Interior Plateau and Insular Lowland, have attracted considerable management attention due to concerns about the impacts of natural and cultural eutrophication on recreational fisheries and water quality. The limnological characteristics of lakes in these two areas differ substantially as B.C. is divided at the most basic level into coastal and interior systems. Coastal lakes tend to be less productive, softwater, highly flushed and warm monomictic (in terms of their stratification patterns). Interior lakes tend to be more biologically productive, hardwater, less flushed and dimictic. As a result, aeration techniques tend to be quite different in their purpose and application in these two areas.

1.1 Southern Interior Plateau

Most lakes in the Southern Interior Plateau limnological region (Fig. 1) are of glacial origin. A few lakes in this region tend towards oligotrophy, however the vast majority

Aquatic Restoration in Canada
Edited by T. Murphy & M. Munawar, pp. 87-108
Ecovision World Monograph Series

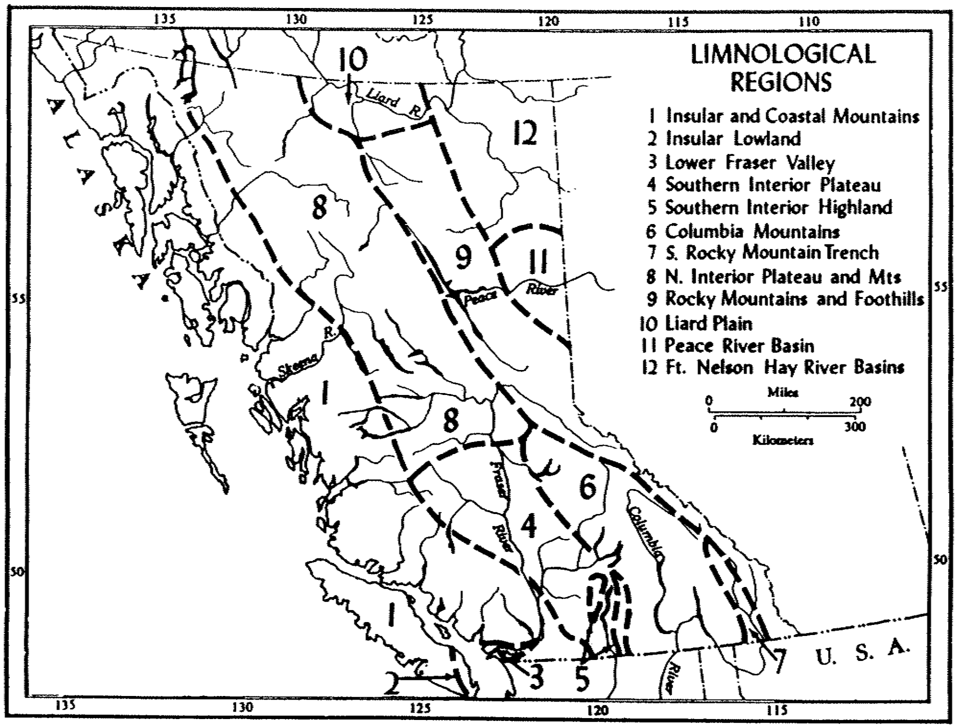

Fig. 1. Limnological regions of B.C. (modified from Northcote and Larkin, 1966).

exhibit moderate to strong natural eutrophy. Total dissolved solids (TDS) content is usually well over 100 mg·L^{-1}, with some lakes exceeding 1,000 mg·L^{-1} and still supporting fish communities (Northcote and Larkin, 1966). In summer months, dense blooms of cyanobacteria (mainly *Aphanizomenon* and *Anabaena*), high surface temperatures, sharp thermal stratification and marked hypolimnetic oxygen depletion are typical. In winter months, extended periods of ice cover (i.e., late November to May) combined with high oxygen depletion rates and shallow mean depths often lead to severe whole-lake oxygen depletion. Both situations can lead to summerkills (Northcote and Larkin, 1966) and winterkills of trout (Halsey, 1968; Northcote and Halsey, 1969; Ashley, 1983).

Many of the small (i.e., < 100 ha) lakes in this arid region are internationally recognized for their prized rainbow "Kamloops" trout (*Oncorhynchus mykiss*) recreational fisheries (Raymond, 1980). The majority of these lakes were originally barren of fish and their trout populations were established by an extensive program of stocking (Larkin, 1954; Nordstrom *et al.,* 1978), and occasional chemical eradication of non-game fish (Stringer and McMynn, 1960; Larkin and Cartwright, 1976). This monoculture status, in combination with limited natural spawning habitat and favourable climatic, edaphic and morphometric features, resulted in highly productive lakes that support popular fisheries. For example, the lakes in the Thompson-Nicola management region (an administrative district within the Southern Interior

Plateau) generate a significant amount of angling effort (Table 1). A recent survey (Stone, 1988) indicated approximately 871,000 angler-days of fishing effort was directed on lakes in the Thompson-Nicola region, of which 68% (i.e., 589,400 angler-days) was on small lakes (i.e., < 500 ha). The total catch for the Thompson-Nicola region lakes was 2,048,900 fish, of which 1,347,100 were retained. Rainbow trout comprised the majority of the harvest (80%), followed by kokanee (*Oncorhynchus nerka*; 11%) and three species of char (*Salvelinus fontinalis*, *S. namaycush* and *S. malma*; 8%) (Stone, 1988).

The regional fisheries management goal for these naturally eutrophic lakes is to provide a variety of sustainable angling opportunities while maintaining the aesthetic appeal of a semi-wilderness location. A variety of fisheries management and lake restoration techniques are often considered to achieve this goal (Ashley *et al.*, 1992). Numerous lake restoration techniques have been documented in the literature (e.g., Dunst *et al.*, 1974). However, given the arid continental climate of the Southern Interior region and semi-wildnerness location of these lakes, many restoration techniques are not applicable due to cost and logistics (e.g., dredging) or water shortages (e.g., dilutional flushing). Increased water storage is a viable option in specific cases, and is usually the first option considered when investigating methods to prevent winterkill. Chemical modification to reduce lake productivity may be a future strategy for reducing winterkill risk in some Southern Interior area lakes. In a preliminary test, Murphy *et al.* (1985) applied 23 tonnes (1983) and 16 tonnes (1984) of $Ca(OH)_2$ to eutrophic Frisken Lake. The lime treatment induced calcium carbonate formation and subsequently removed up to 90% of the chlorophyll *a* and 97% of the soluble reactive phosphorus (SRP) from the epilimnion. However, most of the precipitated phosphorus re-dissolved in the hypolimnion, so the long term utility of this procedure is uncertain. Application of inorganic nitrogen may also be a possible technique for preventing seasonal anoxia and reducing cyanobacteria blooms (Barica *et al.*, 1980), however, no trials have been conducted to date in B.C.

The current technique used to alleviate winterkill conditions in these lakes is artificial circulation during fall and winter months. Although occasional summerkills do occur, management efforts are usually directed at preventing or reducing the severity of winterkill events. This technique was pioneered in British Columbia in

Table 1. Selected characteristics of Thompson-Nicola region lakes.

	Lake Area (hectares)			
	<500	500-1,000	1,000-10,000	>10,000
No. of lakes	1,814	13	17	2
Mean size (ha)	21.4	654	3,247	22,809
Mean TDS ($mg.L^{-1}$)	170	301	104	66
Mean elev. (m)	1289	982	666	370
Effort (1,000's of angler-days per year)	589.4	92.3	74.1	115

the early 1960s (Halsey, 1968) and is used in lakes where the fisheries manager wishes to diversify angling opportunities by providing a year-round fishery with multiple age classes. Although this approach is more technically complex than various hatchery stocking options (Ashley *et al.*, 1992), the high productivity of these lakes allows for the yield of large fish (i.e., 3-5 kg) in 3-4 years, and this type of fishery is very popular among resident and non-resident anglers. Artificial circulation is now standard practice on 18 winterkill lakes (mean depth 2.0 to 17.4 m, surface area 3.2 to 41.3 ha) in the Southern Interior region (Table 2). All of the current artificial circulation installations are destratification systems, although the first hypolimnetic aeration system in Canada was operated on Black Lake (near Penticton) from 1978 to 1981 (Ashley, 1983). Since these lakes are naturally eutrophic, management attention has focused primarily on reducing winterkill risk to increase angling opportunities rather than on improving water quality.

1.2 Insular Lowland

Lakes in the restricted but highly distinctive Insular Lowland limnological region are typically small (<500 ha) with low mean depths (<10 m) (Northcote and Larkin, 1966). These lakes exhibit high surface temperatures, occasionally reaching 26 °C in midsummer, while bottom temperatures may exceed 19 °C. Total dissolved solids

Table 2. Artificial circulation installations in Southern Interior region lakes.

Lake	Area (ha)	Zm (m)	Type of installation	Unit Power
Bleeker	35.6	7.9	surface aerator	1 x 0.75 kW
Burnell	15.0	3.3	surface aerator	2 x 0.75 kW
Dewar	41.3	4.0	surface aerator	2 x 0.75 kW
Higgens	24.6	4.9	surface aerator	2 x 1.5 kW
Horseshoe	5.7	2.2	surface aerator	1 x 0.75 kW
Irish	28.0	4.2	surface aerator	2 x 0.75 kW
Kidd	25.0	4.0	surface aerator	3 x 0.75 kW
Lady King	6.0	3.5	surface aerator	2 x 0.75 kW
Lodgepole	6.8	3.6	surface aerator	1 x 0.25 kW
Logan	11.5	3.5	surface aerator	1 x 0.75 kW
Martins	5.0	6.0	surface aerator	1 x 0.25 kW
Menzies	3.7	6.6	surface aerator	1 x 0.75 kW
Rose	3.2	3.1	surface aerator	1 x 0.37 kW
Skulow	37.8	2.0	surface aerator	2 x 0.75 kW
Stake	23.1	4.3	surface aerator	1 x 0.75 kW
Tulip	10.1	3.2	surface aerator	1 x 0.75 kW
Walloper	36.4	2.7	surface aerator	1 x 0.75 kW
Yellow	30.8	17.4	compressed air	1 x 11.2 kW

concentrations are usually above 100 $mg \cdot L^{-1}$, and over 200 $mg \cdot L^{-1}$ in some Gulf Island ponds. Due to the maritime climate, these lakes generally exhibit warm monomictic stratification; however, brief periods of ice cover may form during winter months. Severe hypolimnetic oxygen depletion is typical for lakes in this region, and summerkills of trout have been recorded in several lakes (pers. comm., P. Law, Ministry of Environment, Lands and Parks, Nanaimo, B.C.).

Phosphorus inputs from agricultural and residential development in this area of rapidly increasing population has accelerated cultural eutrophication, and water quality has deteriorated below Provincial standards for potable water and contact recreation in several lakes. Many rural areas, particularly the Gulf Islands, depend on lakes as their main supply of potable water. The combination of increasing population growth with decreasing water quality and availability has focused public and government attention on protecting and restoring key lakes in this small, but highly valued limnological region. In contrast to the Southern Interior Plateau region, water quality, fisheries and contact recreation are considered of equal importance, with water quality becoming the dominant issue in water scarce locations (e.g., Gulf Islands). Hence, the regional fisheries management goal for these culturally eutrophic lakes is to provide sustainable angling opportunities while demonstrably improving water quality for contact recreation and domestic use.

Once again, few of the documented lake restoration techniques are applicable to this region due to cost and logistics or water shortages (e.g., Gulf Islands). Chemical treatment to reduce lake productivity is not usually an option due to concerns from the public and potable water utilities. Consequently, artificial circulation using destratification or hypolimnetic aeration is often selected as the principal in-situ restoration technique to compliment reductions in point and non-point source nutrient loading (Table 3). In water supply lakes, drawing water from the hypolimnion is advantageous due to cooler temperatures and lowered algal biomass. However, with significant oxygen depletion the hypolimnion may have high concentrations of reduced iron, manganese and noxious gases (e.g., H_2S) that lower the acceptability of the water or greatly increase treatment costs. Hypolimnetic aeration is one of the few techniques that can improve potable water quality *in situ* without disrupting thermal stratification. Preservation of the hypolimnetic environment also allows creation of a "two storey" fishery with warm water species in the epilimnion (typically centrarchids) and cool water species (usually salmonids) in the hypolimnion.

Table 3. Artificial circulation installations in Insular Lowland region lakes.

Lake	Area (ha)	Zm (m)	Type of installation	Unit Power
Glen	16.0	7.2	Compressed air hypolimnetic	2 x 3.7 kW
Langford	60.1	8.5	Compressed air destratification	2 x 5.6 kW
St. Mary	195.0	9.1	Compressed air hypolimnetic	1 x 37.0 kW

2. Technology and methods

Oxygen, although present in the atmosphere at 23 percent by weight, is only sparingly soluble in water. Photosynthetically induced oxygen supersaturation may cause localized increases in dissolved oxygen (i.e., metalimnetic oxygen maxima), however, the maximum dissolved oxygen content of fresh water at 760 mm Hg is 14.16 $mg \cdot L^{-1}$ at 0 °C (Wetzel, 1975). This relatively low solubility means that many of the biological and chemical processes in lakes requiring dissolved oxygen must function within a narrow range of oxygen availability. When the concentration of oxygen decreases below a critical threshold or is absent altogether (i.e., anaerobic), there are major consequences for the biota of lakes and for the fluxes of nutrients, metals and many other important chemical reactions that take place in the water column and the sediments (Mortimer, 1941). Many of the changes that take place in lakes due to both natural and human activities influence oxygen concentrations, hence many of the efforts to manage and restore lakes are oriented towards supplying additional oxygen to lake systems where a deficit might occur. Much of the research and development work on aeration being done in British Columbia and around the world involves dealing with the low solubility and availability of dissolved oxygen in eutrophic lakes and unit processes (e.g., wastewater treatment facilities) requiring additional oxygen.

To this end there are some basic information requirements if efforts to aerate or circulate lake systems are to be successful. Two key factors are the oxygen demand of the water body and the equipment that supplies the oxygen. Oxygen demand is difficult to estimate as it typically increases significantly after aeration has begun (Soltero *et al.*, 1994). Oxygenation equipment is often less efficient or less capable than the specifications might indicate. As a result, considerable effort has been directed at studying the seasonal limnology of winterkill lakes in the Southern Interior Plateau. Winter oxygen depletion rates (WDOR) of these lakes are quite high, ranging from 0.174 to 0.629 g $m^{-2} d^{-1}$ (Ashley *et al.*, 1992). These rates are similar to literature values reported for eutrophic prairie lakes and ponds (Babin and Prepas, 1985; Barica and Mathias, 1979), and reaffirm the highly eutrophic status of these lakes. Year to year variations in WODR range from 1.4 to 2.7x, and work is underway to develop an empirical predictive model of WODR to compare with existing WODR models (e.g., Babin and Prepas, 1985). In many cases, lakes have specific regional characteristics that require consideration (e.g., sheltering from prevailing winds; e.g., Halsey, 1968). Often the use of literature oxygen depletion rates are not directly applicable from one geographic region to another, hence a lake by lake empirical approach has been adopted in B.C.

2.1 Destratification systems

A basic airlift pump destratification design was initially used throughout the Southern Interior Plateau and Insular Lowland limnological regions. For example, at monomictic Langford Lake in the Insular Lowland region near Victoria, B.C., a destratification system was installed in 1984 to reduce internal phosphorus loading and to increase fisheries habitat by preventing the formation of an anoxic hypolimnia (Table 3, Fig. 2). The watershed is highly urbanized and the lake has

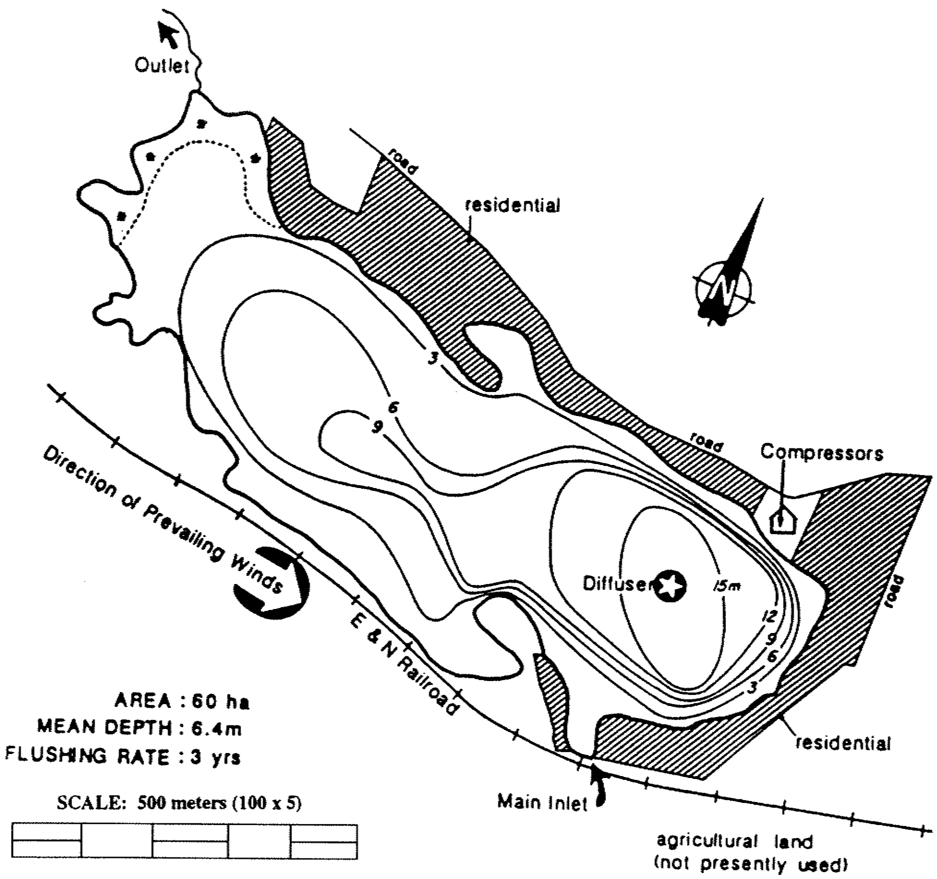

Fig. 2. Langford Lake location morphometry and aerator schematic.

high phosphorus loading due to urban development, septic tanks and agriculture (Nordin and McKean, 1988). The lake is intensively used for recreation and has a popular warmwater fishery for smallmouth bass (*Micropterus dolomieui*).

In the Southern Interior region, near Kamloops, B.C., a similar design was installed in 1981 at Walloper Lake. However, as the number of compressed air destratification installations increased, the combined electricity and maintenance costs became excessive, particularly in the sparsely populated Southern Interior Plateau region. Consequently, the air compressors were replaced with smaller mechanical surface aerators when the compressors reached the end of their service life (approx. 100,000 hrs) or when the operating costs became unmanageable. For example, at Tulip Lake, the destratification system installed in 1981 (5.6 kW rotary vane compressor) was retrofitted in 1985 with a 0.25 kW surface aerator (Fig. 3), thus reducing the monthly electricity cost from $242 to $11. Similarly, at nearby Rose Lake, the original 2.2 kW rotary vane powered destratification installed in 1981 was retrofitted with a 0.25 kW surface aerator in 1985, reducing the monthly electrical cost from $95 to $11.

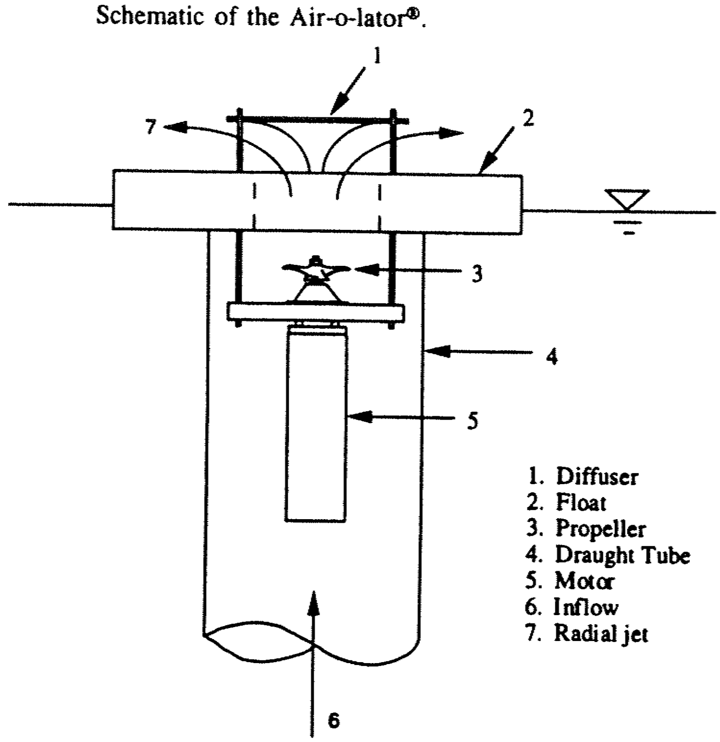

Fig. 3. Surface mechanical aerator schematic (from Rogers *et al.*, 1996).

The main consideration in the engineering design of the destratification systems was determining if it was logistically and economically feasible to supply electric power to the lake. In urbanized areas in the Insular Lowland this was not a major issue, however, many lakes in the Southern Interior Plateau are located in semi-wilderness areas some distance from the electric power grid. Therefore, a benefit-cost analysis was conducted to decide if it was cost-effective to provide electric power (Ashley, 1987) and aesthetically desirable from the perspective of residential development occurring along the electrification route. If the installation of electric power lines was cost-effective and aesthetically acceptable, then various termination sites around the lake were examined in an attempt to reduce the distance and visibility of the power line. It was usually less expensive to purchase longer lengths of compressed air hose than additional distance of power line. Therefore, siting compressed air destratification units in the lake involved locating the deepest area of the lake, anchoring the diffuser unit nearby and installing sufficient lengths of air hose to reach a shore-based compressor. However, in double basin lakes separated by a shallow sill (e.g., 2-3 m), it was usually necessary to locate a diffuser unit in each basin, and air hose costs increased accordingly.

However, in the case of mechanical surface aerators, submersible electric cable length was the limiting factor determining aerator placement. Since most rural power lines in B.C. are single phase, the distance the aerator unit could be located from shore was a function of the maximum length of electrical cable recommended for a given power and voltage of single-phase motor. For example, with a 0.75 kW surface aerator operating on 230 v single phase electricity, the maximum recommended cable distance in Copper Wire Size 12 was 120 m (Table 4; Franklin, 1980). However, this distance could be exceeded by up to 50% if the system was the only load on the power line, hence the maximum distance a 230 volt single phase 0.75 kW aerator could be located off-shore was 180 m when using Copper Wire Size 12. Therefore, mechanical surface aerator units were typically sited to place them closest to the deepest site of the lake within the constraints of the electric cable length, and the power lines were extended around the shoreline to reach these sites. Voltage step-up transformers and electric phase conversion devices were examined to determine if they could increase the cable length in low voltage, single-phase installations. However, the additional cost of the step-up transformers was excessive and the use of phase conversion devices typically voided equipment manufacturer warranties so they were not used.

As can be seen from Table 4, higher power surface aerators cannot be located very far offshore. The approach taken was to use multiple lower aerator units (up to 3) rather than a single high power unit. This strategy had both advantages and disadvantages. Disadvantages included the cost of multiple units and the additional effort and expense of anchoring the surface floats. Advantages included obtaining greater distances offshore, added reliability if one unit failed, since replacement of aerators during the winter was not possible, and the synergistic effect of two or more units creating additional open water areas at no cost. This was achieved by placing the aeration units sufficiently far apart that their ice-free zones did not merge, but with sufficient time, wind action would join the area between the two or more ice-free zones. The ice-free zone initially took the form of an "hourglass" shape, then elongated into an oval shape as the wind gradually increased the size of the opening. Thus, strategic placement and orientation of the units to the prevailing winds could obtain additional ice-free zones and oxygenation without incurring additional equipment or energy costs.

Table 4. Single-phase motor maximum cable length (m) using copper wire[1] (Franklin, 1980).

Volts	Motor Rating	Standard Copper Wire Size[2]		
	kW	14	12	10
115	0.22	41	65	102
115	0.37	31	49	76
230	0.37	123	195	306
230	0.75	76	120	188
230	1.2	63	99	156
230	1.5	55	87	137

[1]Recommended cable distances in meters for multiple use power lines.
[2]American Wire Gauge to SI equivalents are: AWG 14 = 2.08 mm^2; AWG 12 = 3.31 mm^2; AWG 10 = 5.26 mm^2.

In a continuing effort to reduce the installation and operating cost of artificial circulation systems on lakes < 10 ha, a series of laboratory and field trials were conducted using photovoltaic powered surface aerators. Given the arid climate and abundant sunshine in the Southern Interior during winter months, photovoltaics could be an appropriate technology on small, remote lakes. Four configurations have been tested, involving different combinations of photovoltaic panels (ARCO M25, M65 or M75), battery storage and pump sizes (0.75 to 1.1 kW). The results of the field trials have been technically encouraging in terms of system reliability and induced water flow rates (36 to 99 $L \cdot s^{-1}$) (Ward *et al.*, 1986). However, none of the installations have resulted in noticeable increases in winter dissolved oxygen concentrations and further research is required to increase the oxygenation capacity of these systems. The most likely development will be a wind powered-photovoltaic hybrid unit, which can provide sufficient energy to measurably increase winter oxygen concentrations.

2.2 Hypolimnetic aeration systems

St. Mary Lake, a culturally eutrophic lake located on Saltspring Island, is typical of Insular Lowland lakes. This lake is an important resource for Saltspring Island as it supplies potable water for the north portion of the island, and is the focus of considerable recreational activity. Several resorts are located around the lake perimeter, and recreational angling is a key component of their operations. The water quality of St. Mary had deteriorated considerably since 1970. Taste and odour problems, low transparency, year-round cyanobacteria blooms, and severe hypolimnetic oxygen depletion had eliminated most of the rainbow trout (*Oncorhynchus mykiss*) fishery and degraded the drinking water supply. Nordin *et al.* (1983) attributed the decline in water quality to increased phosphorus loading from watershed development (septic tanks, road building and land clearing) to the point where the lake sediments became a net source of phosphorus. Internal loading from the sediments was identified as the main source of phosphorus to the lake, with lesser amounts originating from septic tanks, groundwater, dustfall, and natural watershed loading (Nordin *et al.*, 1983). St. Mary was therefore selected as a study site to evaluate the effectiveness of hypolimnetic aeration for improving water quality and increasing habitat for recreational fisheries.

A full lift hypolimnetic aerator was installed in St. Mary Lake in 1985-86. This system was the largest hypolimnetic aeration installation in Canada at the time, similar in design to the smaller Glen Lake system (Fig. 4; Ashley, 1988) and consisted of two insulated fibreglass separator boxes (5.8 m L x 3.1 m W x 2.1 m D) with 1.5 m diameter x 12.0 m (inflow) and 9.5 m (outflow) galvanized steel pipes attached through the bottom of each separator box. Compressed air was provided by a 37 kW rotary screw compressor (rated at 5.66 $m^3 \cdot min^{-1}$ free air delivery at 7.0 $kg \cdot cm^{-2}$), and delivered to the two aerators via a 621 m main line of 7.62 cm ID polyethylene air line and two branch lines of 207 m 7.62 cm ID polyethylene and 31 m of 5.1 cm ID rubber air line. The original diffuser used in 1986 and 1987 was constructed of 3.81 cm ID galvanized steel pipe, drilled with approximately eighty 3175 m diameter holes. This diffuser was replaced in March 1988 with a 5.1 cm ID aluminium ring structure, fitted with twenty-four 140 m fine bubble silica glass diffusers. The diffuser depth was fixed at 12.5 m.

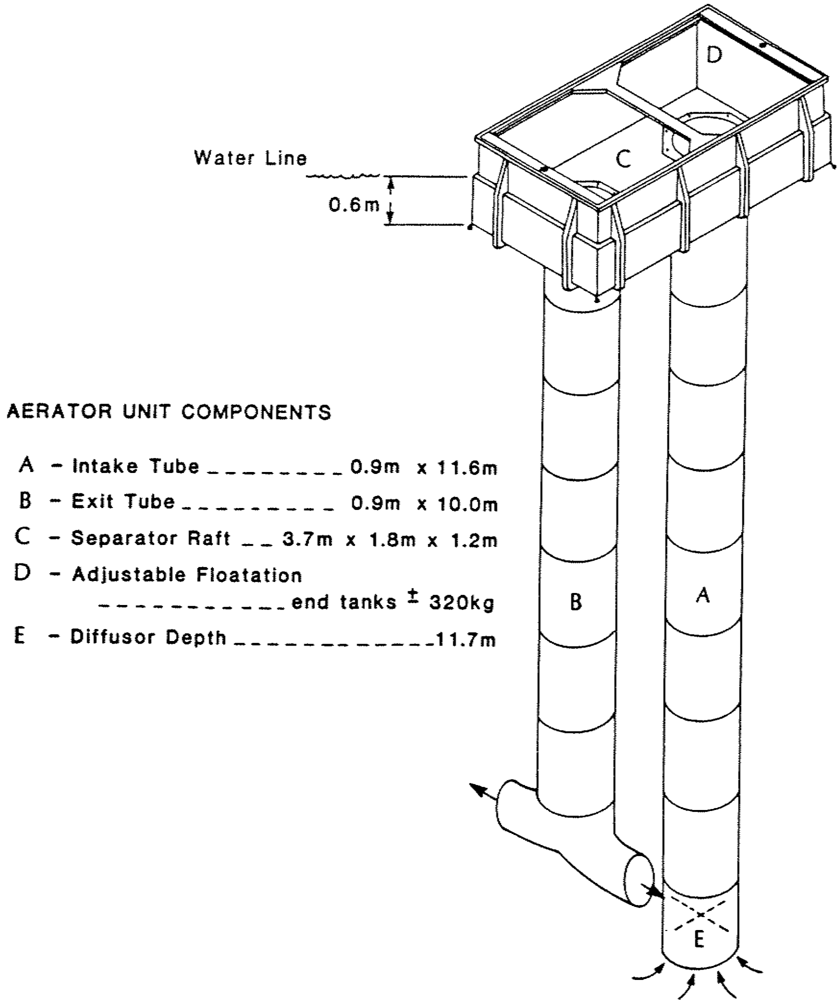

Fig. 4. Hypolimnetic aerator from Glen Lake, similar to the St. Mary Lake design.

3. Results

3.1 Destratification systems

At Langford Lake (near Victoria), the aerator was unable to meet the oxygen consumption during the initial year of operation, however, a more efficient diffuser installed in 1985 succeeded in maintaining oxygen through the water column (Fig. 5). Internal phosphorus loading was reduced, and fisheries habitat expanded as defined by temperature and dissolved oxygen requirements for fish. The phytoplankton community changed from one dominated by cyanobacteria to one dominated by diatoms – a response that has been noted in other cased studies of aeration

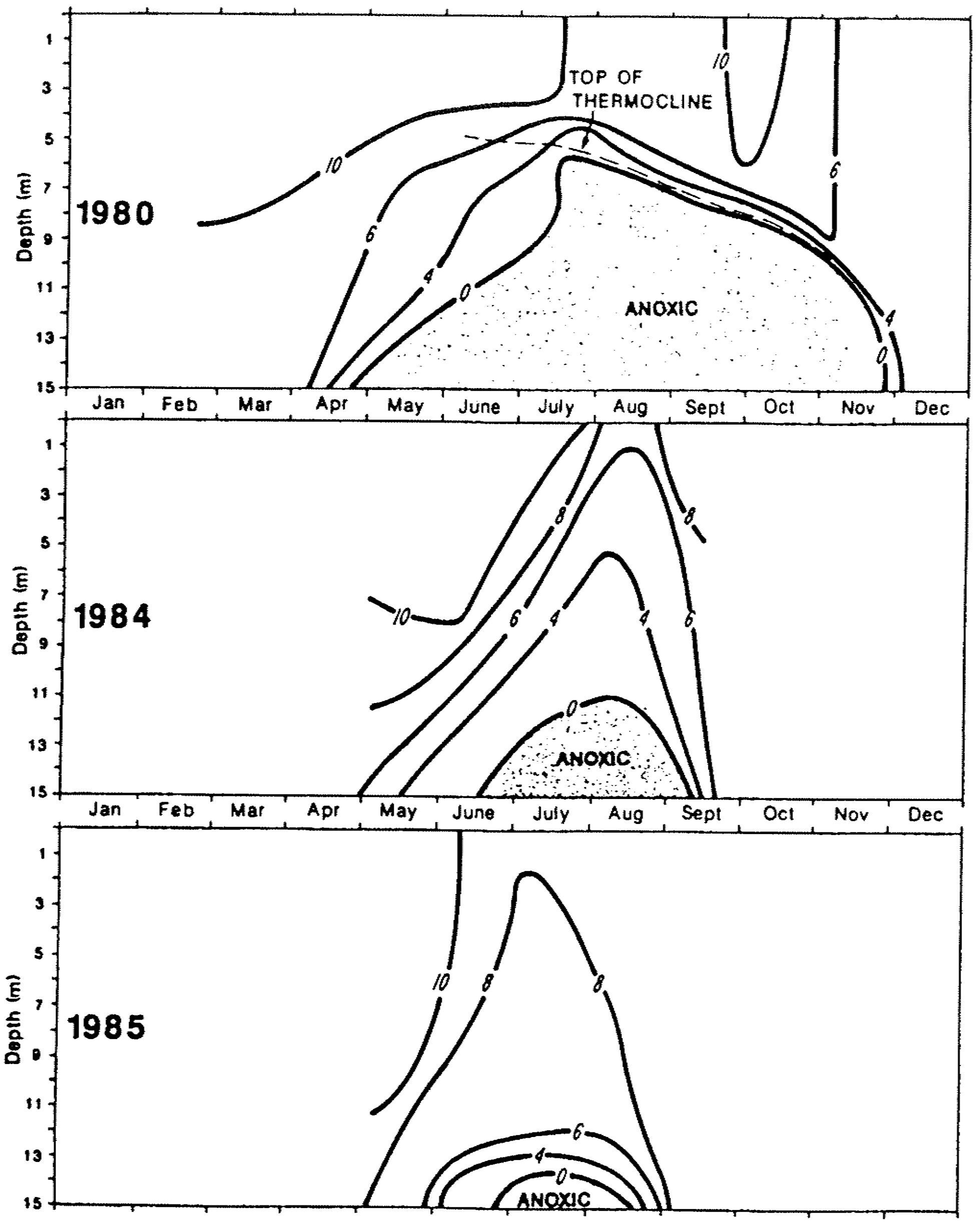

Fig. 5. Langford Lake dissolved oxygen isopleths in 1980 (pre-aeration), 1984 (initial start-up) and 1985 (increased oxygen concentration).

(Cooke *et al.*, 1993) (Fig. 6). Overall chlorophyll concentration did not decrease but the perception of water clarity changed with the disappearance of the cyanobacteria as dominant form. The zooplankton showed an increase in overall standing crop as well as a shift to increased dominance by cladocerans during the summer (Fig. 7).

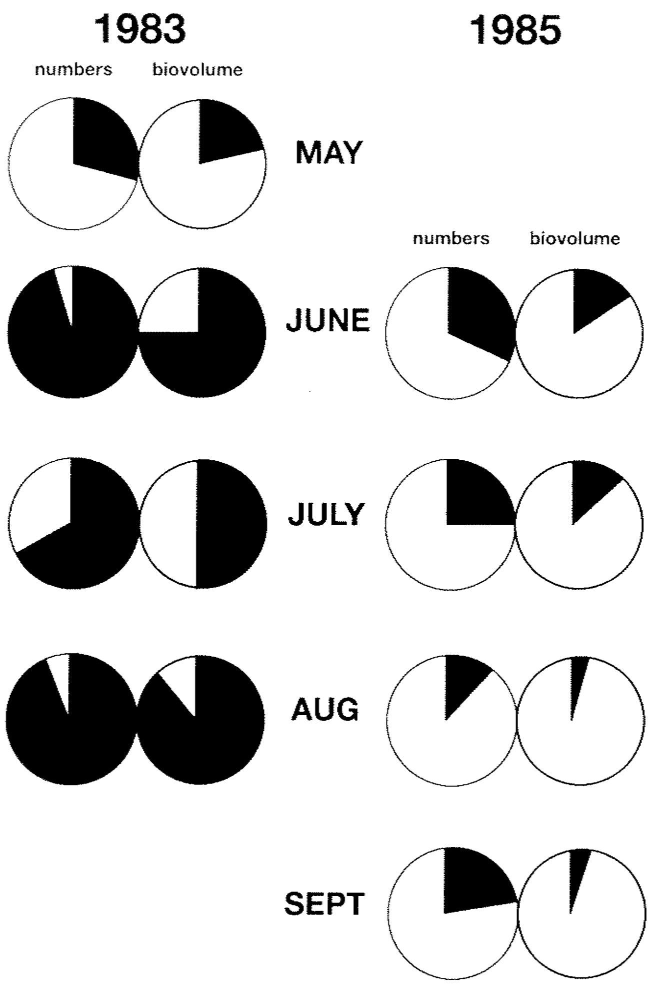

Fig 6. Cyanobacteria as a percentage of phytoplankton number and biomass in Langford Lake before (1983) and after (1985) artificial circulation.

There was also a response by aquatic macrophytes with a marked decrease in the coverage of *Elodea* after aeration. The aeration system remains in operation to the present. The public regard the system as a major factor in a perceived improvement of water quality and the sport fishery in the lake (Nordin and McKean, 1988).

Lakes undergoing destratification in the Southern Interior Plateau were typically isothermal during operation of the aeration system as described by Halsey (1968) and Halsey and MacDonald (1971). Since these lakes were naturally eutrophic, monitoring was minimal and simply consisted of monthly oxygen and temperature profiling, and observation of angling effort throughout the year to determine if fish survived the winter period. The general observation was that compressed air powered destratification systems influenced a slightly larger area of the lake as compared to the surface

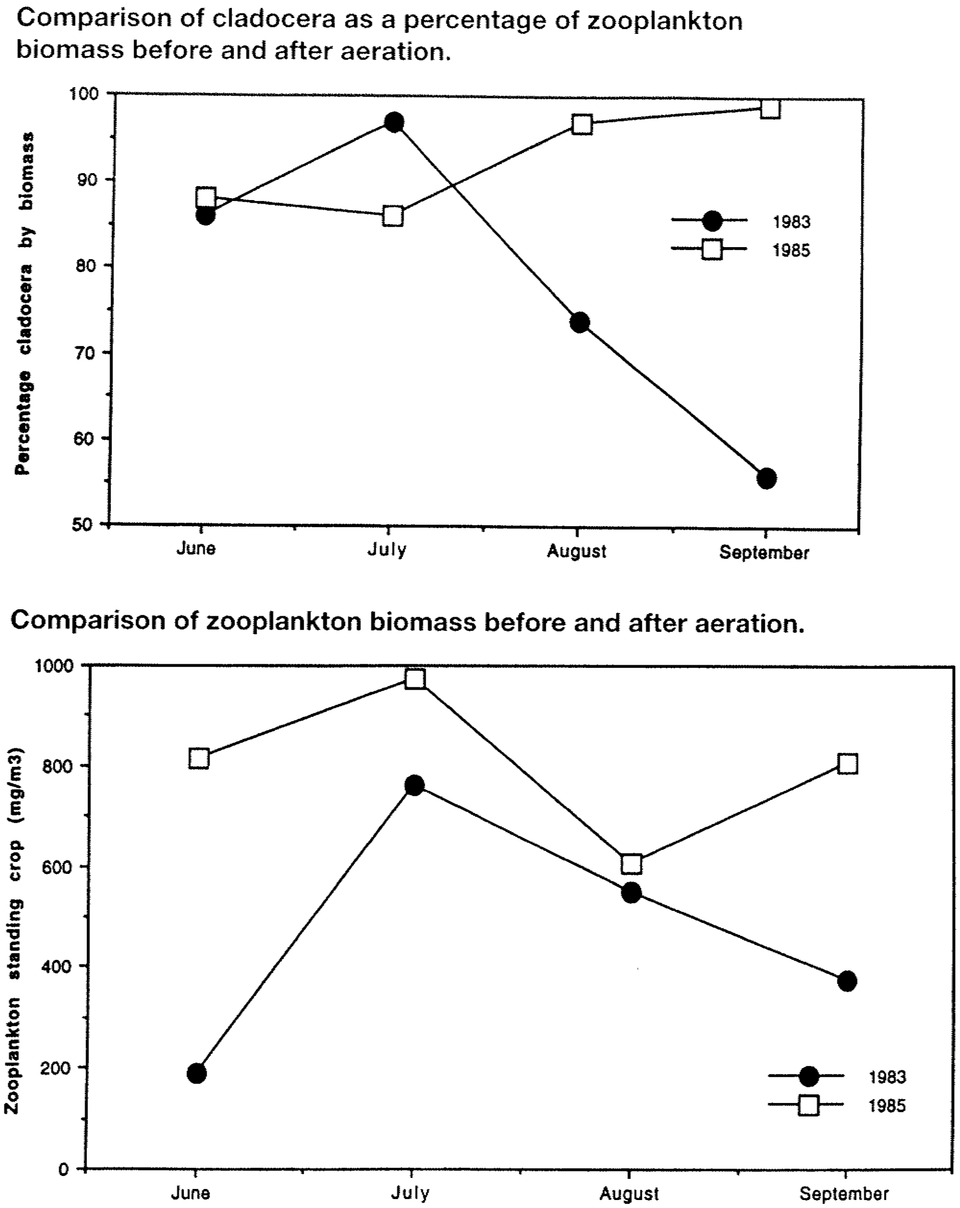

Fig 7. Zooplankton composition in Langford Lake before (1983) and after (1985) artificial circulation showing increased zooplankton biomass and cladoceran density.

aerators. However, the vertical zone of mixing from surface aerators was limited to approx. 5 m as compared to complete mixing from the depth of air release in compressed air systems. Addition of a 3 m draft tube (Rogers *et al.*, 1996) to the aerator float increased the zone of influence to approx. 10 m (K. Ashley, unpub. data). The principle factors influencing the effectiveness of the aeration system were the power of the aeration system in relation to lake size, the trophic status and resulting oxygen demand of the lake, and learning how to operate the system in relation to the lakes annual stratification cycle. For example, in Lodgepole Lake (near Kamloops), the original 5.6 kW compressed air system circulated the entire lake from November to March and achieved oxygen concentrations of approx. 8 $mg \cdot L^{-1}$ and water temperatures < 1°C (K. Ashley, unpub. data). The Menzies Lake (near Merritt) system was typical of surface aerator installations (with 3 m draft tube extension), and oxygen concentrations of 4-8 $mg \cdot L^{-1}$ and temperatures of 1-2°C were achieved from 0 to 12 m throughout the November to March operating period (Rogers et. al., 1996).

3.2 Hypolimnetic aeration systems

During the first two years of operation at St. Mary Lake (1986-1987) the hypolimnetic aeration system was unable to meet the hypolimnetic oxygen demand. The installation of 140 m diameter fine bubble diffusers in 1988 markedly increased the aerators oxygen transfer efficiency (Table 5). Although the total daily input fluctuated in response to variations in hypolimnetic oxygen demand and ambient oxygen concentrations, a trend towards higher daily oxygen input was observed with the 140 m diffusers. Late summer hypolimnetic oxygen saturation in St. Mary Lake increased from 10% in 1979-80 to 40% in 1989-90 (Fig. 8), and a classical "two-story" fishery was created, with warmwater species in the epilimnion (*Micropterus dolomieui*) and cold-water species (*Oncorhynchus mykiss* and *O. clarki*) in the hypolimnion (pers. comm., P. Law, Ministry of Environment, Lands and Parks, Nanaimo, B.C.).

Table 5. Oxygen input for St. Mary Lake hypolimnetic aerator with 3175 µm (1986-87) and 140 µm (1988-90) diffusers.

	East Basin Unit		West Basin Unit			
Date	Input (kg $O_2.d^{-1}$)	Velocity ($m.s^{-1}$)	Input (kg $O_2.d^{-1}$)	Velocity ($m.s^{-1}$)	Total (kg $O_2.d^{-1}$)	Ambient O_2 ($mg.L^{-1}$ @13 m)
27/8/86	44.1	0.70	236.1	1.07	280.2	4.1
10/6/87	111.0	0.88	124.8	0.88	235.8	7.0
24/6/87	138.7	0.88	83.2	0.88	221.9	5.3
12/8/87	208.0	0.88	166.4	0.88	374.4	1.5
8/8/87	249.7	0.88	194.2	0.88	443.9	0.5
140 µm diffusers installed in March, 1988.						
29/7/88	218.4	0.77	410.4	0.93	628.8	2.1
10/8/88	182.0	0.77	351.8	0.93	533.8	1.4
22/8/88	182.0	0.77	395.7	0.93	577.7	1.1
12/11/89	143.4	0.70	204.9	1.00	348.3	6.3
21/6/90	235.8	0.94	235.8	0.94	471.6	5.0

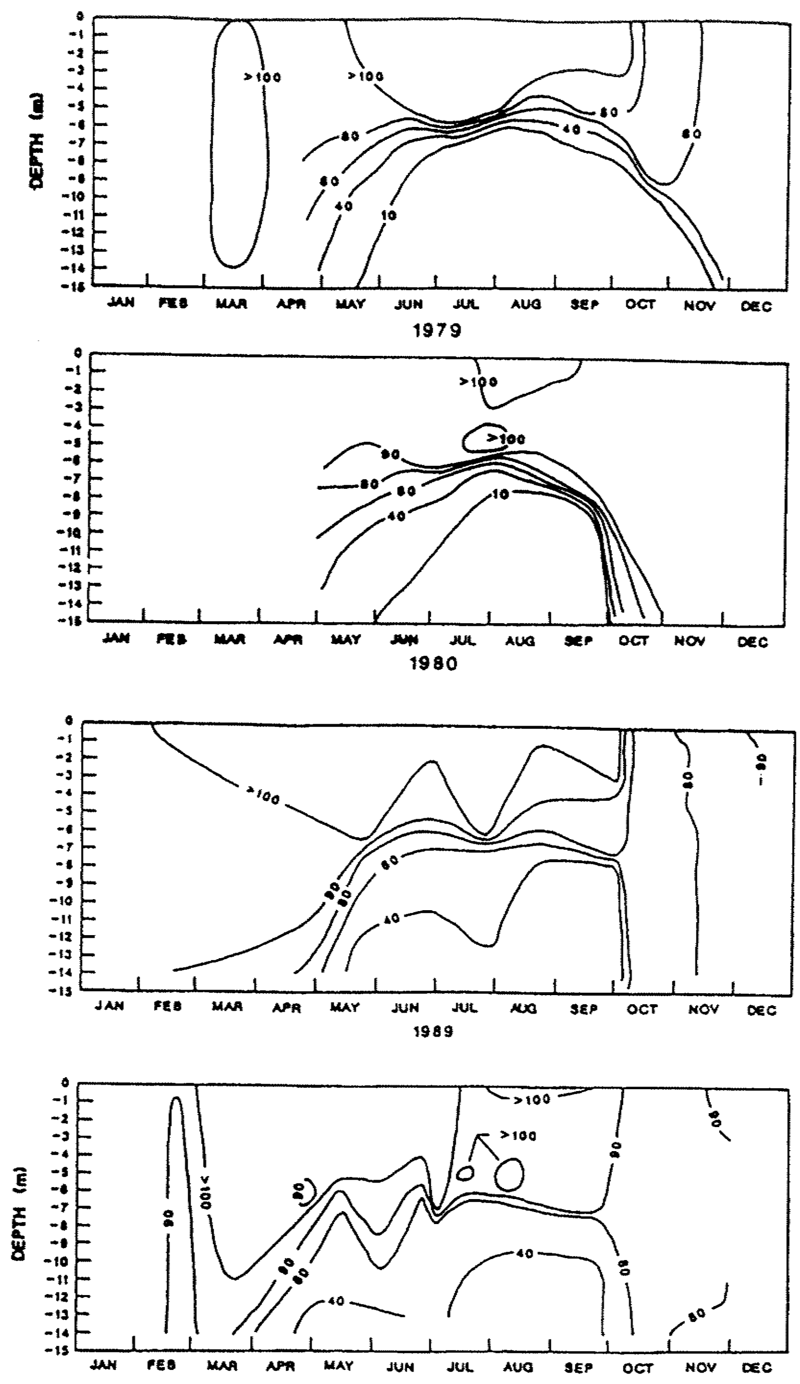

Fig. 8. Isopleths of dissolved oxygen (percent saturation) for two years before hypolimnetic aeration (1979-80) and during hypolimnetic aeration (1989-90) for St. Mary Lake.

Spring overturn phosphorus concentrations were, on average, lower in the aerated period than in the non-aerated period (Fig. 9). In addition, a noticeable decline in taste and odour complaints, filter backflushing and a reduction in chlorine disinfectant use has occurred since 1988 (pers. comm., M. Larmour, North Saltspring Waterworks Utility, Saltspring Island, B.C.). The aerator last operated in 1993 and was removed from the lake in 1994 due to extensive corrosion and stress cracks in the inlet and outlet tubes. The aerator has not been replaced due to a shortage of capital funds from the Ministry of Environment, Lands and Parks and North Saltspring Waterworks Utility.

3.3 Costs

Three factors known to influence the cost effectiveness of lake aeration are economy of scale, frequency of winterkill and energy costs (Ashley, 1987). Economy of scale occurs when unit costs decrease with increasing scale of operation. Most industrial processes benefit from economy of scale and lake aeration is no exception. The total cost (discounted over ten years at 10%) of artificial circulation increases with lake size (Ashley, 1987). However, total costs per hectare decreases indicating an economy of scale (Ashley, 1987). This is a result of several factors including several fixed costs independent of lake size (e.g., compressor shed, electrical contracting fees, power line costs) and economy of scale in purchasing equipment (e.g., compressors, air hose). In terms of future artificial circulation projects, these results suggest that for lakes >100 ha, although the actual costs are high, the economy of scale provides cost effectiveness. In reality, few large lakes in British Columbia will require artificial circulation since lake depth generally increases with

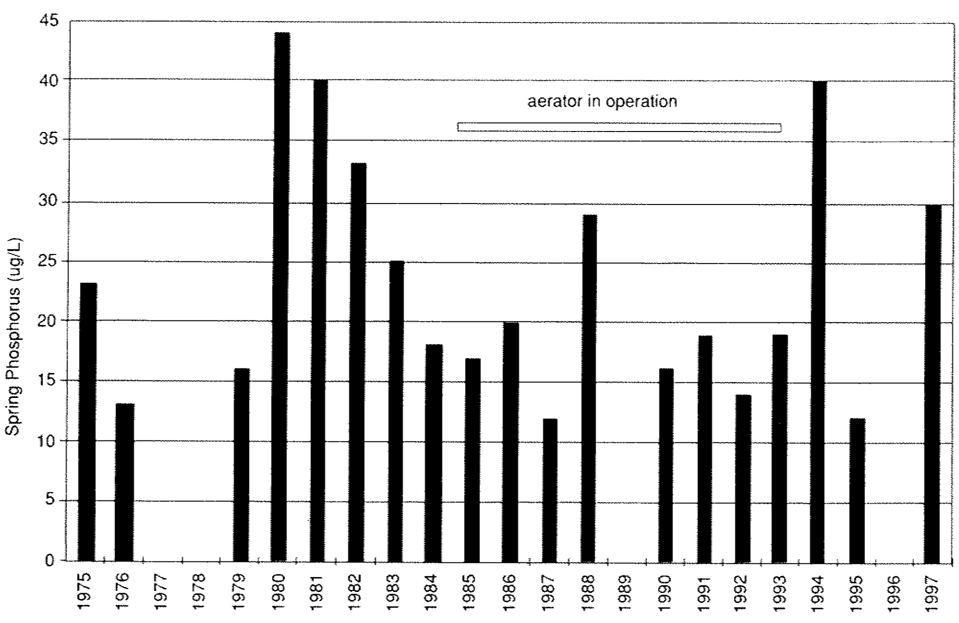

Fig. 9. Spring overturn phosphorus concentrations at St. Mary Lake.

surface area thus decreasing the winterkill risk. However, in the few cases where a large shallow lake experiences frequent winterkill, artificial circulation could be a cost effective fisheries management strategy.

Artificial circulation of small lakes < 100 ha is less expensive in total costs, however more expensive per unit area than large lakes. This relationship increases at 10 ha, therefore we believe lakes < 10 ha should not be artificially circulated unless they will generate a fishery, and no other suitable lakes are located in the area. Our cost-benefit analysis was based on conventional electric powered compressor type of artificial circulation. The increase in cost per hectare at 10 ha indicates this type of circulation technology is not cost effective on lakes < 10 ha. Therefore less expensive equipment should be used to circulate lakes < 10 ha. Solar/wind powered and electric surface aerators are the logical choice for these lakes. We do not believe internal combustion powered equipment (e.g., gasoline, diesel and propane) should be used on lakes of any size due to greenhouse gas emissions, noise and potential fuel spill problems. Extensive experience with gasoline, diesel and propane powered compressors repeatedly demonstrated the reliability of the equipment was not sufficient for unattended remote operation, and the noise, emissions and re-fuelling logistics detracted from the aesthetic value of the recreational angling experience. Natural gas powered equipment was not an option as gas distribution lines are non existent in most rural areas of British Columbia.

A strategy that has not been used in B.C to date is the use of pure oxygen injection to prevent winterkill. This approach was successful in preventing fish kills in a large northern lake (Prepas and Burke, 1997), however, the delivery and on-site storage of liquid oxygen at most Southern Interior Plateau lakes is not likely to be a cost-effective option. Recent developments in the on-site generation of oxygen using pressure swing adsorption (PSA) appear promising and have been used to prevent hypolimnetic oxygen depletion in two Ontario (Gemza, 1997) and one Washington lake (Doke *et al.*, 1995).

3.4 Interesting logistical problems and effects

Several interesting logistical problems and effects were encountered during the course of this work. Firstly, the nature of the lakes' annual circulation pattern in relation to its productivity is key to the effective use of lake aeration. For example, Corbett Lake (near Merritt) experienced incomplete fall circulation due to wind sheltering by the surrounding topography, and 4-6 weeks of fall artificial circulation was sufficient to prevent winterkill (Halsey, 1968; Halsey and Galbraith, 1971). In contrast, Edith Lake (near Kamloops) experienced complete spring and fall circulation, and was nearly saturated with oxygen prior to freeze-up (K. Ashley, unpub. data). However, due to its eutrophic status, oxygen was rapidly consumed and optimal timing for artificial circulation was 4-8 weeks' operation starting in early January. Fall circulation alone, either natural or artificial was often insufficient to prevent winterkill in highly eutrophic lakes, and each lake must have the circulation systems operation tailored to its seasonal circulation pattern and oxygen consumption rates.

Consequently, some lakes will require more than one period of artificial circulation each year. An example would be a eutrophic lake that experiences incomplete fall circulation (e.g., Bleeker Lake near Kamloops). Three to four weeks of artificial circulation may be required in October followed by another 3-4 weeks' circulation in

February. The critical stage of this operational strategy is when to re-start the circulation period in February. If the whole-lake oxygen concentration decreases below approximately 3 mg·L^{-1}, the start-up may cause a fish kill by initially depressing oxygen concentrations below the minimum required to sustain salmonids (Halsey and MacDonald, 1971; Ashley *et al.*, 1992). The solution to this problem is sufficient data collection beforehand (one year minimum, preferably 3-4 years data) to understand the lakes' annual oxygen cycle, and regular monitoring during operation to that aeration is initiated well in advance of critical oxygen concentrations. Operationally, the diffusers (in a compressed air system) can be placed at a shallow depth initially, or located in a shallow zone near the main inlet, to avoid deoxygenating the lake upon start-up.

A related issue involves the loss of heat during extended periods of artificial circulation. A properly designed aeration system can create a large opening in the ice surface (i.e., 30 m dia.) in mid-winter when ambient air temperatures can be as low as -40°C. Apart from creating some highly unusual fog and frost patterns around the lake, this can lead to significant cooling of the lake and unknown effects on the lakes' biota. Rogers *et al.* (1996) found the turbulent heat transfer from water to ice averaged approx. three times the rate of cooling across the ice free area (i.e., polyna), and suggested heat loss may be minimised by reducing turbulence beneath the ice rather than controlling polyna size. This raises the question of how to optimize oxygen transfer between polyna size, heat content, and ice-free surface area available for oxygen exchange. As discussed by Rogers *et. al.* (1996) this is a complex question that requires further research attention.

4. Conclusions and recommendations

In terms of operational maintenance, mechanical problems occurred at a number of installations, and were largely a result of their isolated locations. The electric compressors initially used at most installations were machines designed for industrial use with regular maintenance. The isolated operation of these machines stretched the limit of their mechanical reliability and presented little opportunity to detect mechanical problems at an early stage. Our strategy was to equip the compressors with fail-safe switches (i.e., low oil level, high oil temperature) and provide regular maintenance at the manufacturers' recommended intervals. For remote areas, mechanical surface aerators were the only viable option for aerating lakes. We believe internal combustion powered systems are simply too complex, costly and pollution generating (i.e., noise and greenhouse gases) to be used at any site. An informal relative ranking in terms of decreasing mechanical complexity and maintenance costs based on the collective 35 years of lake aeration experience in B.C. is:

Diesel/Propane compressor	– 1	Highest complexity and operating costs
Diesel/Propane blower	– 2	
Electric compressor	– 3	
Electric blower	– 4	
Electric surface aerator	– 5	
Solar Powered circulator	– 6	
Wind Powered circulator	– 7	Lowest complexity and operating costs

The long-term effects of artificial circulation and subsequent stocking of trout on the invertebrate community in eutrophic lakes is not completely resolved. The net result of continuous circulation may be a decrease in fish yield as the "barren lake" effect caused by frequent winterkills wears off, resulting in slower fish growth (Anderson, 1972). The extent to which increased benthic food production would compensate for possible decreased productivity is uncertain; however, trout stocking rates may have to be adjusted downwards if the ecosystem becomes less productive. It may be beneficial to allow certain lakes to winterkill and remain fallow every few years to retain the high fish yield characteristic of many Southern Interior Plateau region lakes.

British Columbia has a long history of using and developing aeration as a tool for improving fish habitat and water quality in eutrophic lakes. The initial development work in the 1960's pioneered the matching of the limnological characteristics of lakes to the appropriate aeration technique. Since that time a variety of different configuration and adaptations of both destratification and hypolimnetic aeration equipment has been tested and generated a considerable knowledge base which is still being improved. Aeration has proven to be a practical and successful technology in this limnologically varied region of Canada. The knowledge developed in B.C. has been adopted and used in other parts of the world. For example, the aeration expertise developed in B.C. was used to significantly improve the water quality of a eutrophic lake in Washington state (Soltero *et al.*, 1994). Future research efforts in B.C. will focus on improving oxygen transfer processes in hypolimnetic aerators well as examining new hardware that is capable of supplying oxygen more efficiently.

5. Summary

Lake aeration is used in British Columbia to manage the impacts of natural and cultural eutrophication on recreational fisheries and water quality. The management goal for naturally eutrophic lakes in the Southern Interior Plateau limnological region is to increase recreational angling opportunities. In contrast, water quality, recreational fisheries and contact recreation are considered of equal importance in the Insular Lowland limnological region and the management goals for these culturally eutrophic lakes are to provide sustainable angling opportunities while demonstrably improving water quality for contact recreation and domestic use. Destratification systems are installed on 18 winterkill lakes (mean depth 2.0 to 17.4 m, surface area 3.2 to 41.3 ha) in the Southern Interior region. One destratification and two hypolimnetic aeration systems were installed in Insular Lowland region lakes (mean depth 7.2 to 9.1 m, surface area 16.0 to 195.0 ha). Compressed air destratification systems were initially used in the Southern Interior; however, the units were replaced with smaller mechanical surface aerators to reduce operation and maintenance costs. Benefit-cost analysis was used to determine if it was logistically and economically feasible to supply electric power to a lake and submersible electric cable length became the key factor determining surface mechanical aerator placement. The principle factors influencing the effectiveness of mechanical surface aerators were the power of the aeration system in relation to lake size, the trophic status and resulting oxygen demand of the lake, and learning how to operate the system in relation to the lakes annual stratification cycle. Compressed air was used in the Insular Lowland destratification and full lift hypolimnetic aeration systems. Hypolimnetic aeration increased oxygen saturation in St. Mary Lake from 10% in 1979-80 to 40% in 1989-90, created a classical "two-story" recreational fishery and spring overturn phosphorus concentrations were, on average, lower in the aerated period than in the non-aerated period.

Acknowledgements

This review would not have been possible without the assistance of Fish and Wildlife Branch biologists throughout the Southern Interior Plateau (Cariboo, Okanagan and Thompson-Nicola regions) and Vancouver Island region. In particular we would like to thank Brian Chan, Peter Law, Maurice Lirette, Steve Matthews, Al Martin, Dave Smith and Bill Westover for sharing their comments and experiences. Special thanks to Dr. T.G. Northcote for his pioneering efforts on lake classification and lake aeration in British Columbia and enthusiasm for sharing his limnological knowledge with a multitude of students, including both authors of this chapter.

References

Anderson, R.S. 1972. Zooplankton composition and change in an alpine lake. Verh. Internat. Verein. Limnol. 18:264-268.

Ashley, K.I. 1983. Hypolimnetic aeration of a naturally eutrophic lake: physical and chemical effects. Can. J. Fish. Aquat. Sci. 40: 1343-1359.

Ashley, K.I. 1987. Artificial circulation in British Columbia: Review and Evaluation. Fisheries Technical Circular No. 78, Ministry of Environment and Parks, Province of British Columbia. 34 p.

Ashley K.I. 1988. Hypolimnetic Aeration Research in British Columbia. Verh. Int. Verein Limnol. 23: 215-219.

Ashley, K.I., K. Tsumura and B.M. Chan. 1992. Fisheries Management of winterkill lakes in Southern Interior British Columbia. pp. 287-97 In: Aquatic Ecosystems in Semi-Arid Regions: Implications for Resource management. R.D. Robarts and M.L. Bothwell (Eds.). N.H.R.I. Symposium Series 7, Environment Canada, Saskatoon, Canada.

Babin, J., and E.E. Prepas. 1985. Modelling 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 risk in small prairie lakes under extended ice cover. Can. J. Fish. Aquat. Sci. 36:980-986.

Barica, J., H. Kling, and J. Gibson. 1980. Experimental manipulation of algal bloom composition by nitrogen addition. Can. J. Fish. Aquat. Sci. 37:1175-1183.

Cooke, D.G., E.B. Welch, S.A. Petersen and P.R. Newroth. 1983. Restoration and Management of Lakes and Reservoirs. Second Edition. Lewis Publishers. 584p.

Doke, J.L., W.H. Funk, S.T.J. Juul and B.C. Moore. 1995. Habitat availability and benthic invertebrate population changes following alum treatment and hypolimnetic oxygenation in Newman Lake, Washington. J. Freshwater Biol. 10:87-102.

Dunst, R.D., S.M. Born, P.D. Uttormark, S.A. Smith, S.A Nichols, J.O. Peterson, D.R. Knauer, S.L.Serns, D.R. Winter, and T.L.Wirth. 1974. Survey of lake Rehabilitation Techniques and Experiences. Tech. Bull. 75. Wisc. Dept. Nat. Res. Madison, Wisconsin, USA

Franklin Electric. 1980. Submersible motors; installation and field service. Service data, page 290,741. September 22, 1980 (supersedes August 15, 1979).

Gemza, A.F. 1997. Water quality improvements during hypolimnetic aeration in two Ontario lakes. Water Qual. Res. J. Canada 32:365-390.

Halsey, T.G. 1968. Autumnal and overwinter limnology of three small eutrophic lakes with particular reference to experimental circulation and trout mortality. J. Fish. Res. Board. Can. 25: 81-89.

Halsey, T.G. and D.M. Galbraith. 1971. Evaluation of two artificial circulation systems used to prevent trout winterkill in small lakes. Fisheries Management Publication No. 16. Fish and Wildlife Branch, Province of British Columbia.

Halsey, T.G. and S.J. MacDonald. 1971. Experimental trout introduction and artificial circulation of Yellow Lake, British Columbia. Fisheries Management Report No. 63. Fish and Wildlife Branch, Province of British Columbia

Larkin, P.A. 1954. Introductions of the Kamloops trout in British Columbia lakes. Canadian Fish. Cult. 16-15-24.

Larkin, P.A. and J.W. Cartwright. 1976. Effects of rotenone treatment on Courtney and Corbett Lakes (Merritt, B.C.). Fisheries Technical Circular No. 23, Fish and Wildlife Branch, Province of British Columbia.

Murphy, T.P, K.J. Hall, K.I. Ashley, A. Murdoch. M. Mawhinney, and H. Fricker. 1985. In-lake precipitation of phosphorus by lime treatment. National Water Research Institute Series 85-167. 84 p.

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

Nordin, R.N., C. J. P. McKean and J. H. Wiens. 1983. St. Mary Lake water quality: 1979-1981. B.C. Ministry of Environment, Water Management Branch and Surveys and Resource Mapping Branch. 121 p.

Nordin, R.N. and C.J.P. McKean. 1988. Destratification aeration of Langford Lake: Physical, Chemical, and Biological Responses. Ministry of Environment and Parks, Water Management Branch. Victoria, B.C. 28 p.

Nordstrom, L., A. Tautz, J. Allen, and G. Bridges. 1978. An economic assessment of the provincial trout stocking program in the Thompson-Okanagan area of British Columbia (1977-1978). Fisheries Technical Circular No. 40, Fish and Wildlife Branch, Province of British Columbia.

Northcote, T.G. and P.A. Larkin. 1956. Indices of productivity in British Columbia Lakes. J. Fish. Res. Board. Can. 13: 515-540.

Northcote, T.G. and P.A. Larkin. 1966. Western Canada. pp. 451-486 In: Limnology in North America. D.G Frey (Ed.). University of Wisconsin Press.

Northcote, T.G. and T.G. Halsey. 1969. Seasonal changes in the limnology of some meromictic lakes in southern British Columbia. J. Fish. Res. Board. Can. 26: 1763-1787.

Prepas, E.E. and J.M. Burke. 1997. Effects of hypolimnetic oxygenation on water quality in Amisk Lake, Alberta, a deep eutrophic lake with high internal phopsphorus loading rates. Can. J. Fish. Aquat. Sci. 54:2111-2120.

Raymond, S. 1980. Kamloops: An angler's study of the Kamloops Trout. 2nd ed. Amato Publications, Portland, Oregon. 252 p.

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

Soltero R.A., L.M. Sexton, K.I. Ashley and K.O. McKee. 1994. Partial and full lift hypolimnetic aeration of Medical Lake, WA to improve water quality. Water Research 28:2297-2308.

Stringer, G.E. and R.G. McMynn. 1960. Three years use of toxaphene as a fish toxicant in British Columbia. Canadian Fish Cult. 28: 37-44.

Stone, M. 1988. British Columbia freshwater results of the 1985 National Survey of Sport Fishing. Fisheries Technical Circular No. 79, Ministry of Environment and Parks, Province of British Columbia.

Ward, P.R.B., W.G. Dunford and K.I. Ashley. 1986. Ice control in lakes by photovolaics powered water circulation. In: Proceedings of the 15th Annual Conference of the Solar Energy Society of Canada. p. 41-46. Winnipeg Manitoba June 22-25, 1986.

Wetzel, R.G. 1975. Limnology. W.B. Sanders Co, Toronto. 743 pp.