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FISHERIES MANAGEMENT OF WINTERKILL LAKES IN SOUTHERN INTERIOR BRITISH COLUMBIA

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ABSTRACT

Many of the small lakes in the arid Southern Interior Plateau region of British Columbia experience varying degrees of trout mortality in summer and winter. This is due to a combination of high productivity, shallow depths, high oxygen depletion rates, and extended periods of ice cover. Management strategies for maintaining fisheries in these lakes include stocking salmonids with higher survival rates under low oxygen concentrations (e. g., *Salvelinus fontinalis*), stocking with large graded yearling rainbow trout (*Oncorhynchus mykiss*) to provide seasonal fisheries, and the use of artificial circulation to prevent winterkill and maintain annual fisheries. Several field trials have been conducted with photovoltaic designs in efforts to develop a suitable energy source to operate low energy circulation systems on remote lakes. An emerging management concern is the potential effects of global climatic change which may adversely affect trout survival in these shallow and productive lakes.

INTRODUCTION

Many of the small lakes (i. e., < 500 ha) in the arid Southern Interior Plateau region of British Columbia are internationally recognized for their prized rainbow "Kamloops" trout (*Oncorhynchus mykiss*) fisheries (Raymond 1980). For example, on lakes such as Hihium, Roche and Tunkwa there are over 45,000 angler-days per year (B. Chan, unpubl. data). The majority of these lakes were originally barren; their trout populations were established by an extensive program of stocking (Nordstrom et al. 1978), and occasional chemical eradication of coarse 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, results in highly productive lakes that support popular fisheries.

Managing the recreational fisheries in these lakes is a difficult task. The extent of natural spawning habitat is one of the most important limiting factors in the sport fishery (Larkin 1954). Environmental conditions in these lakes often meet or exceed the physiological tolerance limits of rainbow trout. In summer months, dense blooms of cyanobacteria (mainly *Aphanizomenon* and *Anabaena*), high surface temperatures, sharp thermal stratification, and marked hypolimnetic oxygen depletion can lead to occasional summerkills of trout (Northcote and Larkin 1966). In winter months, extended periods of ice cover (from late November to May) combined with high oxygen depletion rates and shallow mean depths often lead to severe oxygen depletion and winterkill of trout (Halsey 1968; Northcote and Halsey 1969; Ashley 1983).

Several management strategies have been developed to provide recreational fisheries in these highly productive lakes. These include: (1) stocking with salmonids that survive better in low oxygen conditions (e. g., *Salvelinus fontinalis*); (2) stocking hatchery rainbow trout at age 1+ which have been selected for large size; and (3) modifying the lake environment to prevent or reduce winterkill and summerkill risk. The purpose of this paper is to discuss the rationale and implications of using these various management strategies.

CLIMATE, LIMNOLOGY AND RECREATIONAL FISHERIES

The Interior Plateau is one of six major physiographic divisions within British Columbia (Holland 1976), with a length of 901 km and a maximum width of 378 km. The Thompson Plateau is the most southern of the plateau areas in B.C. It has a length of approximately 241 km and a width of 121 to 145 km, and includes most of the Kamloops, Princeton and Merritt areas, as well as the Okanagan and North Thompson Valleys. The Thompson Plateau has a gently rolling upland of low relief, for the most part between 1219 m and 1524 m (Holland 1976).

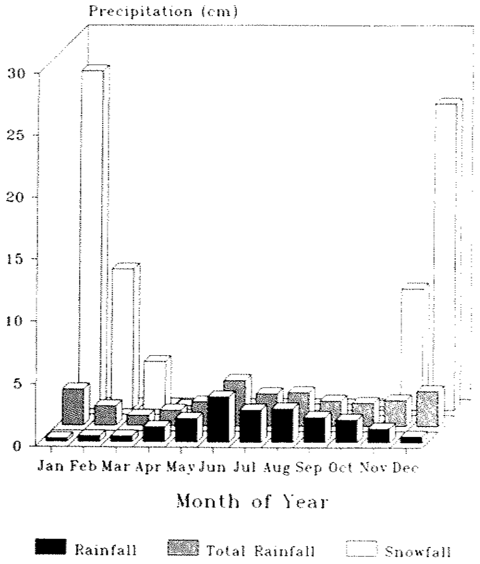

Figure 1. Rainfall, snowfall and total precipitation record at Kamloops airport, British Columbia.

The climate in the Interior Plateau is controlled to a large extent by the north-south orientation of the major mountain chains and its proximity to the Pacific Ocean. The climate of the Kamloops area is typical of the Thompson Plateau. Mean monthly temperatures at Kamloops airport (elev. 346 m) range from -10.2°C in January to 15.7°C in July (Chilton 1981). Mean annual precipitation ranges from 21-35 cm in the arid valley bottoms (270-750 m), 35-60 cm in the mid-elevations (750-1300 m) and 40-185 in the subalpine zone (1300-2200 m) (Farley 1979). Most of the precipitation occurs during June, July and August as rainfall, and December-January as snowfall (Figure 1).

Thompson-Nicola area lakes are located in the Southern Interior Plateau limnological region (Northcote and Larkin 1966). Most small lakes in the area are of glacial origin. Total dissolved solids (TDS) content of these lakes is usually well over 100 mg L^{-1} with some fish producing lakes containing over 1000 mg L^{-1} (Northcote and Larkin 1966). There are approximately 1,846 lakes in the Thompson-Nicola region, the majority of which are less than 500 ha in size (Table 1). Approximately 15 % of the smaller (i. e., < 500 ha) lakes are rated as having a high risk (i. e., > 50% probability) of winterkill or summerkill.

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

	Lake Area (hectares)			
	<500	500-1000	1000-10000	>10000
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 lakes in the Thompson-Nicola region are often used for recreational fishing (Table 1). A recent survey (Stone 1988) indicated there were approximately 871,000 angler-days of fishing on lakes in the Thompson-Nicola region, of which 589,400 were on small lakes (i. e., < 500 ha). The total catch for the Thompson-Nicola lakes was 2,048,900 fish, of which 1,347,100 were retained. Rainbow trout made up most of the harvest (80 %), followed by kokanee (*Oncorhynchus nerka*; 11 %) and three char species (*Salvelinus fontinalis*, *Salvelinus namaycush*, and *Salvelinus malma*; 8 %) (Stone 1988).

MANAGEMENT STRATEGIES

Stocking salmonids which exhibit higher survival under low oxygen

A basic management strategy for providing fisheries in these winterkill lakes is to substitute salmonid species that have higher survival rates under low oxygen conditions than the native rainbow trout. Although salmonids in general are characterized by having relatively high dissolved oxygen requirements (Davis 1975; Doudoroff and Shumway 1970), there are apparent differences in survival rates between brook trout and rainbow trout when stocked into small high-risk winterkill lakes. Brook trout apparently are better able to survive than rainbow trout, and management biologists believe brook trout are better adapted to environmental conditions in these lakes.

Brook trout are now routinely stocked into 34 lakes < 500 ha and one lake > 500 ha in the Thompson-Nicola region, with an additional 2-3 lakes being added each year. The trout are stocked as fry (approximately 5 g) in the spring, and grow to catchable size (approximately 400 g) by late fall. Traditionally, the brook trout fishery has been harvest-oriented. Anglers concentrate on schooling mature fish in the late fall and into the first two months (December and January) of ice cover. In high-risk lakes, whole-lake oxygen concentrations continue to decline throughout the winter and the trout may succumb to low oxygen concentrations in late February. Recently, there has been renewed interest, mainly by fly fishermen, in catching brook trout in the spring and summer. All of the lakes stocked have the capability to produce record-size fish (> 3 kg), and this type of fishery is increasing in popularity.

Table 2. Incipient oxygen response threshold for brook trout and rainbow trout (from Davis 1975).

Species	Size (g)	Temp (°C)	mg.L^{-1} O$_2$	Reference
Rainbow trout	628 to 1136	20	4.59	Irving et al. (1941)
	120 to 250	8.5-15	5.18 to 7.34	Randall and Smith (1967)
	235 to 510	2.3 to 13	6.74 to 8.73	Itazawa (1970)
	400 to 600	13.5	5.35	Hughes and Saunders (1970)
	300	10 to 20	4.71 to 5.75	Cameron (1971)
Brook trout	682 to 1136	20	4.59	Irving et al. (1941)
	17 to 65	5 to 20	6.88 to 9.6	Graham (1949)
	56 to 140	10 to 15	5.18 to 5.75	Beamish (1964)

These empirical observations are unusual considering that the native habitat of brook trout is clear, cool well-oxygenated streams and lakes in northeastern North America (Scott and Crossman 1973). Unfortunately, there have been no concurrent experimental stockings of brook trout and rainbow trout into these lakes to monitor apparent differences in survival between the two species. Only two lakes in the Thompson-Nicola are regularly stocked with brook trout and rainbow trout (Marquart, 22.6 ha; Stump, 778 ha). The literature reveals little difference in incipient oxygen response thresholds (Table 2) or lethal dissolved oxygen concentrations (Table 3) for brook trout and rainbow trout, however two references specifically refer to the low oxygen tolerance of brook trout (Jahoda 1947; Shepard 1955).

Table 3. Lethal oxygen concentrations for brook trout and rainbow trout (from Doudoroff and Shumway 1970).

Species	Size (g) or age	Temp (°C)	% mort.	mg L^{-1} O_2	Reference
Rainbow trout	yearling	11 to 22	50	1.1 to 1.8	Burdick et al. (1954)
	yearling	11 to 22	100	0.8 to 2.4	Burdick et al. (1954)
	10 cm	16 to 20	50	2.4 to 3.1	Downing and Merkens (1957)
	yearling	11 to 13	100	< 1.4	Townsend et al. (1938)
Brook trout	4.5	21 to 23	50	2.3	King (1943)
	17	17 to 20	100	< 2.0	Black et al. (1954)
	27	12 to 23	100	< 1.9	Graham (1949)
	yearling	12 to 21	50	1.6 to 2.1	Burdick et al. (1954)

There are several possible explanations for this apparent discrepancy between field observations in Thompson-Nicola lakes and reported literature values. The temperatures at which the laboratory experiments were conducted were generally higher than those occurring in these lakes during the winter months. Most small lakes in the Thompson-Nicola are frozen for 4-6 months of the year, and typical inverse stratification profiles range from 0.5-1°C under the ice to 3-4°C at the lake bottom (K. Ashley, unpub. data). Salmonids become more sensitive to low oxygen concentrations at higher temperatures as their metabolic rate increases and the solubility of oxygen decreases (Davis 1975), hence the experimental conditions did not accurately represent the field environment.

The possibility also exists that the apparent higher survival of brook trout in winterkill lakes is more complex than simple low oxygen tolerance. For example, the ability to detect pockets of oxygen would be an asset in winterkill lakes. Magnusen et al. (1985) reported several species of fish moved to the ice-water interface, moved toward the inlet, or moved into the outlet to avoid low oxygen conditions in a winterkill lake. Brook trout may have a superior ability to detect pockets of oxygen or areas of upwelling groundwater due to their different reproductive strategies. There is little evidence that rainbow trout spawn on beaches of lakes that do not have rivers flowing into them; however, brook trout can successfully shore spawn if there is a moderate current or groundwater upwelling (Scott and Crossman 1973; Fraser 1985). This ability to detect upwelling current may enable brook trout to home in on localized areas of higher oxygen and avoid winterkill conditions in the rest of the lake.

Stocking with large upgraded rainbow trout

A second management strategy for maintaining recreational fisheries in high-risk winterkill lakes is stocking with manually selected large (i. e., upgraded) yearling (age 1+) rainbow trout in the spring. The trout grow rapidly to catchable size by the fall, and provide a fall and early winter fishery before succumbing to low oxygen concentrations in mid to late February. Although conceptually simple, this strategy serves two important functions in the fisheries management program.

First, this strategy provides a seasonal fishery in a number of lakes where the winterkill risk is known to be high (> 50%). Although brook trout can be used as a replacement stock in marginal winterkill lakes, in high-risk winterkill lakes, the apparent increased survival of brook trout under low oxygen is not evident, so there is no advantage in using this approach. In addition, rainbow trout are the preferred sport fish in the Thompson-Nicola area, followed by kokanee (*Oncorhynchus nerka*) and other pacific salmon (*Oncorhynchus* sp.) (Stone 1988).

Second, this strategy takes advantage of the life cycle of the native rainbow trout. When the larger, fast growing trout are removed from the hatchery, the quality of the fishery in stocked non-winterkill lakes improves. If not removed, 2+ males mature, with a reduction in growth rate and survival, and deterioration of flesh quality and physical appearance (Toftenberg and Hansen 1986; Tsumura et al. 1987). Early sexual maturation can reach 18-40% in the wild Pennask Lake rainbow strain, and 47% in the Premier Lake strain (Tsumura and Hume 1986; Houston 1981).

The value of stocking large yearling trout was recently examined in Pikes Lake, a high-risk winterkill lake (elev. 975 m, area 22.5 ha) located in the Thompson-Nicola region (Tsumura and Blann 1988). One year old Pennask Lake rainbow trout from the Summerland Trout Hatchery were graded into three sizes (Table 4). Two thousand trout from each size class were stocked into Pikes Lake on May 8, 1987. Multiple mesh gillnet gangs were used to sample the fish 169 days later on October 23, 1987. Stretched mesh sizes ranged from 38.1 mm to 101.6 mm in 12.7 mm increments (5 mesh sizes). The nets were set in the late afternoon, cleaned of fish periodically, and picked up after dusk.

Table 4. Subsampled initial (age 1+) and final lengths (SD in brackets). Maturity ratio of graded rainbow trout after 169 days in Pikes Lake. (N = sample size per grade).

	Initial Conditions		Final Conditions		% Mature		
Grade	N	Mean length (mm)	N	Mean length (mm)	Males	Females	Sex ratio
Small	34	84.1 (11.1)	88	249.1 (27.7)	35.2	0	0.7:1
Medium	46	104.9 (8.6)	138	288.5 (26.4)	51.4	0.7	1.2:1
Large	49	126.8 (9.6)	208	328.2 (23.3)	59.6	1.0	2.1:1

The mean lengths and weights of the fish in the three size classes remained significantly different (GT2 test, $P < 0.05$, Sokal and Rohlf 1981) at the termination of the experiment (Table 4). Male maturation rates were 35.2, 51.5 and 59.6% in the small, medium and large grades over the whole population (Table 4). Early sexual maturation rates were negligible among the females in each size category. A significant difference was found between the sex ratios in the three groups (G test, $P > 0.001$), with the large size class containing 2.1 times more males than females, whereas the small and medium grades yielded respective ratios of 0.7:1 and 1.2:1 males to females (Table 4). Although the percentage of early sexual maturation observed in the males only was similar for each size class, more precocious males were present in the large size class due to the 2:1 male:female sex ratio in this group (Tsumura and Blann 1988).

These results suggest that a large proportion of precocious males can be "graded out" of the hatchery inventory as yearlings and used to develop a seasonal fishery in winterkill lakes. The size obtained by the large size class after 169 days in the lake is quite acceptable to anglers. The additional benefit of increasing the proportion of later maturing fish for use in stocking non-winterkill and "trophy lakes" is becoming an important component of fisheries management in the Thompson-Nicola area. Thirty-one high risk lakes in the area have been identified as suitable candidates for stocking upgraded yearlings (Tsumura et al. 1987), and plans for implementing this program are currently being developed.

Modifying the lake environment

A third strategy for providing fisheries in high-risk lakes is to modify the lake environment to prevent winterkill conditions from developing. This strategy 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 strategy is more complex than the previously mentioned stocking strategies, the high productivity of these lakes allows for the yield of large fish (i. e., 4-5 kg) in 3-4 years, and this type of fishery is very popular among Thompson-Nicola anglers.

Considerable effort has been directed at studying the seasonal limnology of winterkill lakes in the Thompson-Nicola area, and developing appropriate strategies to increase dissolved oxygen concentrations during the winter. Winter oxygen depletion rates (WODR) of these lakes are quite high, ranging from 0.174 to 0.629 $g.m^{-2}.d^{-1}$ (Table 5). These rates are similar to values reported for eutrophic prairie lakes and ponds (Babin and Prepas 1985; Barica and Mathias 1979), and reaffirms 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).

The standard technique used to alleviate winterkill conditions in these lakes is artificial circulation during fall and winter months. Artificial circulation is now standard practice on 10 winterkill lakes (mean depth 3 to 8 m) in the Thompson-Nicola region, ranging in size from 3 to 36 ha. On average, one lake is added to the circulation program each year. All of the artificial circulation installations are destratification systems. Technical aspects of the circulation systems are detailed in Ashley (1987).

Table 5. Whole-lake winter oxygen depletion rates (WODR) for selected winterkill lakes in the Thompson-Nicola region ($g.m^{-2}.d^{-1}$)

Lake	Year	WODR	Mean depth (m)
Black	1979-80	0.356	5.1
	1980-81	0.179	
	1981-82	0.224	
	1982-83	0.342	
	1983-84	0.475	
Edith	1979-80	0.439	5.6
	1981-82	0.369	
	1982-83	0.629	
	1983-84	0.503	
Frisken	1979-80	0.345	4.2
	1981-82	0.248	
	1982-83	0.301	
Walloper	1979-80	0.314	2.9
	1980-81	0.174	
	1982-83	0.287	
	1983-84	0.348	

Corbett and Edith Lakes are two examples of lakes in which artificial circulation is used. Corbett Lake (near Merritt, B.C.) experiences incomplete fall circulation due to wind sheltering by the surrounding topography, and 4-6 weeks of fall artificial circulation is sufficient to prevent winterkill (Halsey 1968; Halsey and Galbraith 1971). In contrast, Edith Lake (near Kamloops, B.C.) experiences complete spring and fall circulation, and is nearly saturated with oxygen prior to freeze-up (K. Ashley, unpub. data). However, due to its eutrophic status, oxygen is rapidly consumed (Table 5). The optimal timing for artificial circulation is in January lasting for 4-8 weeks of operation. Fall circulation alone, either natural or artificial, is often insufficient to prevent winterkill in highly eutrophic lakes. The use of artificial circulation must be tailored to each lake's seasonal circulation pattern and oxygen consumption rates.

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 have been conducted using photovoltaic powered surface aerators. Given the arid climate and abundant sunshine in the Southern Interior during winter months, photovoltaics are an appropriate technology for small, remote lakes. Three configurations have been tested, involving different combinations of 8 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 flow rates (36 to 99 $L.s^{-1}$) (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 increase winter oxygen concentrations.

A variety of additional lake manipulation techniques are available (see Dunst et al. 1974). However, given the arid continental climate of the Thompson-Nicola region and remote 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 some 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 Thompson-Nicola 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 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 cyanobacterial blooms (Barica et al. 1980), however, no trials have been conducted in B.C.

FUTURE CHALLENGES

An emerging management concern is the potential effects of global climatic change on the shallow productive lakes in the arid Southern Interior region. However, predicting climatic change within the Southern Interior Plateau region, and in British Columbia as a whole, is very difficult due to the coarse grid scale of the general circulation models and British Columbia's complex topography and proximity to the Pacific Ocean. Nevertheless, given the reliance of interior water supplies during summer months on the melting of winter snowpacks, some general trends have been observed. Over the past eight years, winter temperatures have been 1°C above normal and winter snowpacks in the interior have been declining (Coulson 1989). This reduced water supply has led to declining groundwater levels (Figure 2), and Coulson (1989) speculatively estimates a 10% increase in evapo-transpiration and a 10% decrease in basin precipitation could result in a net loss of water from Okanagan Lake on an annual basis. This is obviously a speculative scenario, however, the implications are very serious.

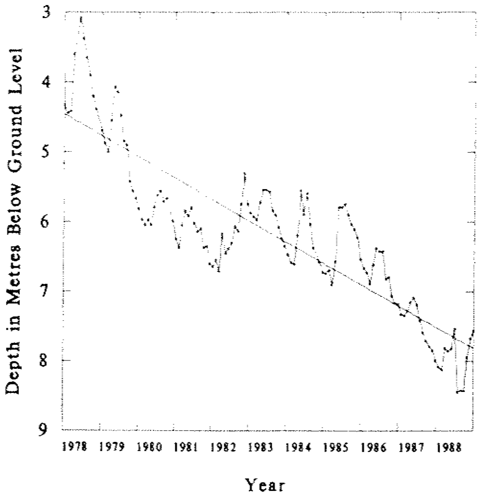

Figure 2. Well water depth from 1977 to 1988 at 83 Mile, British Columbia (from Coulson 1989).

The implications of increasing temperatures and declining surface and groundwater supplies on salmonid fisheries in these arid region lakes are equally serious. Reduced streamflow and possible goundwater warming may reduce natural recruitment in some lakes by depressing oxygen concentrations and altering growth and survival of eggs and larvae (Meisner et al. 1988). In terms of in-lake effects, Schindler et al. (1990) has detected trends in a 21 year time series (1968-1989) of data collected from a small lake (Lake 239) in the Experimental Lakes Area (ELA) in northern Ontario. Schindler's (1990) data indicates a 2-3°C increase in mean water temperature has occurred since 1968. The snow cover now melts earlier and ice-out is earlier resulting in a 2-3 week increase in the ice-free season. The water renewal time has increased from 7-8 years to over 20 years resulting in a considerable increase in the concentration of dissolved ions. Surface wind speed on the lake has increased, resulting in an increase in the thermocline depth. This reduces the volume of the hypolimnion, and may ultimately exclude cold stenothermal organisms such as *Mysis relicta* and *Salvelinus namavcush* by eliminating their thermal refuge.

The above scenario is quite possible for small eutrophic lakes in the Thompson-Nicola area. Rainbow trout are already near their physiological limits for oxygen and temperature during summer stratification. Increased surface temperatures and longer periods of stratification may further reduce the habitable volume for salmonids which may increase the incidence of summerkill. Lowered water levels due to reduced precipitation, surface runoff and groundwater input, and increased evapo-transpiration will compound this effect by reducing the storage volume for overwintering trout, and increased incidence of winterkill is a likely scenario. Increased competition for water between agriculture and fisheries will undoubtedly intensify as water supplies become scarce and conflicts develop between consumptive and non-consumptive use.

In conclusion, providing recreational fisheries in British Columbia's semi-arid Southern Interior region is a complex task. Through a combination of strategies using different species, size at stocking and artificial circulation, management biologists have been able to provide a variety of angling opportunities in a number of shallow eutrophic lakes in which limnological conditions are often at or near the physiological tolerance levels for salmonids. Further laboratory and field research is required to determine if physiological differences in low oxygen tolerance actually exist between rainbow and brook trout. In addition, continued research is required in developing models for predicting winter oxygen depletion rates and reducing winterkill risk via low power artificial circulation equipment and chemical treatments to reduce lake productivity. An emerging management concern is the potential effects of global climatic change which may adversely affect trout survival in these lakes via increased water temperatures, decreased lake storage volumes and lowered hypolimnetic dissolved oxygen concentrations.

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