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EVALUATION OF AERATION/CIRCULATION AS A LAKE RESTORATION TECHNIQUE

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ABSTRACT

Artificial circulation and hypolimnetic aeration are management techniques for oxygenating eutrophic lakes subject to water quality problems, algal blooms, and fishkills. Artificial circulation is achieved by injecting diffused air into lower waters, by mechanical pumping of water from one depth stratum to another, or by inducing turbulence at the surface using large axial-flow pumps. Complete mixing leads to isochemical and isothermal conditions with depth. In contrast, hypolimnetic aeration by air or oxygen injection affects primarily bottom waters; in some instances, low dissolved oxygen concentrations persist in the metalimnion. In general, both restoration methods lower the concentrations of reduced compounds (e.g., Fe, Mn, NH_4, H_2S) in lake waters, providing benefits for water supply systems. Aeration may cause supersaturation of nitrogen gas, thereby raising the potential danger of gas bubble disease in downstream fishes when hypolimnetic waters are released from a reservoir. In some instances, aeration/circulation has aggravated oxygen deficits and increased the potential for massive fishkills. Usually, adverse impacts can be attributed to faulty design of the aeration device, improper application of the technique, or inadequate understanding of biological response mechanisms.

Whole lake mixing may reduce regeneration of nutrients from profundal sediments, while often controlling blooms of blue-green algae. Models predict that overall algal biomass will decrease in deeper lakes when light limitation is induced by mixing. If destratification elevates epilimnetic CO_2 levels and causes a sufficient drop in pH, dominance in the algal community will likely shift from a nuisance blue-green species to a mixed assemblage of green algae. This more edible resource combined with an expansion of habitat and provisioning of a prey refuge in lower waters leads to more abundant zooplankton and invasion of large-bodied daphnids. In most cases, treatment enhances the abundance and species richness of benthic macroinvertebrates in the profunal zone, causing a shift from predatory chaoborids to a diverse assemblage of detritivores. Habitat expansion and shifts in community structure of benthic macroinvertebrates potentially elevate the abundance of fish food organisms. Although short-term increases in fish growth and yield have been attributed to improvements of food and habitat resources, documentation of long-term changes is lacking. In southern regions, artificial circulation provides benefits for warm-water fishes only.

Hypolimnetic aeration maintains the natural thermal structure of the lake while oxygenating bottom waters. Thus, this technique is preferred for management of water supply systems and cold-water fisheries. The potential benefits of hypolimnetic treatment in controlling algal blooms are more limited than those realized with whole lake mixing. While hypolimnetic treatment usually lowers phosphate concentrations in bottom waters, the long-term effects on internal loading of nutrients is unknown. Hypolimnetic aeration or oxygenation appears to allow habitat expansion in zooplankton and benthic macroinvertebrates as well as fishes.

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GENERAL INTRODUCTION

Artificial aeration or circulation of lakes is commmonly used for managing the ecological consequences of eutrophication. Unlike techniques that prevent nutrient influx from the watershed (e.g. diversion of septic effluents, treatment of inflowing waters, or modification of land use practices) aeration/circulation affects nutrient cycling within the lake only. Nevertheless, it can be used to enhance water quality by alleviating a variety of problems arrising during thermal stratification and deoxygenation of the hypolimnion. Aeration/circulation has proved beneficial in management of domestic water supplies, downstream releases from reservoirs, and industrial water systems. By inducing dramatic changes in biological communities through influences on species abundance and distribution, diversity, and trophic structure, the technique has potential usefulness in control of algal blooms and improvement of fisheries. In some instances, treatment has aggravated already existing problems or caused new problems to arise, but these results can usually be attributed to faulty design of the aeration device, improper application of the technique, or inadequate understanding of the biological community and its response mechanisms.

The broad range of aeration/circulation techniques has been divided into two major groups: artificial circulation and hypolimnetic aeration. Procedures which are designed to either mix the whole lake or provide aeration without maintaining the normal thermal structure are classified as artificial circulation techniques. Within this category, systems range from high-energy mixing devices to low-energy aeration procedures; mechanical pumps, rising air bubbles and jets of water can serve as mixing devices. In most cases, mixing has been induced after the development of normal thermal stratification; hence it is usually termed artificial destratification. Destratification restores oxygen to deficient hypolimnetic waters whereas artificial circulation before the onset of stratification can maintain aerobic conditions near the lake bottom. Either technique leads to habitat expansion for zooplankton, benthos and warm-water fish. However, complete mixing may eliminate the cold-water habitat at mid-water or near the lake bottom and cold-water fishes such as the salmonids may disappear from the lake. Under certain circumstances, artificial circulation can eliminate excessive algal growth or shift the community away from a uni-specific bloom of a blue-green alga toward a mixed assemblage of more desirable green algae.

Hypolimnetic aeration allows oxygenation of the bottom waters of a lake without disrupting the normal pattern of thermal stratification. Both air and oxygen in compressed form have been pumped into lakes. Hypolimnetic aeration can effectively maintain aerobic conditions without loss of the cool hypolimnetic water preferred for domestic and industrial uses and required for the maintenance of cold-water fisheries.

ARTIFICIAL CIRCULATION

MIXING DEVICES AND APPLICATIONS

The techniques used to circulate lakes can be broadly classified as diffused air systems or mechanical mixing systems. The former category includes all aeration devices exploiting the "air-lift" principle; i.e. water is upwelled by a plume of rising air bubbles. Mechanical systems employ standard diaphragm pumps, fan blades, or water jets to move water. After reviewing design and field performance of a variety of destratification techniques, Lorenzen and Fast (1977) concluded that diffused air systems are less expensive and easier to operate than mechanical mixing devices.

Compressed air is usually injected into the lake through a perforated pipe or other simple diffuser (e.g. Fast 1968; Haynes 1973). Release of air in deep water forms a trail of rising air bubbles which entrain water all along their paths, creating turbulent mixing around a central zone of upwelling (Kobus 1968; see figure A-1 in Lorenzen and Fast 1977). Kobus (1968) has shown that the amount of water flow induced by a rising bubble plume is primarily a function of air release depth and air flow rate. Therefore, artificial circulation is generally most effective if air is injected at the maximum depth possible (Fast 1968). Lorenzen and Fast (1977) conclude that about 9.2 m^3/min of air per 10^6 m^2 of lake surface (= 30 SCFM per 10^6 ft^2) will provide adequate water movement for surface aeration, while maintaining minimal variation in temperature (< 2^oC) and algal concentrations throughout the water column. According to this scaling rule, most aeration systems used in the past have been undersized (Table 1).

In a thermally stratified lake, mixing will normally be induced above the air release depth only. Although an aerator located near the surface of the lake may be unsuitable for destratifying a lake, it can be effective in preventing the onset of stratification (e.g. Riddick 1957). In any case, once a complete mix has been achieved, intermittant operation of the system may be sufficient to maintain circulation depending on local meteorological conditions, such as wind exposure and solar radiation.

Although most air compressors have been driven by electricity or gasoline combustion, alternative energy sources are possible. For example, Rieder (1977) has successfully coupled a wind power generating system with an air compressor capable of destratifying small prairie lakes.

Mechanical mixing devices have been used less frequently than diffused air systems, although they may be quite successful in certain circumstances (e.g. Irwin et al. 1966; Toetz 1977a, b; Garton et al. 1978). A pumping rate of about 10.9 m^3/min was sufficient to destratify Stewart Hollow Reservoir and Vesuvius Reservoir within 8 days (Table 1; Irwin et al. 1966). However a pumping capacity of about 1.3 m^3/min over a period of 10.1 days did not give a complete mix of West Lost Lake (Hooper et al. 1953).

The axial flow pump designed by Quintero and Garton (1973) (also see Garton and Punnett 1978; and Garton et al. 1978) uses a large fan blade to

TABLE 1 SELECTED LAKES AND THEIR PHYSICAL-CHEMICAL RESPONSES TO ARTIFICIAL CIRCULATION

Lake	Location	Reference	Depth (m) Max	Depth (m) Mean	Depth (m) Air	Volume $\times 10^{-6}$ (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Aeration Intensity[a] Q_A/V $\times 10^6$	Aeration Intensity[a] Q_A/A $\times 10^6$	ΔT[b] (°C) Before	ΔT[b] (°C) After	Lake Response[c] S D	D O	PO_4	T P	NO_3	NH_4	Fe Mn
Cline's Pond	Oregon	Malueg et al 1971	4 9	2 5	4 9	0 003	0 4	0 028	10 2	7 00	5	0	+	+	+		0	0	
Parvin Lake	Colorado	Lackey 1972	10	4 4	10	0 049	19	2 1	2 5	11 10	6	<1		+			0		-
Section 4 Lake	Michigan	Fast 1971a	19 1	9 8	18 3	0 110	1 1	2 21	20	200	15	0	-	+					
Boltz Lake 1966	Kentucky	Symons et al 1967, 1970 Robinson et al 1969	18 9	9 4	18 9	3 614	39	3 17	0 88	8 17	5-10	<2	-	-		-	+	+ -	-
University Lake	North Carolina	Weiss and Breedlove 1973	9 1	3 2	9 1	2 591	80 9	0 40	0 15	0 49		<2	-	+ 0	-	-	+	-	-
Kezar Lake	New Hampshire	N H W S P C C 1971 Haynes 1973	8 2	2 8	8 2	2 008	73	2 83	1 41	3 88	11	<1	+	+	+	+	+ -	-	-
King George VI 1965 1966	United Kingdom	Ridley et al 1966	16				142		water jet		5 5 6 5	6 4		+ +					
Indian Brook Res	New York	Riddich 1957	8 4		3 2		7 3	4 53		62 06	9	0		+					-
Prompton Lake	Pennsylvania	McCullough 1974	10 7		10 7	4 193		4 53	1 08			1							
Cox Hollow 1966 1967-69	Wisconsin	Wirth and Dunst 1967 Wirth et al 1970	8 8	3 8	8 8	1 480	38 8	2 04	1 38	5 26	17	<3	+ 0	+ +	- -		+	- -	- -
Stewart Lake 1974 1975	Ohio	Barnes and Griswold 1975	7				2 4				19 18	5 7		+ +	0 0		- -		
Wahnbach Res 1961-62 1964	W Germany	Bernhardt 1967	43	19 2		41 618	214	2 01 5 95	0 048 0 143	0.94 2 78	14	6		+ 0 +					- -
Starodworskie Lake	Poland	Lossow et al 1975	23		23		7	0 27		3 81	15	<2		+	-	-	+	-	
Queen Elizabeth II Res. 1965 1966	United Kingdom	Ridley et al 1966	17 5		17 5		128		water jet		6 4	0 0		+ -	 +				
Lake Roberts	New Mexico	R S Kerr Res Center 1970 McNall 1971	9 1		9 1	1 233	28 3	3 54 2 26	2 87 1 84	12 51 8 00	6 4 6	0 0		+ -		- +			
Falmouth Lake	Kentucky	Symons et al 1967, 1970 Robinson et al 1969	12 8	6 1	12 8	5 674	91	3 26	0 58	3 58			-	+ -		-	+ 0	-	-
Test Res II	United Kingdom	Knoppert et al 1970	10 7	9 4	10 7	2 405	25 4	2 01	0 84	7 92		0	-	+		0	-	-	
Ham's Lake 1973 1975	Oklahoma	Steichen et al 1974 Toetz 1977a, b Garton et al 1978	10	2 9	1 2	115	40		axial-flow pump		13 5 10	<1 <2	 +	+ +	 +		 -	 -	 -
Test Res I	United Kingdom	Knoppert et al 1970	10 7	9 4	10 7	2 097	22 7	2 01	0 96	8 86		0	0	+		0	-	-	
Mirror Lake 1972 1973	Wisconsin	Smith et al 1975 Brynildson and Serns 1977	13 1	7 6	12 8	0 360	5 3	0 45	1 13	0.55	13	0 0		+ +	- 0	+ -			
Stewart Hollow Res	Ohio	Irwin et al 1966	7 6	4 6	pump 7 6	0 148	3 2		axial-flow pump		22 15	13 <2		0 0					
Cladwell Res.	Ohio	Irwin et al 1966	6 1	3 0	pump 6 1	0.123	4 0		axial-flow pump		20	7		+					
Pine Res.	Ohio	Irwin et al 1966	5 2	2.1	pump 5 2	0.121	5 7		axial-flow pump		13	3		-					

TABLE 1. (continued)

Lake	Location	Reference	Depth (m) Max	Depth (m) Mean	Depth (m) Air	Volume $\times 10^{-6}$ (m^3)	Area (ha)	Aeration Intensity[a] Q_A (m^3/min)	Q_A/V $\times 10^6$	Q_A/A $\times 10^6$	ΔT[b] (°C) Before	ΔT[b] (°C) After	Lake Response[c] SD	DO	PO_4	TP	NO_3	NH_4	Fe Mn
Vesuvius Res	Ohio	Irwin et al 1966	9 1	3 6	pump 9 1	1 554	42 5	axial-flow pump			16	2		0					
Vaxjosjon	Sweden	Bengtsson and Gelin 1975	6 5	3 5	6	3 1	87	7 2	2 32	8 28		0		+		+			
Corbett Lake	British Columbia	Halsey 1968 Halsey and Galbraith 1971	19 5	7	19 5	1 689	24 2	4 50	2 66	18 52	2-4	0		+					
Buchanan Lake	Ontario	Brown et al 1971	13	4 9	13	0 42	8 9	0 28	0 67	3 17		0	-	+		-		-	-
Lake Maarsseveen	United Kingdom	Knoppert et al 1970	29 9	14	19 29 9	8 018	60 7	2 49	0 31	4 10	8	0							
Arbuckle Lake 1975 1977	Oklahoma	Toetz 1977a, b; 1979	24 7	9 5	6 pump 2 pump	8930	951	axial-flow pump			11 9	9 13	0 0	0 +	0 +		0 +	0 -	0
Casitas Res	California	Barnett 1975	82	26 8	39- 55	308	1100	17 84	0 06	1 62		d	+ 0						-
Hyrum Res	Utah	Drury et al 1975	23	11 9	15 2	23 1	190	2 83	0 17	1 49	6	2-4	-	+	0	0	-	-	
West Lost Lake	Michigan	Hooper et al 1953	12 8	6 2	pump 11 5	0 089	1 4	pump			13	9	-	+		+			
Waco Res	Texas	Biederman and Fulton 1971	23	10 7	23	128	2942	3 11	0 02	0 10	17	~6		+					
Lake Catherine	Illinois	Kothandaraman et al 1973	11 8	5	8 5	3 034	59 5	0 76	0 25	1 27	2	0-14	0	+	0	0	0	0	0
El Capitan 1965 1966	California	Fast 1968	62	9 8 9 4	21 3 28 3	17 99 21 05	183 9 222	6 09 6 09	0 34 0 29	3 31 2 74	~9 ~6	<3 <3	- -	+ +					- -
Lake Calhoun	Minnesota	Shapiro and Pfannkuch 1973	27 4	10 6	23	18 01	170 4	2 83- 3 56	0 16- 0 20	1 66- 2 08	16	9[d]	-	+					
Eufaula Res	Oklahoma	Leach et al 1970	27	16 2	27	703 1	41400	33 90	0 05	0 06	10	7		0					
Pfaffikersee	Switzerland	Thomas 1966 Ambuhl 1967	35	18	28	56 5	325	6	0 11	1 85				+			+	-	

[a] Q_A = rate of air injection (m^3/min), V = volume (m^3), A = area (m^2)

[b] ΔT = temperature differential between surface and bottom water

[c] Response parameters: SD = secchi depth, DO = dissolved O_2, PO_4 = phosphate,
TP = total phosphorus, NO_3 = nitrate, NH_4 = ammonium
Fe = iron, Mn = manganese

Direction of change in average concentration for whole lake + = increase, - = decrease, 0 = no significant change

[d] Mixed to air release depth

move water from the lake surface downward. A pump with a capacity of 102 m^3/min completely destratified Ham's Lake after 3 days of operation in 1975 (Toetz 1977b). On the other hand, an array of 16 pumps with a total capacity of 1,600 m^3/min failed to mix Arbuckle Lake completely, although it did lower the thermocline (Toetz 1979). Arbuckle Lake is more than twice as deep as Ham's Lake (Table 1).

The Metropolitan Water Board of London induces mixing in water supply reservoirs by discharging relatively warm river water from jet-type inlets located near the bottom of each impoundment. A series of 9 jets, each with a capacity of about 108 m^3/min achieved adequate circulation in Queen Elizabeth II Reservoir (Ridley et al. 1966).

EFFECTS OF ARTIFICIAL CIRCULATION ON WATER QUALITY

The onset of anaerobic conditions in the hypolimnion of a stratified lake causes extensive chemical transformations in the surficial sediments, which result in a transfer of nutrients to the overlying water (Mortimer 1941, 1942; Hutchinson 1957). The subsequent accumulation of Fe, CO_2, H_2S, NH_4^+ and other chemicals in the hypolimnion creates problems of quality control for utilities supplying domestic and industrial waters (e.g. Teerink and Martin 1969). Oxygenation of hypolimnetic waters raises the redox potential near the lake bottom, greatly lowering concentrations of reduced chemical species and eliminating taste and odor problems. Most aeration systems have been installed with this goal in mind (Smith et al. 1975; Fast 1979a).

In a survey of 26 water suppliers conducted by the American Water Works Association, 86 percent of the utility managers considered their artificial destratification projects a success (AWWA 1971). However, 46 percent reported that mixing created new water quality problems. Most of the problems created by treatment involved elevation of turbidity levels or algal blooms.

Chemical Parameters

In most cases, artificial destratification increases the concentration of dissolved oxygen in bottom waters immediately (e.g. Hooper et al. 1953; Lackey 1972; Haynes 1973); dissolved oxygen in the former epilimnion may show a corresponding decrease due to a reduction in photosynthesis (Haynes 1973) or mixing of hypolimnetic waters with high BOD into the surface layer (Ridley et al. 1966; Thomas 1966). Over a period of several weeks, the oxygen content of the whole lake is increased (Table 1). The method of destratification is probably irrelevant to the rate of oxygenation as long as an adequate mix can be maintained. Since the direct transfer of oxygen between rising air bubbles and water is unimportant except in very deep lakes, the primary mode of aeration is through atmospheric exchange at the lake's surface, even with diffused air systems (King 1970; Smith et al. 1975).

Under some circumstances, oxygen depletion can not be prevented by normal levels of artificial aeration (Table 1). For example, during mixing of Lake Roberts in July, a combination of reduced phytosynthetic activity in cloudy weather and an unusually high BOD caused by decomposing Anabaena scums created anoxic conditions throughout the lake leading to a massive fish-kill (R.S. Kerr Research Center 1970; McNall 1971).

Oxygen levels influence redox reactions involving Fe, Mn and Al; in turn, these elements and their complexes partly determine the availability of nitrogen and phosphorus compounds through release processes occurring at the surface of profundal sediments (Mortimer 1941, 1942; Hutchinson 1957). Because of the importance of nutrient regeneration to algal production and the interaction of chemical and biological components in controlling nutrient levels, the effects of artificial circulation on phosphate and nitrate concentrations will be discussed below in the section on plankton.

As hypolimnetic waters are brought to the lake's surface, excess gases such as CO_2, H_2S, and NH_3 are released to the atmosphere (R.S. Kerr Research Center 1970; Toetz et al. 1972; Haynes 1973). Along with oxygen and other chemical species, these gases become isochemical with depth (Toetz et al. 1972). Temporary rises of H_2S and NH_3 may occur in surface waters following mixing (R.S. Kerr Research Center 1970). Undoubtedly, nitrification of NH_4^+ to NO_3^- is an important mechanism for elimination of reduced ammonia compounds (Brezonik et al. 1969). After mixing, the concentration of CO_2 in the surface layer rises as hypolimnetic levels decrease. The CO_2 content of the entire lake often falls slightly (Riddick 1957; Haynes 1973; Steichen et al. 1974), although temporary increases are sometimes observed; e.g. during the 1966 mixing of Boltz Lake (Robinson et al. 1969). Since changes in ambient CO_2 levels and related pH effects have an important influence on species interactions in the phytoplankton community, these topics will be discussed in detail in a later section.

Some air injection systems may cause supersaturation of nitrogen gas (N_2) relative to surface hydrostatic pressures (Fast 1979a, b). Dissolved nitrogen concentrations of only 115 to 120 percent saturation can induce substantial mortality among salmonids in rivers (Rucker 1972) and in laboratory experiments (Blahm et al. 1976). Normally, the entire water column is close to 100 percent saturation with respect to depth-specific temperatures and pressures (Hutchinson 1957). Any rise in N_2 above the ambient concentrations is a potential problem when reservoir waters are released downstream.

Fast (1979a, b) discusses the problem of N_2 supersaturation during artificial destratification of Casitas Reservoir in 1977. After 80 days of aeration at 46 m depth, N_2 levels in the zone of induced mixing (15 to 45 m) were at 125 percent saturation relative to surface pressures. The waters below 46 m had even higher N_2 concentrations, up to 140 percent saturation relative to the surface. Presumably, the aeration system did not greatly influence N_2 levels below the depth of air release, so such high concentrations may be normal for this reservoir.

During spring circulation, N_2 levels throughout the lake generally equilibrate at 100 percent saturation with respect to surface temperature and pressure. Any warming of the hypolimnion during summer will result in supersaturation relative to surface pressure and ambient temperature at depth. But hydrostatic pressure probably maintains this "excess" gas in solution throughout the metalimnion and hypolimnion. Even after hypolimnetic aeration of Lake Waccabuc, N_2 levels for most of the water column were below the 100 percent saturation values adjusted for both temperature and pressure (Fast et al. 1975a).

In any event, absolute concentrations of N_2 will increase with depth in stratified lakes, and the lower waters will be supersaturated relative to the surface (Hutchinson 1957; Fast 1979a). If the body fluids of fish equilibrate at N_2 levels in deep water, and then the fish migrate to near the surface, gas bubbles could form causing stress or mortality. To what extent this occurs naturally, and whether aeration aggravates the problem remains unknown. In Casitas Reservoir, fish-kills were avoided because surface waters remained close to saturation and bottom waters were not released downstream (Fast 1979b).

Physical Parameters

In almost every case, artificial circulation during summer promotes an increase in the heat content of the lake, even when mixing is incomplete (e.g. Toetz et al. 1972; Haynes 1973; Toetz 1977b, 1979; Kothandaraman et al. 1979). Usually, the temperature of the upper waters decreases by a few degrees, whereas deep waters are warmed by as much as 15 to 20 ^{o}C to approximately the same temperature as the surface. Circulation during winter actually reduces water temperatures overall because bottom waters are no longer insulated from the cooler air by a surface layer of water or ice (Lackey 1972; Drury et al. 1975).

Isothermy is difficult to establish because the destratification process becomes less efficient as the lake comes closer to a complete mix (Fast 1979a). Unfortunately, most destratification devices are low energy systems, and a majority have been undersized with respect to the scaling rule suggested above (Table 1; Lorenzen and Fast 1977). When more thermal energy is absorbed at the lake's surface than the circulation device can distribute, then microthermal stratification of 2 to $3^{o}C$ provides algal populations a surface refuge with high light levels (e.g. Fast 1973a; Drury et al. 1975).

In small lakes, horizontal mixing is relatively complete, but in large reservoirs, the destratification system will influence a limited area (e.g. Leach et al. 1970; McCullough 1974). Of course, unaffected sections of the lake may provide excellent experimental controls.

Artificial circulation has varied effects on water transparency, depending on the intensity of mixing and the contribution of phytoplankton to turbidity levels before treatment. In four of the lake case histories examined, artificial mixing resulted in greater water transparency; and in 13 cases, transparency decreased or stayed the same (Table 1). When mixing is induced during a surface bloom of blue-green algae, transparency will increase immediately due to distribution of the algae throughout a greater water volume (Haynes 1973). Thereafter, water clarity may be enhanced by destruction of the bloom through light limitation in deep lakes (Lorenzen and Mitchell 1975) or through a change in some other environmental factor in shallow lakes (Malueg et al. 1971). In contrast water clarity was reduced in Section Four Lake when intense aeration resuspended inorganic sediments and detritus from the lake bottom, nullifying the effect of a slight decline in phytoplankton (Fast 1971a). A rise in total seston after mixing generally correlates with a decrease in transparency (Fast 1971a; Drury et al. 1975; Garton 1978; Garton et al. 1978). In West Lost Lake and Hyrum Reservoir, algal blooms were responsible for the observed changes (Hooper et al. 1953; Drury et al. 1975).

EFFECTS OF ARTIFICIAL CIRCULATION ON PHYTOPLANKTON

The effects of artificial circulation on phytoplankton populations are extremely variable (see Toetz et al. 1972 for an earlier review), not only because application of techniques and efficiency of mixing devices vary among investigations, but also because alternative biological communities exhibit different responses to the same kinds of perturbations. Moreover, the desirability of a particular response depends on management goals. For example, an increase in planktonic algae will be considered a nuisance if it causes filter clogging and "taste and odor" problems in a water supply system (Teerink and Martin 1969) yet the same "bloom" could have beneficial effect by stimulating fish production (e.g. Johnson 1966; Oglesby 1977). An understanding of the mechanisms underlying responses of specific biological systems is essential to enhancement of our predictive power in future applications of circulation techniques.

At one time, artificial circulation was regarded as a method for reducing algal growth by one or several of the following mechanisms (Fast 1975):

1. "Preventing nutrient regeneration during anaerobic conditions and thereby reducing internal loading"

2. "Increasing the mixed depth of the algae and thereby reducing algal growth due to light limitation"

3. "Subjecting the algae to turbulence and rapid changes in hydrostatic pressure as they are swept through a large vertical distance of the water column".

It is now obvious that other effects of artificial circulation may negate these influences and in some instances produce an opposite result, i.e. increased algal biomass. In fact, of the 40 experiments in which destratification was relatively complete, only 65 percent (=26 experiments) led to any significant change in algal concentrations; of these, about 30 percent resulted in more algae than before destratification. Table 2 summarizes the responses of phytoplankton to artificial circulation for each lake. When more than one experiment was conducted in a lake, the predominant response is given unless the data are too variable to indicate an overall trend; then, the responses for individual experiments are given. Where mixing was complete, aeration caused a decrease in algal density or

TABLE 2. RESPONSES OF PHYTOPLANKTON TO ARTIFICIAL CIRCULATION[a]

Lake	Reference	Algal Density[c]	Algal Standing Biomass[d]	Mean Chlorophyll-a Concentration	Green Algae	Blue-green Algae	Ratio Gr : Bl-gr
Complete Mixing							
Cline's Pond	Malueg et al. 1971	-		-	0	-	+
Parvin Lake	Lackey 1973a	-			-	0[e]	0
Section 4 Lake	Fast 1971a Fast et al. 1973	-[f]	-		-		
Boltz Lake	Symons et al. 1967, 1970 Robinson et al. 1969	-	-		-	-	+
University Lake	Weiss and Breedlove 1973	-		0	+	-	+
Kezar Lake	Turner et al. 1972 Haynes 1973 N.H.W.S.P.C.C.1971 Lorenzen and Mitchell 1975	-	-	0	+	-	+
King George VI	Ridley et al. 1966	-			-	+	-
Indian Brook[b]	Riddick 1957	-					
Prompton Lake[b]	McCullough 1974	-					
Cox Hollow[b]	Wirth and Dunst 1967 Wirth et al. 1970	-					
Stewart Lake	Barnes and Griswold 1975			-			
U.K. Reservoir[b]	Ridley 1970					-	
Wahnbach Reservoir	Bernhardt 1967					-	
Queen Elizabeth II		0					
Lake Roberts	McNall 1971 R.S. Kerr Res. Cen. 1970	±				±	
Falmouth Lake	Symons et al. 1967, 1970 Robinson et al. 1969	+			+	-	+
Test Res. II	Knoppert et al. 1970	+	+		0	+	0
Buchanan Lake	Brown et al. 1971	+	+	+	+	-	+
Ham's Lake[f]	Steichen et al. 1974 Toetz 1977a, b Garton 1978	0		0	0	0	0
Test Res. I	Knoppert et al. 1970	0+	0+			0+	0-

TABLE 2. (continued)

Lake	Reference	Algal Density[c]	Algal Standing Biomass[d]	Mean Chlorophyll-*a* Concentration	Green Algae	Blue-green Algae	Ratio Gr : Bl-gr
Mirror Lake	Smith et al. 1975 Knauer 1975	0[g]	0[g]			0[g]	
4 Lakes[h]	Irwin et al. 1966	0				-	+?
Starodworskie Lake[f]	Lossow et al. 1975				-	+	-
<u>Incomplete Mixing</u>							
Casitas Res.[b]	Barnett 1975	-				-	
Hyrum Res.	Drury et al. 1975	+	+	+	-	+	-
West Lost Lake	Hooper et al. 1953	+	+			+	
Pfaffikersee	Thomas 1966	+				+	
Waco Res.[b]	Biederman and Fulton 1971	0			0		
Lake Maarsseveen[b]	Knoppert et al. 1970	0			0		
Lake Catharine	Kothandaraman et al. 1979	0					0
El Capitan[f]	Fast 1973a	+?					0
Arbuckle Lake	Toetz 1977a, 1979	0		0			0
Lake Calhoun	Shapiro and Pfannkuch 1973		+	+	0	+	-

[a] + = increase, - = decrease, 0 = no significant change
[b] qualitative information only
[c] cells or colonies per liter; weighted mean for water column unless noted
[d] weight per square meter of lake surface
[e] increase observed, but control year was unusual
[f] samples were taken near lake surface
[g] increase observed, but it was correlated with large input of allochthonous nutrients
[h] Stewart Hollow Lake, Caldwell Lake, Pine Lake, Vesuvius Lake

biomass in 13 of 23 lakes. In three lakes, the amount of phytoplankton remained about the same, and in seven lakes it increased or the overall response was unclear. Where mixing was incomplete, algal density generally stayed the same or increased following treatment (Table 2). Although artificial circulation usually has a negative influence on blue-green algae, its effect on green algae is ambiguous.

Changes in phytoplankton populations after circulation treatment are discussed below under three primary modes of influence: physical, chemical, and biological mechanisms.

Physical Mechanisms

In lakes where algal production is potentially limited by light, several models predict a decrease in net photosynthesis and a reduction in standing crop of algae as depth of the mixed layer increases (Murphy 1962; Lorenzen and Mitchell 1975; Oskam 1978). Since destratification effectively increases the depth of mixing, algae will then be spending a considerable amount of time in dimly lit zones, perhaps below the compensation level in deep lakes. Accordingly, Haynes (1973) observed a sharp decline in primary production soon after aeration of Kezar Lake (although values thereafter rose gradually to predestratification levels). At Lake Vaxjosjon (Sweden), average primary production (gC $m^{-2}d^{-1}$) during summer of 1970 decreased by about 30-40 percent relative to the control year (Bengtsson and Gelin 1975). When aerators were operative for only two brief periods in summer 1971, average production was only slightly lower than pretreatment levels.

Lorenzen and Mitchell (1975) have found good agreement between the predictions of their model, relating maximum standing crop of algae to mixed depth, and the results of experiments at Kezar Lake, New Hampshire (Figure 1). Although the model ignores the effects of mixing on algal losses by sinking, grazing, and parasitism, it does appear to give a reasonable estimate of maximum standing stock in a variety of circumstances. Perhaps more importantly, it explains the apparently conflicting results obtained by different studies of changes in algal abundance after mixing (Table 2). If algae are limited by nutrients before circulation, a slight increase in mixing depth could cause an elevation of standing crop (e.g. point A to point B in Figure 1), a result opposite to that found in the light-limited condition. Thus primary productivity and productivity per cell during aeration of oligotrophic Section Four Lake were up to three times higher than values during the control year (Fast 1971a). The particularly intense aeration/circulation of this lake (Table 1) resuspended large quantities of bottom detritus and probably made nutrients more available to algae. If mixing shifts the controlling mechanism from nutrient limitation to light limitation, a moderate increase in mixed depth will cause a substantial rise of peak algal biomass or at best only a slight decline (A to C or B to C respectively in Figure 1). However, for large increases in mixed depth, the imposition of light limitation can cause substantial decreases in areal algal biomass (A and B to D in Figure 1). It should be noted that when water column biomass decreases with increased mixed depth, the concentration of algae will decrease dramatically because less biomass is distributed in a much larger water volume. Finally, because of differences in growth

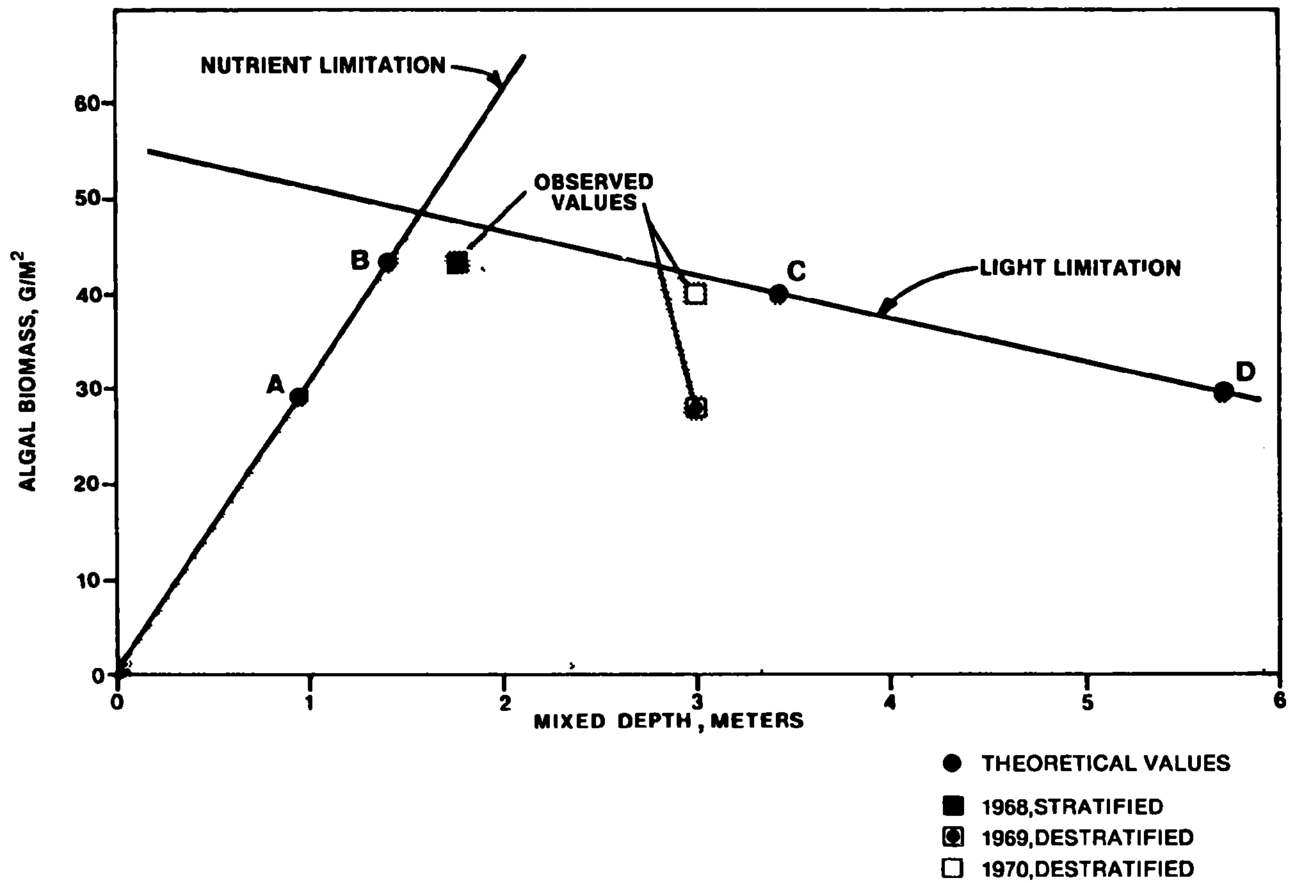

FIGURE 1 THEORETICAL AND OBSERVED PEAK BIOMASS OF ALGAE IN KEZAR LAKE (ADAPTED FROM LORENZEN AND MITCHELL 1975)

parameters among algal species, a major shift in species composition of phytoplankton could generate a change in peak quantity of algae apart from the effects of mixed depth.

Where algal abundance is relatively low, e.g. in oligotrophic lakes, artificial destratification usually produces little change in cell concentrations (Knoppert et al. 1970; Biederman and Fulton 1971; Toetz 1977a, b; but see Fast 1971a). In some instances, standing stock may have increased due to change in mixing depth, whereas in others, the change was small as a result of incomplete destratification. In any event, since the slope of the ascending curve in Figure 1 equals the peak nutrient-limited concentration of algae (Lorenzen and Mitchell 1975), the slope will be smallest for oligotrophic lakes because these yield less algae per unit volume than do entrophic lakes. Hence, any given change in mixed depth over the range of nutrient-limited biomasses will result in only small displacements of standing crop in oligotrophic lakes compared with potential shifts in richer lakes.

A critical problem arises when surface waters heat rapidly and an undersized circulation device is unable to achieve a complete mix (i.e. isothermy). The resulting microstratification provides a shallow-water "refuge" for some blue-green algae (e.g. Aphanizomenon flos-aquae), yielding greater population densities after the aeration treatment (e.g. Thomas 1966; Drury et al. 1975). The influence on standing crop is unpredictable, depending upon the magnitude of the actual decrease in mixed depth and the mode of limitation (cf. Figure 1). In El Capitan Reservoir, incomplete mixing resulted in microstratification near the lake surface and an increase in net primary productivity over pretreatment levels (Fast 1973a). The use of a mechanical device like the Garton pump (Quintero and Garton 1973; Garton and Punnett 1978; Garton et al. 1978), which induces mixing by moving surface waters downward, might prevent microstratification and associated problems.

When circulation treatment is effective, the increased depth of mixing does lead to an expansion of the depth distribution of phytoplankton (Fast 1971a; Haynes 1973). Apart from long-term effects on standing crop, if a roughly uniform profile of cell concentration versus depth is obtained soon after mixing, population densities decline and water clarity is enhanced (e.g. N.H.W.S.P.C.C. 1971; Haynes 1973).

On the other hand, artificial circulation sometimes reduces light penetration by creating more turbid waters through resuspension of bottom deposits (Hooper et al. 1953; Fast 1971a). Water-jet inlet systems such as the one used at Queen Elizabeth II Reservoir (United Kingdom)(Ridley et al. 1966) especially aggravate this problem by reducing sedimentation of debris.

The high turbulence also helps to retain algal cells in suspension, reducing population losses due to sinking. Population decline in Asterionella formosa has been related to sinking losses by Lehman and Sandgren (1978). Induced turbulence could account for increases in Asterionella observed by Bernhardt (1967) and Fast et al. (1973) after treatment.

Artificial circulation effectively reduced the abundance of blue-green algae in only 19 of the 30 experiments in which mixing was complete; however, these 19 cases represent 76 percent of the instances where any change was noted. Blue-green species often control their depth distribution via buoyancy regulation to take advantage of specific optima in light, temperature and/or nutrients (Fogg and Walsby 1971; Konopka et al. 1978). Following artificial circulation, Bernhardt (1967) and Weiss and Breedlove (1973) observed dispersion of metalimnetic populations and overall decline of Oscillatoria rubescens and O. tenuis respectively. Mixing may eliminate the competitive advantage of blue-green algae due to buoyancy regulation. Mixing also potentially affects sensitive species by rupturing gas vacuoles as cells are swept rapidly through zones of differing hydrostatic pressure. Whatever the mechanism, Anabaena spp. are among the most sensitive forms (Ridley 1970; Knoppert et al. 1970; Malueg et al. 1971; Steichen et al. 1974; Barnett 1975).

Chemical Mechanisms

Occasionally, researchers interested in elevating fish yield have successfully stimulated phytoplankton growth by mixing nutrient-rich bottom waters into the trophogenic zone, which is generally poorer in dissolved inorganics required by algae (Hooper et al. 1953; Hasler 1957; Schmitz and Hasler 1958). In this case, an incomplete mix is desirable for deep lakes where the maximum depth is greater than the mixed depth necessary to achieve significant light limitation (cf. Figure 1). Johnson (1966) reported an increase in production of phytoplankton and fishes after incomplete destratification of Erdmann Lake; unfortunately, his experimental design was confounded by application of rotenone before mixing. Also aeration treatments have more direct effects on fish populations (see below).

More often, mixing techniques have been applied in attempts to reduce algal blooms by curtailing regeneration of nutrients from profundal sediments (Toetz et al. 1972; Dunst et al. 1974; Fast 1979a). Direct aeration of bottom waters combined with increased exchange across the air-water interface leads to reoxygenation of the hypolimniom. Only five studies reported a decrease in whole lake O_2 following artificial circulation (Table 1); in these cases, resuspension of bottom detritus probably increased BOD beyond the neutralization capacity of the oxygenation technique. If the hypolimnion was previously anoxic oxygenation will immediately reduce average $PO_4^{\equiv}$ concentration in the deep water and in the lake as a whole by precipitation of Fe^{+++} and Mn^{++} complexes (Fitzgerald 1970; Wirth et al. 1970; Haynes 1971; Weiss and Breedlove 1973; Toetz 1979), although $PO_4^{\equiv}$ may occasionally increase in the upper waters (R.S. Kerr Research Center 1970; Toetz 1979). When aeration is insufficient, e.g. during destratification of Queen Elizabeth II Reservoir by water jets, mixing may result in uniform $PO_4^{\equiv}$ levels throughout the water column without causing a decrease in the lower waters (Ridley et al. 1966).

An effective circulation will immediately reduce concentrations of NH_4^+ in the hypolimnion and throughout the lake, mainly by nitrification of NH_4^+

to NO_3^-, as the latter shows a corresponding rise (Brezonik et al. 1969; Weiss and Breedlove 1973; Toetz 1979).

Formation of an oxidized microzone at the sediment-water interface forms a barrier to the release of dissolved phosphate ions from the decomposing sediments (Mortimer 1941, 1942); hence the term "bottom-sealing" has sometimes been applied to circulation techniques (Shapiro 1979). Recent work (Porcella et al. 1970; Kamp-Nielsen 1974, 1975) indicates that some phosphorus still moves across the interface into the well-oxygenated water, but aerobic muds might still act as a net "sink" for phosphorus (Mortimer 1971; Graetz et al. 1973).

Fast (1971a, 1975, 1979a) questions whether artificial circulation reduces internal loading of phosphorus as has previously been assumed. Although $PO_4^{\equiv}$ concentrations are indeed lowered by destratification, the flux of nutrients from profundal sediments to the overlying water and subsequent uptake by the plant community could actually increase. Under aerobic conditions, the higher temperatures in the sediments after destratification will stimulate decomposition and release of phosphorus to overlying waters (Hargrave 1969, Kamp-Nielsen 1975). Simultaneously, nutrient exchange across the mud-water interface is facilitated by increased flow of water over the sediments and invasion of burrowing macroorganisms which mix the sediments vertically (see below). Although tubificid worms are unimportant in stimulating phosphorus release from sediments (Davis et al. 1975; Gallepp et al. 1978), chironomid larvae do facilitate phosphorus transfer from mud to water, possibly in a density-dependent manner (Porcella et al. 1970; Gallepp et al. 1978). Lastly, it is unlikely that circulation techniques can reduce internal loading of nutrients from sources other than the profundal sediments; e.g. "leakage" from littoral macrophytes (Demarte and Hartman 1974; Lehman and Sandgren 1978).

Even if artificial circulation does reduce phosphorus regeneration from the sediments, significant changes in the biota will occur only if 1) internal loading of nutrients is large relative to input from the watershed and 2) algal growth is limited by phosphorus (Fast 1975). Although the latter appears true in many instances (Likens 1972), Lane and Levins (1977) caution against overreliance on the concept of a single limiting nutrient. Also, lakes with nuisance algal blooms are usually eutrophic and, by definition, experience high external loading. In Mirror Lake, Wisconsin, blooms of Oscillatoria noted by Smith et al. (1975) during the fall 1972 and spring 1973 mixing experiments were probably caused by allochthonous inputs of phosphorus via storm sewers rather than by some direct effect of circulation (Knauer 1975).

In any event, the effects of destratification on the concentrations of dissolved inorganic nutrients in the upper waters of a lake are unpredictable due to interactions with biota and organic factions (Toetz et al. 1972; Fast 1975). For example, aeration of Lake Roberts during June did not prevent a bloom of Anabaena, and total phosphate dropped throughout the lake, probably because of uptake by the algae (R.S. Kerr Research Center 1970; McNall 1971). During July however, aeration was followed by a massive die-off of Anabaena, perhaps due to a period of intense cloud cover and nutrient depletion. A rise in total phosphate accompanied the algal population crash. Artificial circulation often elevates total phosphorus levels by resuspension of organic detritus from the bottom or maintenance of dead cells in suspension (Hooper et al. 1953; Fast 1971a; Haynes 1973; Wirth and Dunst 1967). A fraction of this detritus will be liable to decomposition, and subsequent release of inorganic forms of phosphorus will occur. Robinson et al. (1969) attributed an increase of organic nitrogen in Boltz Lake and Falmouth Lake to release of celluar contents by dead algae as they lysed or broke apart due to mixing. Finally, excretion of phosphorus by zooplankton may be an important recycling mechanism within the epilimnion (Devol 1979).

Biological Mechanisms

An effective destratification often causes a dramatic shift in species composition of the phytoplankton community, from dominance by one or a few species of blue-greens to predominately an assemblage of green algae (Table 2). Fortunately, green algae remain dispersed in the water without forming nuisance "scums" on the surface as many blue-greens do. Moreover, zooplankton readily graze on green algal species, whereas they reject the inedible and sometimes toxic blue-greens or grow poorly on them (Arnold 1971; Porter 1973; Webster and Peters 1978). On the other hand, some gelatinous greens actually profit from passage through the gut of a *Daphnia* (Porter 1975).

King (1970) suggested that blue-green algae dominate the plankton of enriched lakes because of their efficiency in taking up CO_2 at the low ambient concentrations and high pH of these waters. Presumably, their ability to fix nitrogen, regulate vertical position, and avoid being eaten by grazers contribute to the competitive advantage of blue-greens over other algae.

Shapiro (1973; and et al. 1975, 1977) has induced the blue-green to green shift in experimental enclosures by adding CO_2 or HCl, both of which lower the pH of the water. Moreover, addition of NO_3^- and $PO_4^{\equiv}$ facilitates the shift. Since the blue-greens decline precipitously before the greens begin growing rapidly, Shapiro et al. (1975, 1977) suggest that the shift is mediated by the action of cyanophages, viruses specific to blue-green algae (Shilo 1971; Lindmark in Shapiro 1979), rather than by a direct competitive replacement. At high pH, cyanophages are inhibited, but when pH is lowered, they are capable of lysing blue-greens. Indeed, the release of large quantities of $PO_4^{\equiv}$ and NH_3 to the water after the sudden decline of blue-greens in the enclosures suggests that lysis is occurring.

Destratification essentially mimics Shapiro's experimental treatments by adding CO_2 and nutrients to the surface waters through: 1) mixing of hypolimnetic CO_2 and nutrients into the surface layer, 2) recarbonation of waters by atmospheric exchange, and 3) decreasing the ratio of primary production to respiration through deepening of the mixed layer. In experimental enclosures, a change in algal species composition occurs only at pH values less than 8.5, and the results are unpredictable between pH 7.5 and 8.5 (Shapiro et al. 1975, 1977).

Whether or not artificial circulation results in a shift from blue-green algae to green algae apparently depends on the effect of mixing upon pH in the upper waters. Although the results are not clear-cut, lakes where the ratio of green algae to blue-green algae increased following circulation generally showed a decrease in pH, whereas pH stayed the same or increased in mixing experiments that failed to produce the shift to greens or even stimulated growth of blue-green algae (Table 3). Where pH remained high after treatment, perhaps addition of CO_2 through circulation couldn't satisfy algal demands for CO_2 due to stimulation of photosynthesis by recycling of hypolimnetic nutrients (Shapiro et al. 1975).

In Kezar Lake during 1969, mixing caused a temporary rise in pH, but after 20 days of aeration, the pH dropped from 9.0 to 7.1, and at least a small increase in the ratio of greens to blue-greens ensued (N.H.W.S.P.C.C. 1971). Destratification by pumping hypolimnetic water to the surface maintained relatively low pH in the epilimnia of four Ohio lakes and prevented the usual fall blooms of blue-green algae (Irwin et al. 1966).

Although mixing caused a temporary decrease of epilimnetic pH in Ham's Lake (1973 experiment) and Starodworski Lake (Poland), the pH remained above 7.3 in both cases, failing to produce a shift from blue-green algae to green algae (Tables 2 and 3). In Hyrum Reservoir, where aeration caused microstratification and a reduction in mixed depth, pH of the surface waters rose sharply to 9.2 during a bloom of Aphanizomenon (Drury et al. 1975). Partial mixing in Arbuckle Lake, El Capitan Reservoir and Lake Catherine generated little change in pH and no apparent shifts in algal species composition.

EFFECTS OF ARTIFICIAL CIRCULATION ON ZOOPLANKTON AND SPECIES INTERACTIONS IN OPEN WATER

Artificial circulation generally leads to an increase in the abundance of zooplankton and an expansion of their vertical distribution (Table 4) . Several studies reported no effects of mixing on the zooplankton but this result is probably due to inadequate sampling design (Eufaula Reservoir, Bowles 1972), incomplete mixing (Hyrum Reservoir, Drury et al. 1975; Arbuckle Lake, McClintock 1976, Toetz 1977b), or lack of control data (Ham's Lake, Arbuckle Lake, McClintock 1976). Because the data are limited, conclusions expressed below about the effects of artificial circulation on individual zooplankton species must remain tentative.

Depth Distribution

During normal summer stratification, the absence of oxygen in the hypolimnion restricts zooplankton to the upper waters of lakes (Fast 1971b; Heberger and Reynolds 1975; Brynildson and Serns 1977). The onset of low oxygen and high carbon dioxide conditions in the hypolimnion produces an upward displacement of microcrustacea on a seasonal basis (Langford 1938; Heberger and Reynolds 1975). Some zooplankters avoid the hazardous chemical conditions associated with summer stratification by entering a resting stage. For example, Cyclops bicuspidatus thomasi in Lake Erie is

TABLE 3. EPILIMNETIC pH CHANGES ASSOCIATED WITH ARTIFICIAL CIRCULATION

Lake	Reference	Direction of Change	pH Values Before	pH Values After
Group I[a]				
Cline's Pond	Malueg et al. 1971	-	6.2-9.6[c]	6.4-7.2
University Lake	Weiss and Breedlove 1973	-	7.6[d]	7.3,7.0
Kezar Lake	N.H.W.S.P.C.C. 1971 Haynes 1973	1968 -	9.4	6.7
	N.H.W.S.P.C.C. 1971 Haynes 1973	1969 +	6.6	9
Stewart Hollow	Irwin et al. 1966	-	6.8	5.5
	Irwin et al. 1966	-	6.8	6.5
Cladwell Lake	Irwin et al. 1966	0	7.3	7.0-7.5
Pine Lake	Irwin et al. 1966	0	6.9-7.2	6.7-7.1
Vesuvius Lake	Irwin et al. 1966	-	6.8-7.3	6.8-7.0
Buchanan Lake	Brown et al. 1971	-	7.1	6.7
Group II[b]				
Parvin Lake	Lackey 1972	0	6.6-7.2[d]	6.7-7.2
Test Res. I & II	Knoppert et al. 1970	0?	?	>9
Starodworski Lake	Lossow et al. 1975	-	9.0-9.4[d]	7.3-8.6
Lake Calhoun	Shapiro and Pfannkuch 1973	0	8.0-8.5[d]	8.0-8.5
Ham's Lake	Steichen et al. 1974	1973 -	8.5	7.5
	Toetz 1977b	1975 0	>8	>8
Arbuckle Lake	Toetz 1977b	1975 -	7.71[d]	7.39
	Toetz 1979	1977 0	~7.5[d]	~7.5
Lake Catharine	Kothandaraman et al. 1979	0	>8[d]	>8
Hyrum Res.	Drury et al. 1975	±	7.8-8.9[d]	7.2-9.2
El Capitan Res.	Fast 1968	0	7.5-8.6[d]	7.7-8.3

[a] Group I = Lakes in which the ratio of green algae to blue-green algae increased after treatment

[b] Group II = Lakes in which the ratio of green algae to blue-green algae decreased or stayed the same after treatment

[c] Control section

[d] Control year, summer values

TABLE 4. RESPONSES OF ZOOPLANKTON TO ARTIFICIAL CIRCULATION[a]

Lake	Reference	Abundance[b]	Depth Distribution	Ratio Copepods: Cladocerans
Buchanan Lake	Brown et al. 1971	+	+	
Lake Roberts	McNall 1971	+		
Lake Calhoun[e]	Shapiro and Pfannkuch 1973	+	+	-
Stewart Lake	Barnes and Griswold 1975	1974 - 1975 +		
Indian Brook Reservoir	Riddick 1957	+	+	
Mirror Lake	Brynildson and Serns 1977	1973 + 1974 +	+ +	+ -
Parvin Lake	Lackey 1973b	-	+	+
El Capitan Reservoir	Fast 1971b	+	+	
Starodworski Lake[c]	Lossow et al. 1975	+	0	
Eufaula Reservoir[d,e]	Bowles 1972	0	0	0
Ham's Lake[c]	McClintock 1976	0	0	0
Arbuckle Lake[c,e]	McClintock 1976	0	0	0
Hyrum Reservoir[d,e]	Drury et al. 1975	0	0	0

[a] + = increase, - = decrease, 0 = no significant change

[b] Weighted mean density or standing stock

[c] Zooplankton distributed to bottom before mix

[d] Inadequate sampling design or lost samples

[e] Incomplete mix

essentially epibenthic during July; but when oxygen is depleted near the bottom in August, the copepodites encyst and enter a diapause stage (Heberger and Reynolds 1975). This disappearance of C. b. thomasi from the water column is not observed in the other Great Lakes where oxygen remains abundant. Moreover, the relative abundance of C. b. thomasi has increased in Lake Erie over the years since 1929-1930 as oxygen depletion has become a more serious problem (Bradshaw 1964). Aeration should select against species like C. b. thomasi that are tolerant of low oxygen concentrations; unfortunately, too little data exist to test this prediction.

In general, artificial destratification allows zooplankton to redistribute themselves throughout the water column (Table 4), although this may be a passive process for weak swimmers like rotifers and Holopedium (McNaught 1978). Before aeration of El Capitan Reservoir, the zooplankton occupied the upper 10 m, but after 17 days of mixing, 85 percent were found below 10 m (Fast 1971b). At the air release station, however, the upwelling water concentrated zooplankton near the surface where they were fed upon by shad. Lackey (1973b) found that the depth distributions of Cladocera and rotifers were generally unaffected by artificial circulation, but Diaptomus spp. tended to occur in deeper water during the treatment year.

Even in lakes where zooplankton occupy the entire water column before treatment, circulation usually shifts the vertical profile of the population toward lower depths. Although zooplankton were distributed throughout all depths in Ham's Lake before destratification, only 6 percent of the total community was found at 6 m and below (McClintock 1976). During August when mixing was strongest, 42 percent were found at 6 m or below. Lossow et al. (1975) observed a concentration of Daphnia hyalina near the bottom of Starodworski Lake (Poland) following destratification.

Some species with unique distributions, e.g. the cold-water form Daphnia longiremis, are eliminated from lakes at the time of oxygen depletion (Heberger and Reynolds 1975). Artificial aeration should allow such species to persist throughout the summer, unless treatment elevates the water temperature above their upper tolerance limit.

Zooplankton Abundance

In one of the most complete studies to date, Brynildson and Serns (1977) documented a four-fold increase in Daphnia spp. after mixing of Mirror Lake in September, 1974. In an earlier experiment D. pulicaria doubled but D. galeata mendotae decreased by two-thirds, leaving the average density of daphnids about the same as before mixing. During the 1974 experiment, D. pulicaria declined by one-half and was replaced by smaller species, D. g. mendotae and especially D. retrocurva. Total aeration during spring 1973 stimulated early onset of a normal population pulse in D. pulicaria, presumably by supplying oxygen to ephippial eggs lying in mud below 5 m. Although the density of small cladocerans including Bosmina longirostris and Diaphanosoma leuchtenbergianum showed no significant change after circulation, calanoid and cyclopoid copepods increased during both experiments.

During aeration of Starodworski Lake, the relatively large *Daphnia hyalina* appeared for the first time and became especially abundant in lower water (Lossow et al. 1975). *Bosmina longirostris* declined to particularly low densities during summer of the treatment year. In contrast, the larger *B. coregoni*, which is characteristic of lakes with well oxygenated hypolimnia, increased greatly. Predation pressure on *Bosmina* spp. was probably less during aeration since *Chaoborus* larvae declined; *Chaoborus* spp. are significant predators on small zooplankton, including *Bosmina* (cf. Pastorok, in press).

Shapiro et al. (1975) found that the abundance of *Daphnia* spp. increased 5 to 8 times during artificial circulation of Lake Calhoun compared with the previous control year. Moreover, the large-bodied *D. pulex* invaded the lake and became reasonably common after treatment. Other zooplankters, including cyclopoids, *Diaptomus*, *Bosmina* and *Diaphanasoma* showed population increases, although none were as dramatic as the changes in *Daphnia* spp. Although Lackey (1973b) reported a significant decline in the population of *D. schodleri* and Cladocera in general during treatment of Parvin Lake, the control year may have been unusual due to absence of the late summer bloom of *Aphanizomenom flos-aquae* (cf. Lackey 1973a).

Aeration should favor those species which normally cannot tolerate low oxygen concentrations. Heisey and Porter (1977) showed that filtering and respiration rates of *D. g. mendotae* decline linearly with decreasing oxygen over a wide range of concentrations. *D. magna* shows a greater tolerance of low O_2 and its rates are independent of ambient oxygen above 3 mg O_2 per liter. *D. g. mendotae* populations should exhibit a stronger response than *D. magna* following artificial circulation; unfortunately, no studies involved *D. magna*, and the evidence for *D. g. mendotae* is equivocal (e.g. Brynildson and Serns 1977). In general, copepods may be less tolerant of low oxygen conditions than cladocerans are (Heberger and Reynolds 1975; Gannon and Stemberger), although individual species vary widely in their requirements (Heisey and Porter 1977). An increase in the ratio of copepods to cladocerans following artificial circulation could be interpreted as a shift of the community away from species characteristic of eutrophic lakes toward species indicative of oligotrophic lakes (Gannon and Stemberger 1978), but the limited data show variable responses in zooplankton composition (Table 3). Perhaps this ambiguity can be traced to Brooks' (1969) assertion that species composition of zooplanktonic herbivores is mainly controlled by competition for resources among species and especially by the character and intensity of fish predation on the zooplankton (see below).

The growth of zooplankton populations following destratification could be caused by several factors. First, mixing often resuspends organic detritus from the bottom sediments, thus creating additional food resources for filter-feeders, especially Cladocera (Saunders 1972). This effect might be nullified by resuspension of mineral particles which interfere with filtering mechanisms and decrease growth of herbivores. In any event, resuspended detritus would be refractory material, poorly assimilable by zooplankters. Secondly, the shift from blue-green algae to green algae after some mixing treatments (Table 2) furnishes a more edible resource to herbivorous zooplankton. Finally, by bringing oxygen to the bottom waters of a lake, circulation extends the habitat for both zooplankton and plantivorous fishes, distributing them throughout a greater volume (Table 4 and see below for information on fish distribution). Furthermore, the dimly lit bottom waters can serve as a refuge for zooplankton, protecting them from planktivorous fishes which depend on relatively high light levels for efficient feeding (Zaret and Suffern 1976). The reduction in encounter rate between fish and their prey lessons predation pressure on the zooplankton, allowing population growth and invasion of large-bodied forms, especially *Daphnia* (Shapiro et al. 1975; Shapiro 1979; cf. Hrbacek et al. 1961; Andersson et al. 1978; and DeBernardi and Guissani 1978).

In turn, large herbivores such as *Daphnia pulicaria* are more effective grazers of algae than are small zooplankton (Haney 1973; Hrbacek et al. 1978). They also release less phosphorus per unit body weight than the smaller forms do (Bartell and Kitchell 1978). During the year following removal of fish from the Poltruba backwater, Hrbacek et al. (1961) observed a decline in algal populations; although total zooplankton numbers were lower than the previous year, large species (e.g. *Daphnia hyalina*) became dominant in the community. Andersson et al. (1978) found that dense populations of fish in experimental enclosures resulted in low numbers of planktonic cladocerans, high concentrations of chlorophyll, and blooms of blue-green algae. In enclosures without fish, large cladocerans prospered and grazed the phytoplankton down to low levels.

EFFECTS OF ARTIFICIAL CIRCULATION ON BENTHIC MACROINVERTEBRATES

Aeration/circulation of stratified eutrophic lakes has a potential for significantly affecting the benthic faunal communities. During stratification, the profundal benthos of eutrophic reservoirs may be limited due to anoxic conditions and reduced profundal sediments. In such situations, the profundal benthos may be either non-existant or limited to a few highly adapted taxa such as *Chironomus* spp., *Chaoborus* spp. or oligochaetes.

Several recent studies have examined the responses of benthic macroinvertebrate fauna to lake circulation. Most of the case studies involved circulation by diffused air techniques; however, an axial flow pump was used at Ham's Lake.

Destratification of Ham's Lake, using an axial flow pump resulted in measureable changes in the density and structure of macrobenthic communities (Wilhm and McClintock 1978). Three biotic parameters - organism density, diversity and species number - displayed significant correlations with dissolved oxygen concentrations in benthic samples collected at both stratified and destratified sites during 1976. At the stratified sites the dissolved oxygen was less than 0.2 mg/l at the 5-m depth. Benthic samples collected at those locations were dominated by *Chaoborus* (>90 percent of organisms) and had correspondingly low diversities and species number (<4). Species numbers at the 5-m destratified site varied between 8 and 16, with higher diversities and lower percentages of *Chaoborus* than the stratified site.

Aeration of Lake Starodworskie (Poland) resulted in marked changes in the benthic faunal assemblages. Prior to aeration the benthic macrofauna other than *Chaoborus* (mainly Chironomidae and Oligochaeta) were generally confined to depths less than 10 m (Sikorowa 1978). Alternatively, *Chaoborus* were relatively common (1,000-5,000 per m^2) at depths greater than 10 m. After aeration the total densities of profundal macrofauna increased considerably, ranging from 2.5 to 18.0 times the pre-aeration densities, depending upon depth. Littoral densities also increased to about 5 times pre-aeration values. However, species composition changed considerably. By the second year of aeration, *Chaoborus* was only a very minor component of the benthos, displaying a 99 percent reduction of the population. The benthic habitat was occupied primarily by Chironomidae, Oligochaeta, Hydracarinae and Heleidae.

In Lake Catherine installation of a venturi-type aeration device resulted in a partial destratification (Kothandaraman et al. 1979). Based on a limited number of benthic samples it appears that the benthic organism density and number of taxa were elevated near the aerator when compared with a nearby stratified lake or a stratified station in Lake Catherine.

Prior to destratification the profundal zone of El Capitan Reservoir was devoid of benthic macroinvertebrate fauna (Inland Fisheries Branch 1970). The existing benthos was comprised of chironomids, oligochaetes, clams and nematodes which occurred only at depths less than 10 m during the prolonged summer stratification. During two summers of destratification by aeration, the benthic communities colonized the deeper areas of the reservoir. During the first summer of destratification, chironomids occurred to depths of 27 m, although at lower densities than in the littoral zone.

Aeration of University Lake resulted in elevation of the density and taxa number of chironomids (Weiss and Breedlove 1973). The greatest increases over the control year values occurred in profundal areas near the air diffusers. It is not clear whether chironomid assemblages over the entire lake bottom were affected, or if the effects of aeration were confined to profundal areas. The study results were confounded by different nutrient impacts during the control (low runoff) and aeration (high runoff) years. Weiss and Breedlove (1973) also noted the occurrence of high *Chaoborus* densities near the air diffuser during the aeration year; however, there were no quantitative comparisons between control and treatment years.

Destratification of a mesotrophic montane reservoir (Parvin Lake) resulted in no significant changes in the abundances of *Asellus* (Isopoda), *Chaoborus* or *Lumbriculus* (Oligochaeta) (Lackey 1973c). Abundances of the amphipod *Hyalella* increased at the shallow-water station (2 m) during destratification; however, no changes in abundances occurred at the deeper stations. A generalized decline in chironomid abundance was detected at all areas sampled. The decline was most pronounced in the profundal zone (10 m) where average chironomid densities following destratification were only about 2.5 percent of pretreatment values.

A decline in chironomid abundances was also observed at oligotrophic Section Four Lake following aeration (Fast 1971a). Midges emerged from somewhat deeper water during aeration, although in general the depth distribution of benthic fauna was unaffected.

For eutrophic reservoirs the documented responses of benthic communities to lake aeration/circulation have been relatively consistent; i.e. increases in number of taxa, diversity and biomass, expecially in the profundal areas (Table 5) . The only cases of a generalized decline or no change in organism densities were associated with two lakes receiving low nutrient inputs, Parvin Lake and Section Four Lake. Although the hypolimnion of Parvin Lake was normally anoxic during late summer while the deeper areas of Section Four Lake remained oxic, the mechanisms producing declines in chironomid densities may have been similar. Both lakes normally had dominant chironomid assemblages in deep water prior to aeration. For example, although the Parvin Lake hypolimnion was anoxic during late summer, the mean density of organisms in July-August was $325/m^2$. The decline in overall densities may have resulted from increased midge emergence due to the warmer bottom temperatures during lake circulation. In both lakes, the other insect larvae and invertebrates such as Asellus and Hyalella, which were abundant in littoral areas, did not invade the hypolimnion following aeration. Therefore, overall profundal biomass declined.

Four of the five lakes in which Chaoborus formed a significant component of the profundal benthos displayed similar responses, i.e. a general decline in Chaoborus densities following aeration. The exception was Parvin Lake in which Chaoborus densities did not change significantly during aeration. Two of the aerated lakes displayed pronounced changes in Chaoborus during aeration. In Cox Hollow Lake there was an overall decline in Chaoborus associated with replacement of C. punctipennis by C. albatus (Wirth et al. 1970). Prior to aeration Chaoborus was the only profundal macroinvertebrate in Stewart Lake, but following treatment the larvae were almost completely absent, having been replaced by oligochaetes and chironomids (Barnes and Griswold 1975).

C. punctipennis is a commonly encountered chaoborid in stratified eutrophic lakes. This species appears to be highly adapted to co-occurrence with fish by undergoing vertical diel migrations into anoxic bottom strata. Field studies have indicated that the migratory C. punctipennis occurs in lakes with fish while the non-migratory C. americanus is excluded from fish lakes (von Ende 1979). Moreover, introduction of fish predators into lakes has resulted in the virtual elimination of C. americanus and pronounced reductions in the densities of C. trivittatus, a deeper dwelling species (Northcote et al. 1978).

Therefore, the larvae of certain Chaoborus spp. appear to avoid fish predators by occupying dark anoxic waters during the day. Chaoborus then migrate to surface strata at night where they feed and recharge with oxygen under conditions of reduced fish predation.

Oxygenation of deeper waters may also affect the vertical migratory behavior of Chaoborus. In a series of laboratory experiments, LaRow (1970)

TABLE 5. RESPONSES OF BENTHIC MACROINVERTEBRATES TO ARTIFICIAL CIRCULATION

Lake	Reference	Organism density	No. of Species (or diversity)
Ham's Lake	Wilhm and McClintoch 1978	+	+
Starodworskie Lake	Sikorowa 1978	+	+
Lake Catherine	Kothandaraman et al. 1979	+	+
Parvin Lake	Lackey 1973c	varied[b]	0
El Capitan Reservoir	Inland Fisheries Branch 1970	+	+
Cox Hollow Lake	Wirth et al. 1970		+
University Lake	Weiss and Breedlove 1973	+[a]	+[a]
Stewart Lake	Barnes and Griswold 1975		+
Section Four Lake	Fast 1971a	-	

[a] Chironomids only
[b] Chironomids -, others 0

demonstrated that under high oxygen concentrations most Chaoborus larvae (88.2 percent) did not migrate to the surface layers, but remained in the bottom stratum. Under low oxygen conditions a high percentage migrated to the surface stratum after sunset.

The documented distributional characteristics of Chaoborus are consistent with the observed declines in Chaoborus densities during lake aeration. Aeration of bottom strata would remove the anoxic refugia of Chaoborus, thus exposing the species to intense fish predation. Since third and fourth instar Chaoborus are relatively large organisms (6 to 15 mm) they are a preferred food item for zooplanktivorous fish (Northcote et al. 1978; von Ende 1979).

In lakes showing declines in Chaoborus densities during aeration, the profundal areas were occupied by increased densities of other fauna such as oligochaets, chironomids and other insect larvae. Such detritivores responded to the generally rich deposits of organic material by establishing relatively high standing crops. In some cases there was a noticeable decline in the amount of leaf litter in the bottom sediments following extended periods of aeration.

In summary, aeration may not only increase the standing crop of benthic fauna, but may modify the trophic structure of the community by a reduction in zooplankton predators (i.e. Chaoborus) and an increase in benthic detritivores. The increased production of profundal benthos would provide a potential increase in the availability of fish food organisms. Organisms such as chironomid larvae are frequently important food items for a variety of fish species. The high utilization of benthic fauna and the influence of fish predation on prey population densities is indicated in field studies such as Andersson et al. (1978).

EFFECTS OF ARTIFICIAL CIRCULATION ON FISHES

In stratified lakes, fishes may be prevented from utilizing the total potential habitat due to low oxygen levels in the hypolimnion. This may be especially critical for cold-water species such as salmonids which may be compressed into a narrow layer of available metalimnetic habitat by warm water above and anoxic conditions below.

The responses of fishes to lake aeration/circulation techniques have not been intensively studied. However, several case studies are available which have examined depth distribution, survival and growth rates following lake aeration.

Prior to destratification of Mirror Lake, trout and yellow perch were confined to the epilimnion and metalimnion (Brynildson and Serns 1977). During the spring and late summer the maximum depth occurrence of the two fish species was about 5 m and 7 m, respectively, corresponding to a dissolved oxygen level of about 3 to 4 mg/l. After destratification fish were distributed throughout the water column to the maximum depth of 13 m. Trout were essentially evenly distributed while yellow perch occurred from 4 to 13 m.

Total aeration of Mirror Lake in the fall and hypolimnetic aeration in winter also decreased the trout winter-kill as evidenced by the significant angler catch of "carry-over" stocked trout (Brynildson and Serns 1977).

After partial destratification of Lake Arbuckle in late summer, gizzard shad, freshwater drum, white crappie and black bullhead all displayed increased depth distribution when compared with pre-circulation conditions (Gebhart and Summerfelt 1976). In 1975 the total available fish habitat (as defined by the 2 mg/l DO isopleth) was increased from 53 percent of lake volume in August to 99 percent of total volume in September following treatment. It is interesting to note that although freshwater drum and white crappie were essentially confined to the epilimnion and metalimnion during mid-summer, considerable numbers of gizzard shad and black bullhead were collected from the anoxic hypolimnion to a depth of 20 m. Apparently these two species, both of which feed on bottom detritus, were migrating into the hypolimnion for short periods to feed.

Increases in available fish habitat at Lake Arbuckle were generaly associated with faster growth rates in fishes (Gebhart and Clady 1977). This relationship was especially evident in bottom-feeding species such as gizzard shad and channel catfish. The authors indicated that the maximum increases in fish growth rates occur when available habitat is expanded early in the growing season (i.e. May).

In a study of Section Four Lake, Fast (1971a) observed no positive or negative effects on rainbow trout due to aeration. Although the depth distribution was modified in that trout occurred primarily near the bottom during aeration, there appeared to be no other effects of the warmer, isothermal conditions.

A survey of anglers on University Lake indicated that the catch per unit effort (primarily bluegill) increased during aeration (Weiss and Breedlove 1973). Anglers were observed to concentrate near the bubble zone which seemed to act as a fish attractant.

The angler harvest of bluegills at Cox Hollow Lake was also increased during a multi-year aeration project (Wirth et al. 1970). The increased habitat and production of benthic fauna did not result in concommitant increases in the growth of the stunted bluegill population, however.

Aeration of Stewart Lake resulted in a decline ($\sim$30 percent of pre-aeration levels) in the total bluegill population by the second summer of aeration (Barnes and Griswold 1975). Fish mortalities during the initial aeration period may have resulted from lowered dissolved oxygen; however, the overall effect was beneficial to the stunted sunfish and catfish populations. By the second summer of aeration, there was evidence of improved growth rates and condition factors for both fish species.

Aeration of Casitas Reservoir in southern California has allowed the establishment of a year-round trout fishery (Barnett 1975). Although trout are stocked only during cooler ambient temperatures ($<20^{o}C$), the aeration provides habitat adequate for trout survival during the summer (T < 22^{o}C, DO > 5 mg/l). As a result of the multi-year survival, a trophy trout fishery has developed when fish become concentrated in the summer.

Nighttime aeration of Puddingstone Reservoir did not result, however, in the formation of conditions suitable for year-round trout survival (Fast and St. Amant 1971). The lake oxygen concentrations were increased to >6 mg/l throughout the water column but temperature was also elevated to 25.5^{o}C, resulting in conditions unsuitable for trout survival.

At another southern California reservoir (El Capitan) warmwater fish species such as channel catfish and threadfin shad expanded their depth distribution considerably following aeration (Fast 1968). Walleye also increased their depth distribution, although not to the same extent as the other species.

Increased depth distribution of fishes following aeration/circulation was also observed at Lake Calhoun by Shapiro and Pfannkuch (1973). Echo soundings during aeration revealed that yellow perch, bluegill and crappie occupied most of the formerly uninhabited hypolimnion.

Lake aeration/circulation has also been shown to be beneficial as a salmonid management technique by providing rearing habitat for anadromous species and preventing over-winter mortality in ice-covered lakes. Johnson (1966) demonstrated a more than 3X increase in coho salmon smolt migration and survival during a 3-year period of aeration of Erdman Lake. The higher smolt production was attributed to increased available habitat and primary production, but the effect of aeration is unclear because rotenone was applied to the lake just before aeration.

Halsey (1968) has demonstrated that incomplete autumnal turnover and oxygenation may be a cause of winter fish mortalities in ice-covered lakes. Winter mortalities were prevented at Corbett Lake (British Columbia) by a short period of aeration just prior to ice formation. The aeration resulted in sufficient oxygen under the ice, while under natural conditions the low autumnal oxygen concentrations were rapidly depleted during ice cover.

The importance of proper selection of aeration depth and time in preventing winter trout mortalities is exemplified by the studies of Halsey and Macdonald (1971). Fall aeration of Yellow Lake for a period of four days prior to ice formation resulted in overall oxygen concentrations of <3 mg/l, at which time aeration was terminated. The reduced oxygen concentration after aeration resulted in the death of an estimated 5,000 trout.

The most commonly measured parameter in evaluating the effects of aeration/circulation on fish populations is depth distribution. In all cases where depth distribution has been evaluated, fish have been observed to expand their vertical distribution downward in response to lake destratification.

It is generally assumed that the results of expanded habitat following destratification are beneficial to fish populations because of increased food supply and alleviation of crowding into eplimnetic strata during the summer. Of the surveyed studies, those at Lake Arbuckle were probably the most comprehensive in examining fish response. The results at that lake (Gebhart and Clady 1977) did indicate an apparent increased growth of bottom-feeding fishes; however, the results were not apparent in all species and displayed some variance according to year of study. Increased growth was also observed at Stewart Lake (Barnes and Griswold 1975), although the apparent cause was the selective elimination of much of the previously stunted bluegill populations. Therefore, although the stimulation of fish growth and production by aeration/circulation appears to be a conceivable benefit of the technique, it has not been evaluated in most of the past or current projects. It should also be emphasized that fish would generally display a more delayed response to lake aeration than lower trophic levels. Most of the review studies were of limited duration and fish populations may not have reached equilibrium with the modified lake environment. Moreover, some of the lakes contained already stressed populations (e.g. overcrowded and stunted centrarchids) which would be slow to respond to habitat improvements.

An increase in the angler catch rate of game fish was noted in several cases. Increase in fish harvest rate could be due to two quite different responses in the fish populations. The short-term increase in fish catch immediately after aeration may be due to an attraction of fish to the aeration point due to rheotactic response or increased food availability. Anglers generally respond quickly to fish concentrations, with resultant increases in catch rate.

A longer-term benefit to fish catch may be due to increased fish survival during critical periods. This would be especially true for salmonids occurring in eutrophic lakes with ice cover during the winter. In such lakes with severe "winter-kill" problems, the management approach is usually to stock the lake following ice breakup in the spring. With poor multi-year survival the occurrence of large game fish is limited. By aerating the lake during fall and/or winter, mortality rates are reduced, and the potential for fall trout stocking with over-winter survival of large fish exists.

Several of the successful lake circulation projects from a fishery standpoint were located in cooler climatic areas of North America. In warmer areas, the potential benefits for cool-water fisheries (e.g. trout) are more limited. Circulation of the lake in summer will increase the heat budget and may result in adverse water temperatures for maintenance of salmonid fisheries, such as occurred in Puddingstone Reservoir. Localized aeration resulting in only partial destratification could allow for some cooler areas with sufficient DO for trout survival (e.g. Casitas Reservoir); with only partial circulation, however, the potential for other benefits such as water quality changes would be considerably less.

Adverse impacts of aeration/circulation may be associated with lake mixing during stratified conditions when hypolimnetic oxygen depletion has already occurred. Following destratification the oxygen demand associated with sediments and reduced compounds can lower dissolved oxygen in the entire lake to levels which are not adequate to support fish life. Although a dissolved oxygen concentration of at least 5 mg/l would generally be required to maintain good game fish populations (U.S. EPA 1976), fish can survive for short periods at considerably lower oxygen levels. However, if dissolved oxygen concentrations drop below 2 to 3 mg/l considerable mortalities of desirable game species would be expected.

HYPOLIMNETIC AERATION AND OXYGENATION

INTRODUCTION

Hypolimnetic aeration and oxygenation are recently developed methods for adding dissolved oxygen to the bottom waters of a lake without disrupting the normal pattern of thermal stratification. Because these techniques improve water quality without greatly altering the lake's heat budget, they represent a viable alternative to artificial circulation whenever restoration plans specify maintenance of a cold water resource. Since hypolimnetic systems preserve the original pathways for atmospheric exchange, oxygen transfer is mainly confined to the interface between injected bubbles and hypolimnetic water, and oxygenation is slower than with artificial circulation.

The major goals of most programs of hypolimnetic aeration have been to improve water quality and provide new habitat or expand existing habitat for cold-water fishes. Unlike artificial circulation which modifies algal distributions, hyolimnetic aeration has only indirect effects on most phytoplankton populations.

HYPOLIMNETIC AERATION DEVICES AND APPLICATIONS

Fast and Lorenzen (1977) reviewed 21 designs for hypolimnetic aerators and proposed dividing them into the following categories: 1) mechanical agitation, e.g. aeration of withdrawn water onshore by discharge into a splash basin before returning it to the hypolimnion, 2) pure oxygen injection, 3) air injection systems, including a) full air-lift design, which lifts bottom water to the surface in a vertical tube and then returns it to the hypolimnion, b) partial air lift design, which aerates hypolimnetic water without transport to the surface, and c) downflow air injection system, which mechanically pumps water upward and injects air as it is returned to the hypolimnion.

The first reports of hypolimnetic aeration described the mechanical agitation system used at Lake Bret, Switzerland (Mercier and Perret 1949; Mercier and Gay 1954; Mercier 1955). Although the system was relatively inefficient in terms of oxygen dissolution for a given energy input, it successfully elevated oxygen content of the hypolimnion and improved water quality by reducing concentrations of iron and carbon dioxide.

Partial and full air lift systems circulate water within vertical tubes by injecting compressed air at the bottom. As rising air bubbles "lift" hypolimnetic water, oxygenation occurs and waste gases along with some CO_2, H_2S, and NH_3 are vented to the atmosphere. Although the partial air lift systems have greater effluent O_2 concentrations, they aerate less water volume and the total O_2 dissolved is less than with full air lift designs. Most of the energy used to compress the air is "lost" in waste discharge since the air does not expand greatly while it is in contact with the water. The LIMNO system, a partial air lift design, is the most widely used aerator at the present time.

Fast et al. (1976) and Lorenzen and Fast (1977) compared costs of pure O_2 injection by side stream pump (SSP), a partial air lift design (LIMNO), and two full air lift systems. Although the SSP system had a relatively low capital cost, the full air lift design used by Fast (1971a) is the least expensive design considering overall costs of construction, installation and operation; and it is almost twice as efficient as the other systems in terms of energy consumed to dissolve a given amount of oxygen.

The physical characteristics of some lakes and their hypolimnetic aerators are summarized in Table 6. Fast et al. (1976) and Lorenzen and Fast (1977) present methods for estimating the size of a hypolimnetic aerator needed for any site. The steps involved in this process are: 1) estimation of hypolimnetic volume, 2) estimation of oxygen depletion rates in the hypolimnion, 3) estimation of required oxygen input capacity and expected aeration period each year, and 4) selection of an appropriate aeration/oxygenation system based on the foregoing information. In general, the aeration system should be oversized to allow for unpredictable variations in O_2 consumption, hypolimnetic volume, equipment shutdown, or other factors. In addition, intermittent operation of an oversized system may be less costly and more efficient than continuous operation of a smaller system.

EFFECTS OF HYPOLIMNETIC AERATION/OXYGENATION ON WATER QUALITY

The physical and chemical changes associated with hypolimnetic aeration/oxygenation are summarized in Table 6.

Unlike artificial circulation, hypolimnetic aeration generally maintains cold temperatures in the hypolimnion while increasing dissolved O_2. Successful operation of hypolimnetic aerators usually elevates temperatures of the bottom waters by less than $4^{\circ}C$ throughout the summer (Table 6). In the Hemlock Lake experiment, the temperature of the hypolimnion rose more than $2^{\circ}C$ per week, and eventually, the lake destratified early (Fast 1971a). However, this can be attributed to a defect in design of the system, since water leaked through the walls of the vertical tower.

In almost all aeration experiments, O_2 concentration in the hypolimnion increased, from 0 mg/l to as much as 7 mg/l (Lake Waccabuc, Jarlasjon, Larson Lake and Wahnbach Reservoir) or more (Hemlock Lake, Ottoville Quarry). The rise in average O_2 concentration for the whole lake reflects elevation of hypolimnetic values (Table 6). In Mirror Lake and Spruce Run Reservoir, the aerators were undersized, and hypolimnetic O_2 concentrations

TABLE 6. SELECTED LAKES AND THEIR PHYSICAL-CHEMICAL RESPONSE TO HYPOLIMNETIC AERATION

Lake	Location	Reference	Depth (m) Max	Depth (m) Mean	Depth (m) Air	Vol x10^{-6} (m^3)	Area (ha)	Aeration Intensity Q_{air} (m^3/min)	T (°C)	Hypolimnion Response[a] DO	PO_4	TP	NO_3	NH_4	Fe Mn
Lake Waccabuc	New York	Fast et al 1975a Garrell et al 1977	13		13	4 053	53 6	7 93	0	+	- 0		+	-	
Mirror Lake 1972	Wisconsin	Smith et al 1975	13 1	7 6	12.8	0 400	5 3	0 45	+3°	0	-	0	0	0	
Mirror Lake 1973										0	+	+		+	
Larson Lake	Wisconsin	Smith et al. 1975	11 9	4 0	11 9	0.188	4.8	0 45	0	+	-	-		-	
Jarlasjon	Sweden	Bengtsson and Gelin 1975	24	9 3	24	7 8	84	22 8	+1°	+	-	-	+	-	-
Spruce Run Res. 1973	New Jersey	Whipple et al 1975	13.1		12 2			0.15	0	+	0		0	-	-
Spruce Run Res. 1974									0	+	0		0	-	-
Hemlock Lake	Michigan	Fast 1971a	18 6		18 6		1 8	2 8	+2°/wk[b]	+					
Ottoville Quarry	Ohio	Fast et al 1975b Overholtz et al 1975	18		18	0.063	0 73	0 11	+3°	+					
Wahnbach Res	W Germany	Bernhardt 1967, 1974	43	19 2		41 63	214 5	9	+4°	+	-	-	+	-	-

[a] Response parameters DO = dissolved O_2, PO_4 = phosphate, TP = total phosphorus, NO_3 = nitrate, NH_4 - ammonium, Fe = iron, Mn = manganese

Direction of change in hypolimnetic concentration + = increase, - = decrease, 0 = no significant change

[b] Eventual destratification due to water leakage through walls of aerator tower

never rose above 1.7 mg/l and 3 mg/l, respectively. Anoxic zones developed within the metalimnion during treatment of Lake Waccabuc (Garrell et al. 1977), Jarlasjon (Bengtsson and Gelin 1975) and Larson Lake (Smith et al. 1975). If the aerator is undersized, anoxic zones will probably occur above and below the water outfall, as in the 1973 experiment at Spruce Run Reservoir (Whipple et al. 1975). In some cases, a metalimnetic minimum of dissolved O_2 serves as a barrier to fish movements (Bengtsson et al. 1972), whereas in others, it does not (Whipple et al. 1975; Serns 1976)).

Like artificial circulation, hypolimnetic aeration can effectively reduce concentrations of Fe, Mn, H_2S, NH_4^+, CO_2, and other chemicals associated with anoxic conditions (Table 6). In general, a rise in hypolimnetic NO_3^- concentration accompanies the decrease in NH_4^+, suggesting increased nitrification in the oxygen rich waters (Bengtsson and Gilen 1975; Garrell et al. 1977).

Air injection can cause supersaturation of nitrogen gas (N_2) in the hypolimnion relative to surface hydrostatic pressures (also, see above--ARTIFICIAL CIRCULATION). During hypolimnetic aeration of Lake Waccabuc, N_2 concentrations in bottom waters increased from near saturation to 150 percent saturation after 80 days of system operation (Fast et al. 1975a). Even higher levels of N_2 are possible with longer periods of aeration or greater release depths (Fast 1979a, b). At 150 percent saturation, N_2 would have caused a severe die-off of fishes if the hypolimnetic waters had been released to a stream. Within Lake Waccabuc, however, fish may have adjusted their behavior to avoid any potential problems (Fast et al. 1975a).

Aeration effectively reduces hypolimnetic phosphate concentrations (Bernhardt 1974; Smith et al. 1975; Bengtsson and Gilen 1975). In the long term, phosphorus flux from the sediments may be diminished because hypolimnetic aeration creates an oxidized microlayer at the mud-water interface without stimulating decomposition by raising sediment temperatures (e.g. Bengtsson and Gilen 1975).

The overall effectiveness of hypolimnetic aeration in regulating nutrient availability to aquatic plants depends upon the importance of phosphorus regeneration from the sediments relative to influx from the watershed. During the first year of aeration at Lake Waccabuc, phosphorus content of the hypolimnion decreased by about 30 percent; in contrast, phosphorus concentrations increased greatly during the second year of treatment (Garrell et al. 1977). High precipitation during spring and summer of the second year probably facilitated transport of nutrients in septic effluents to the lake. Consequently, external loading swamped the effect of aeration on internal nutrient dynamics (Garrell et al. 1977).

Unlike artificial destratification, hypolimnetic aeration appears to have little effect on pH of the epilimnion (Smith et al. 1975), and no changes in water transparency have been noted. This is not surprising considering the general lack of influence on depth of mixing, sediment resuspension, and epilimnetic algal densities. In some cases, hypolimnetic aeration may affect algal abundance indirectly by modifying species composition and abundance of zooplankton (Fast 1979a; also, see below), but this response requires further documentation.

EFFECTS OF HYPOLIMNETIC AERATION/OXYGENATION ON PLANKTONIC MICROORGANISMS

Because hypolimnetic aeration leaves the normal vertical profiles of most algae intact, any influence on algal densities would probably be mediated by chang in nutrient cycling and shifts in species composition and abundance of zooplankton, benthic fauna, and fish (Fast 1979a). As mentioned above, hypolimnetic aeration may decrease internal loading of phosphorus but the ultimate effect on algae depends on the relative rates of internal versus external loading. In the event that internal loading is important, the greatest effect of aeration on algal standing crop should be observed after natural destratification at a time when hypolimnetic nutrients accumulated in the absence of treatment would normally be recycled. In the long term, control of phosphorus release from the sediments could reduce primary production in some lakes, but much aeration research remains to be done in this area.

Since hypolimnetic aeration has little or no influence on epilimnetic concentrations of CO_2 and pH, changes in species composition comparable to the dramatic shift from blue-green algae to green algae after whole lake mixing have not been observed.

On the other hand, hypolimnetic aeration can cause profound changes in the zooplankton community. After hypolimnetic aeration, changes in food resources for the zooplankton may be less important than with artificial circulation, but responses in the predation regimes are similar. By providing new habitat for both fish and zooplankton, aeration essentially dilutes the populations and reduces the intensity of predator-prey interactions(cf. Fast 1979a; Shapiro 1979). In addition, the dimly lit hypolimnion can serve as a daytime refuge for the large bodied zooplankton that would otherwise be selectively eaten by visually hunting fishes. Thus, a relatively large species, *Daphnia pulex*, invaded Hemlock Lake during hypolimnetic aeration and exhibited a significant population growth of about 88 times its initial density (Fast 1971a). Apparently, *D. pulex* was previously excluded from the lake by intense planktivory in the epilimnion, and the smaller herbivores dominated the zooplankton community. Following treatment, the small bodied cladocerans *Bosmina* and *Diaphanasoma* increased to a lesser extent than *Daphnia*, and the population of the copepod *Diaptomus* remained essentially the same. A combination of competitive pressure from *D. pulex* and predation by *Chaoborus* larvae may have prevented more dramatic responses in these relatively small herbivores. Fast (1971a) reported a significant increase in the abundance of *Chaoborus* spp. following aeration. These insect larvae, which "prefer" small to medium sized prey, remove a considerable portion of the zooplankton standing crop each day (Pastorok, in press).

Without aeration, all zooplankton in Hemlock Lake were limited to shallow water (<11 m) above the zone where O_2 was depleted (Fast 1971a, b). After treatment, *D. pulex* probably exhibited a typical diel migration pattern, remaining in bottom waters during the day to avoid predation and moving up at night to exploit the phytoplankton crop in the epilimnion. Fast (1979a) suggests that the intense grazing activity of D. pulex may have limited phytoplankton populations; but it is difficult to assess the role of nutrient depletion and regeneration in causing the exaggerated oscillation of algal density during the treatment year.

Confer et al. (1974) and Fast et al. (1975b) observed slight increases in hypolimnetic zooplankton densities during aeration/oxygenation of several lakes, but the effect of aeration on zooplankton and algal abundance in Lake Waccabuc was insignificant (Confer et al. 1974). Considering the technical problem of water leakage from the aerator tower during the Hemlock Lake experiment (Fast 1971a), the foregoing conclusions about responses of zooplankton to hypolimnetic aeration must be regarded as tentative.

Although Linder and Mercier (1954) found little change in total zooplankton abundance following hypolimnetic aeration of Lake Bret, the copepods, including Cyclops strenuus, C. leuckarti, and Diaptomus gracilis, were more common during August and September of the treatment year. After becoming rare during cultural eutrophication of the lake, Diaphanasoma brachyurum and the rotifer Notholca longispina increased following treatment; Linder and Mercier (1954) considered these species indicative of a return to oligotrophic conditions. The crustaceans as a whole were distributed closer to the surface of the lake following treatment, possibly because light extinction with depth was greater at that time.

When algae are concentrated in relatively deep water, hypolimnetic aeration can affect the population directly. In Mirror Lake for example, circulation currents produced by a hypolimnetic aerator distributed an Oscillatoria rubescens population throughout the bottom waters; previously, the dense population (1.9 mg/l biomass and 14 mg/l in 1972 and 1973, respectively) occupied a narrow zone at the interface between the metalimnion and the hypolimnion (Smith et al. 1975). Subsequent releases of phosphorus and nitrogen by the algae affected the concentrations of these nutrients in the hypolimnion, and decomposition of dead cells offset any decrease in BOD due to artificial oxygenation (Smith et al. 1975).

EFFECTS OF HYPOLIMNETIC AERATION ON BENTHIC MACROINVERTEBRATES

Only three studies have examined the effects of hypolimnetic aeration on benthic macroinvertebrates.

Although hypolimnetic aeration of Hemlock Lake eventually caused destratification, the water column remained stratified for 10 weeks during treatment, and the changes in benthic fauna illustrate the expected outcomes. During the treatment year, total numbers of benthic organisms almost doubled while biomass decreased slightly compared to the previous control year (Fast 1971a). Chironomids accounted for a large portion of the change, increasing their numbers by 65 percent and their biomass by 52 percent. Chaoborus spp. increased their numbers by 250 percent, although biomass fell by 22 percent probably because of a predation induced shift toward a smaller species. The numbers of oligochaetes were also elevated by treatment, but mayflies and odonates showed no response.

As a result of aeration, the depth distribution of chironomids and Chaoborus spp. shifted toward the profundal zone, especially during late summer. Predation by trout increased in bottom waters as their own depth distribution expanded (see below), and selective removal of large Chaoborus would explain the shift from C. flavicans to C. punctipennis, a smaller species.

In Lake Jarlasjon (Sweden), the benthic fauna did not recolonize the bottom after aeration in spite of improved oxygen levels (Bengtsson and Berggren 1972). However, the bottom of this lake was heavily contaminated by oil.

The relative abundance of benthic species varied greatly between the control arm and an experimental arm of Spruce Run Reservoir; but no effect of aeration could be substantiated because of the difference in morphometric features of the two areas (Whipple et al. 1975).

EFFECTS OF HYPOLIMNETIC AERATION/OXYGENATION ON FISH

Eutrophic lakes usually do not support cold-water fisheries on a sustainable yield basis. During the summer months, epilimnetic temperatures are too high for prolonged survival, and lower waters are generally devoid of oxygen. Although fish do use habitats low in dissolved oxygen, the lower limit for acceptable survival and growth is about 5 mg/l (U.S. EPA 1976). In certain circumstances, some trout may survive in limited refuges of cold oxygenated water, e.g. near incoming streams or cold springs.

Artificial circulation can extend the habitat of warmwater fishes and their food organisms (e.g. Brynildson and Serns 1977), but by raising water temperature it may eliminate any existing habitat for cold-water species. Hypolimnetic aeration maintains cold, oxygenated water capable of supporting salmonid populations. Although few studies have sampled fish populations during hypolimnetic aeration, the data generally show good survival of stocked trout and expansion of existing habitat for natural populations of cold-water fishes (e.g. Fast 1971a, 1973b; Overholtz et al. 1977; Garrell et al. 1978).

During summer of a control year at Hemlock Lake, rainbow trout were limited to the upper 10 m of the lake by anaerobic conditions in the hypolimnion (Fast 1973b). Using a hypolimnetic aerator, Fast raised the dissolved oxygen levels in the bottom waters from 0 mg/l to over 9 mg/l (saturation). As mentioned above, aeration gradually destroyed thermal stratification, but the lake did remain thermally stratified for 10 weeks during treatment. Immediately before aeration, trout occupied depths between the surface and 6 m; but after only 20 days of treatment, the fish were distributed throughout the water column. During the control year, the trout fed almost exclusively on Chaoborus; after aeration, Daphnia pulex and Chaoborus were the most important prey, respectively. Both of these food species undergo extensive vertical migrations, accounting for the wide-ranging distribution of trout. In addition, gradual lowering of water temperatures in the epilimnion by "leakage" across walls of the aerator tower made a greater portion of the lake available to trout.

Hypolimnetic oxygenation of a small quarry (0.73 ha) by Overholtz et al. (1977) resulted in the creation of suitable trout habitat in the hypolimnion during the summer. After oxygenation most trout occurred in the hypolimnion at temperatures less than 20°C and at depths below 4 m. During the same period gizzard shad preferred depths less than 5 m (>12°C), although oxygen concentrations were adequate for survival throughout the water column. During the summer of 1975 hypolimnetic oxygen concentration reached 16 to 20 mg/l (at 8 to 12°C) without apparent adverse effects on trout survival.

Hypolimnetic aeration of Lake Waccabuc resulted in summer utilization of the hypolimnion by rainbow trout, a condition prevented previously by anoxic conditions (Garrell et al. 1978). During a 24-mo period the stocked trout displayed good growth. Stomach content analysis indicated that the fish were feeding primarily on Chaoborus and Chironomidae in the hypolimnion. A few fish stomachs contained organisms representative of the epilimnion, indicating a migration through the low-oxygen metalimnion. Indeed, sonar traces done by Fast et al. (1975a) confirmed that trout were distributed throughout the lake, some having moved into shallower water after being stocked directly into the oxygenated hypolimnion.

In southern lakes, hypolimnetic aeration may create a "two-story" fishery with warm-water species in shallow water and cold-water species in deep water, each species being limited to a portion of the lake by their respective thermal tolerences (Fast 1975, 1979a). In more northern areas, epilimnetic temperatures during summer would be suitable for trout survival, and cold-water fish might be found throughout the lake (e.g. Northcote et al. 1964). During hypolimnetic aeration, a metalimnetic deficit of dissolved oxygen will not necessarily prevent fish movements between upper and lower waters (Serns 1976; Garrell et al. 1978).

SUMMARY

Artificial circulation and hypolimnetic aeration are cost-effective restoration techniques which can solve a variety of problems arising from anoxia in the hypolimnion of a eutrophic lake. The major benefits derived from aeration/circulation are enhancement of water quality for consumptive uses, control of algal blooms, and improvement of recreational fisheries. Although the biological effects of aeration/circulation are notoriously unpredictable in general, some specific benefits are realized quite consistently, e.g. improvement of habitat for fishes. Moreover, the risk of adverse impacts can be minimized by proper application of techniques and further refinements in the design of aeration/circulation systems.

Before making a commitment to a particular management strategy and system design, it is important to evaluate site-specific interactions between biological and chemical components of the lake system, i.e. mechanisms controlling algal populations, BOD levels, and oxygen depletion rates in the hypolimnion. The possible detrimental effects of a properly executed aeration/circulation program are summarized below under adverse impacts. Any undesirable outcomes that can probably be avoided by refinement of technique are listed as technical problems associated with system design and application.

SYSTEM DESIGN AND APPLICATION: TECHNICAL PROBLEMS

A. Artificial Circulation

1. Placement of air release. If the air diffuser is located too far above the lake bottom, an anaerobic zone will persist below the air release depth.

2. Undersizing the system. When the system capacity is undersized with respect to the lake volume and area, an incomplete mix will result. In the case of a Garton pump or similar mechanical device located at the lake surface, the thermocline may be lowered, but an anoxic zone would persist near the lake bottom. If an air diffuser system is undersized, microstratification at the lake surface will encourage algal blooms. With any system, horizontal mixing will be limited in very large lakes when only one device is used.

3. Oversizing the system. If artificial mixing is too vigorous, sediments may be stirred and resuspended in the water column.

4. Oxygen depletion. When a lake is destratified too quickly after a long period of anoxia, mixing of hypolimnetic waters and bottom muds high in BOD into the surface layers may cause O_2 depletion throughout the lake and a fish-kill.

B. Hypolimnetic Aeration

1. Undersized aeration capacity. By underestimating the oxygen consumption rate in the hypolimnion or by overestimating the rate of oxygen dissolution by the system, the aerator may provide insufficient oxygen.

2. Unintentional thermal destratification. Side stream pumping of pure O_2 may mix the lake or cause significant warming of the hypolimnion if the discharge velocity is high. Water leakage through the vertical 'er of a full air lift system will cause similar problems.

Assuming an effective application of techniques, i.e. sufficient oxygenation by hypolimnetic aeration or complete lake mixing in the case of artificial circulation, aeration/circulation will produce some or all of the following benefits and adverse impacts.

BENEFITS

A. Improvement of Water Quality

1. Both artificial circulation and hypolimentic aeration can provide adequate aeration, although circulation does so more rapidly. Either technique minimizes taste, odor and corrosion problems by oxygenating bottom waters, raising their pH and lowering concentrations of reduced compounds. Hypolimnetic aeration maintains a cold water resource as well.

2. Artificial circulation generally reduces the temperature of the surface water and lowers evaporation rates.

3. As long as sediment stirring is avoided, enhancement of water clarity can be expected when aeration/circulation distributes algae throughout all depths and controls blooms.

B. Control of Nuisance Algae

Figure 2 summarizes the mechanisms which may contribute to the beneficial effects of artificial circulation on phytoplankton populations.

1. A shift from blue-green algae to green algae will probably follow artificial circulation when pH declines to 7.5 or below resulting in "activation" of cyanophages. pH changes as hypolimnetic CO_2 is mixed into the surface waters and as algal uptake of CO_2 falls due to a reduction in light availability.

2. The abundance of blue-green algae may also decrease due to disruption of vertical profiles and the potential effects of variations in hydrostatic pressure.

3. The increases of mixed depth and suspended silt will probably induce light limitation of peak algal biomass, especially in deep lakes. However, the prediction of a reduction in algal crop depends on maintenance of a uniform vertical distribution or nearly so; moreover, if algae are limited by nutrients rather than light before treatment, a moderate increase in mixed depth may actually cause greater algal growth. In any event, a given change in mixed depth will usually produce a larger change of algal biomass in eutrophic lakes than in oligotrophic lakes.

4. Artificial circulation stimulates sediment decomposition, resulting in mineralization of organic fractions and consolidation of the sediments. In the long-term, treatment probably reduces internal loading of nutrients by oxygenating hypolimnetic waters and surficial profundal sediments, creating a sink for phosphorus compounds. However, the importance of mixing, sediment composition and decomposition rates in determining nutrient exchange across the mud-water interface demands further investigation.

5. At present, there is no evidence that hypolimnetic aeration will control algal blooms.

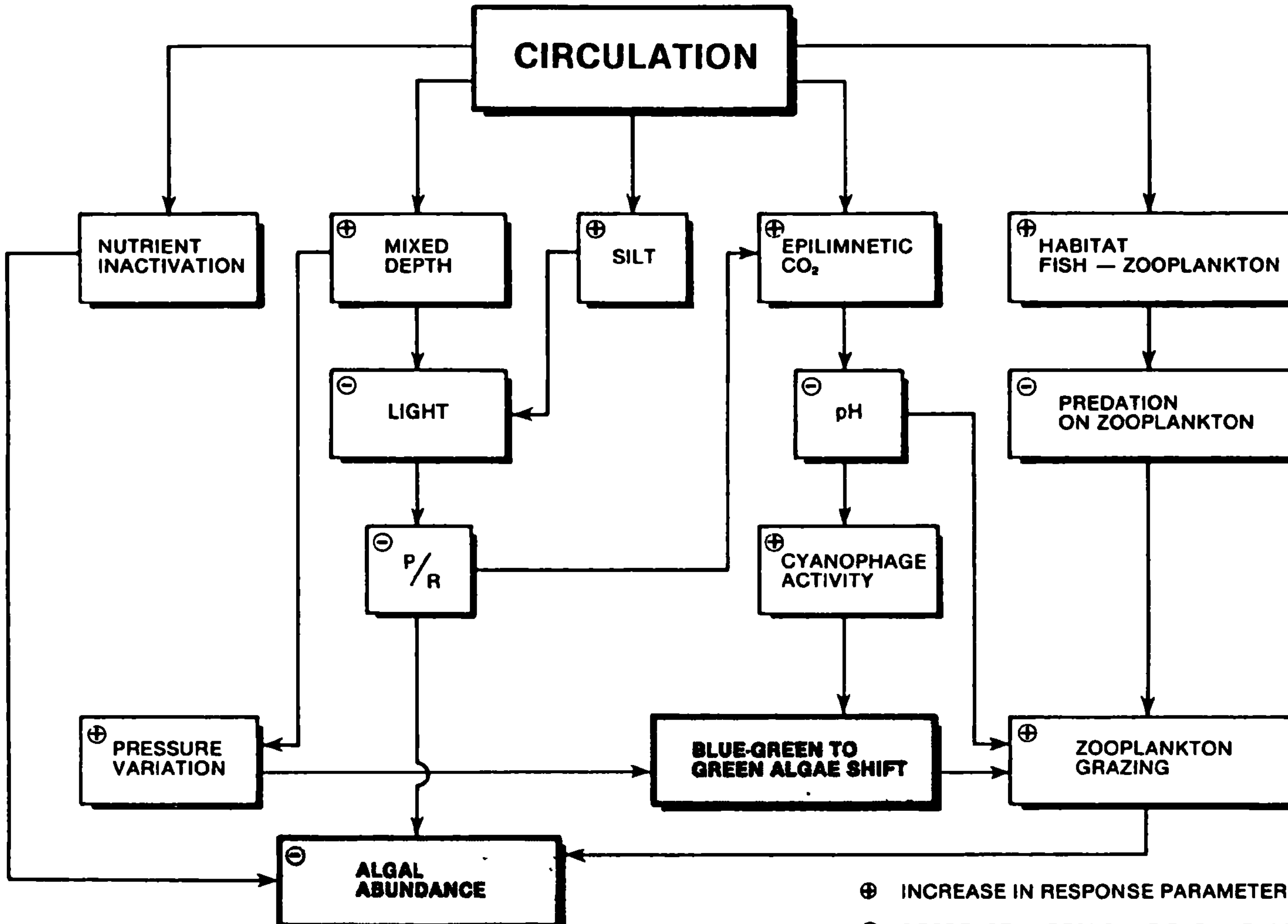

FIGURE 2 BENEFICIAL EFFECTS OF ARTIFICIAL CIRCULATION ON PHYTOPLANKTON (ADAPTED FROM SHAPIRO 1979)

6. Artificial circulation effectively increases the grazing pressure on phytoplankton by shifting the community toward more edible forms and by elevating the abundance of large zooplankton.

7. The relative importance of light, nutrients and grazing in controlling algal biomass will undoubtedly vary among sites; this accounts for some variation in the responses of different communities to treatment.

C. Effects on Benthic Macroinvertebrates

1. Aeration/circulation may produce changes in benthic organisms without corresponding shifts in planktonic biomass and production, e.g. Ham's Lake experiment (1976).

2. The distribution and abundance of benthic macroinvertebrates increases following aeration/circulation. Changes in abundance may be greater after hypolimnetic aeration than they are with circulation because the latter elevates water temperatures, causing rapid turnover of populations and earlier emergence of benthic insects.

3. Aeration/circulation induces a shift in trophic structure of the macroinvertebrate community, with infaunal detritivores (mainly chironomids, oligochaetes) replacing predatory insects (Chaoborus) which exploit zooplankton prey.

D. Improvement of Fisheries

1. Aeration/circulation prevents winter-kill and summer-kill of fishes by alleviating anoxic conditions and eliminating toxic gases.

2. Artificial circulation expands habitat for warmwater fishes. In northern lakes where surface temperatures remain below 22°C throughout the summer, mixing should create or expand habitat for cold-water fishes.

3. Hypolimnetic aeration creates habitat for cold-water fishes and fosters a two-story fishery.

4. By enhancing their habitat and food supply, aeration/circulation has great potential for improving growth of fishes, environmental carrying capacity, and overall yield. However, little evidence exists for these long-term benefits. In addition, an increase in recreational yield may result simply from a change in catch per unit effort due to concentration of fishes near the aeration device.

5. Accrual of maximum fisheries benefits will be achieved by treatment before the development of full stratification.

ADVERSE IMPACTS

A. Water Quality

1. Destratification facilitates a temporary recycling of nutrients by mixing hypolimnetic waters into the trophogenic zone.

2. Artificial circulation may raise suspended silt levels by slowing rates of sedimentation and possibly increasing sediment resuspension. Often, water transparency decreases due to silt load and temporary algal blooms.

3. Hypolimnetic aeration has no known adverse impacts on water quality.

B. Nuisance Algae

Figure 3 summarizes the potential mechanisms producing undesirable changes in phytoplankton communities after artificial circulation/destratification.

1. The recycling of hypolimnetic nutrients and elevation of total posphorus by artificial destratification may stimulate a temporary algal bloom.

2. An immediate dilution of algae following destratification effectively lowers zooplankton filtering rates and the intensity of grazing on phytoplankton. This may cause short-term increases in algal biomass before zooplankton populations grow to post-treatment levels.

3. Decline of algal sinking rates following artificial destratification will favor heavy algae without buoyancy adaptations.

4. A temporary rise in algal biomass following destratification may favor blue-green algae by depleting CO_2 and keeping pH levels high. In turn, the intensity of zooplankton grazing is effectively reduced.

5. The assemblage of blue-green algae and the alternate green algal association represent alternative stable states of the community. Maintenance of blue-green algae following some destratification experiments probably results from initial stimulation of algal growth by nutrient recycling and failure to lower surface pH values.

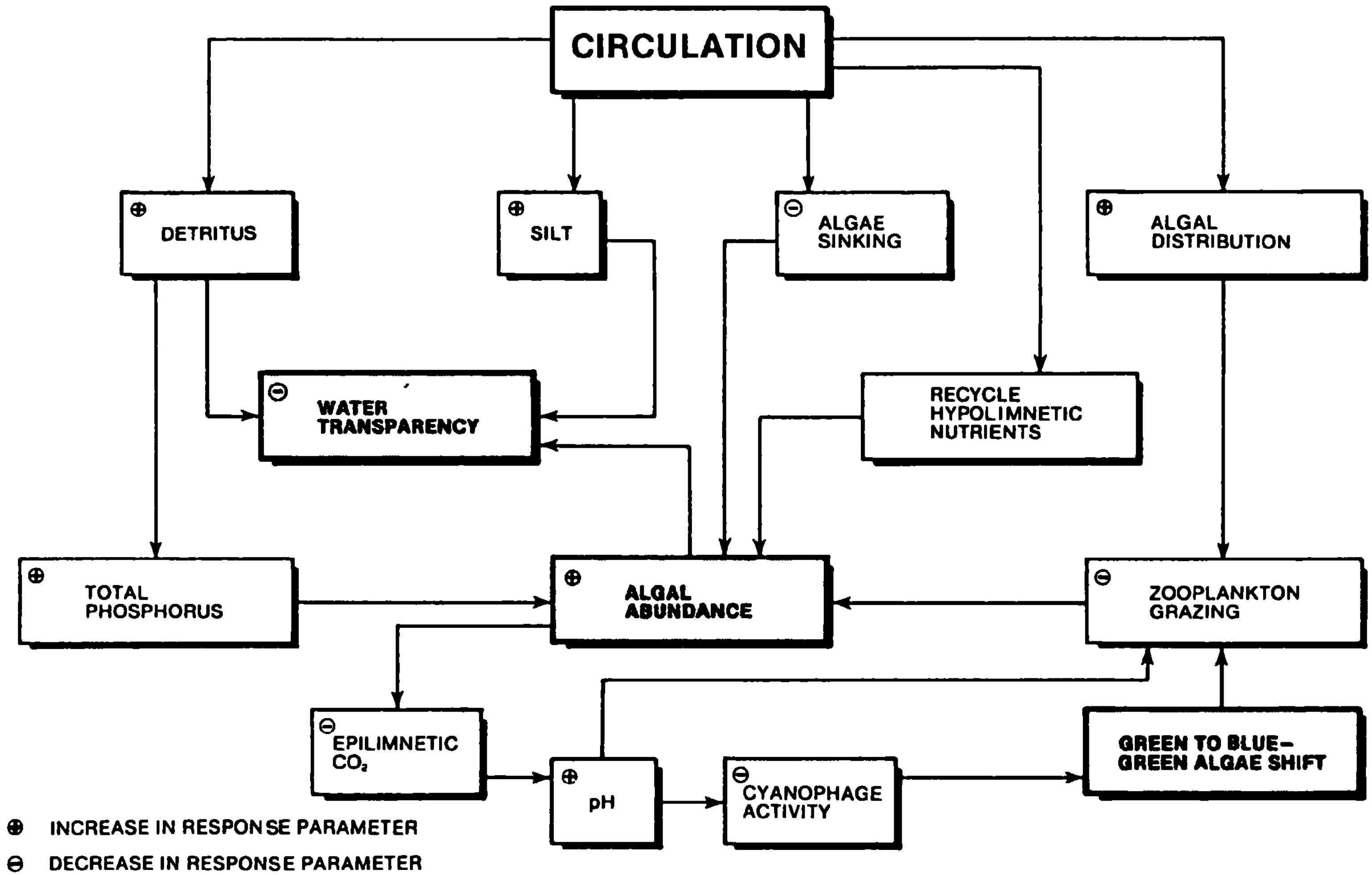

FIGURE 3 SOME ADVERSE IMPACTS OF ARTIFICIAL CIRCULATION AND THEIR ROLE IN PROMOTING BLUE-GREEN ALGAE BLOOMS (ADAPTED FROM SHAPIRO 1979)

C. Macrophytes

1. In lakes with shallow littoral shelves, macrophytes may invade or expand to nuisance levels if water transparency improves following artificial circulation.

D. Fisheries

1. Aeration/circulation may raise N_2 gas concentrations to levels capable of inducing gas bubble disease in fish.
2. Artificial circulation may eliminate habitat for coldwater fishes in southern lakes where metalimnetic populations existed before treatment.
3. Regardless of precautionary measures, artificial destratification involves some risk of extensive oxygen depletion and fish-kills.

RECOMMENDATIONS

A. System Design and Application

1. Aeration/circulation is recommended as an inexpensive, efficient restoration technique, potentially useful for treating the symptoms of eutrophication when alternative management schemes, such as the control of nutrient influx, are deemed too costly or technically unfeasible.
2. Release of compressed air or a mechanical pump will achieve adequate mixing in shallow and moderately deep lakes. However, a combination of a surface pump and a bottom aerator will probably give the best results in very deep lakes, especially where intense surface heating could cause thermal microstratification and associated algal blooms if only air diffussion is used.
3. The full-air lift design is recommended for hypolimnetic aeration because it is the least costly system to construct, install, and operate. In terms of oxygen dissolved per kilowatt-hour, it is almost twice as efficient as other systems. However, each system has unique properties that might be considered relevant for a prospective aeration site. Injection of pure oxygen should be considered as an alternative to aeration when a potential for N_2 supersaturation exists and downstream releases are inevitable.
4. Air diffusers should be located near the lake bottom to avoid development of anoxia in the deepest portion of the lake basin. Diffusers should be oriented such that released air does not stir the surficial sediments directly.
5. Approximately 9.2 m^3/min of air per 10^6 m^2 of lake surface (= 30 SCFM per 10^6 ft^2) is recommended to attain good mixing. Unless

necessary to achieve an adequate mix, more intense aeration should be avoided because of problems resulting from resuspension of bottom sediments.

Hypolimnetic aeration rates should be determined by the method outlined in Lorenzen and Fast (1977).

6. Unless an elevation of algal productivity is desired, artificial circulation techniques should be applied before full development of thermal stratification to avoid post-treatment recycling of nutrients accumulated in the hypolimnion.

7. When the hypolimnion is already anoxic, aeration might be started slowly and gradully intensified to force nutrient precipitation and oxygenation of the bottom layer and avoid mixing high BOD waters into the surface stratum. This might avert possible oxygen depletion throughout the lake and a subsequent fish-kill.

B. Improvement of Water Quality

1. When a cold water supply is needed, and control of algal blooms is not critical, hypolimnetic aeration is recommended. On the other hand, artificial circulation is preferred whenever limitation of algal biomass is desirable, oxygenation of the metalimnion is required, or loss of cool water is acceptable. Although untested, the combination of a hypolimnetic aerator with a mid-water mixing device might be used to lower the themocline and oxygenate the entire lake while maintaining cold bottom water.

2. Either aeration/circulation method is recommended for use by water supply managers seeking to alleviate "taste and odor" problems resulting from high concentrations of Fe, Mn, H_2S and other chemicals which accumulate in the anoxic hypolimnion.

3. When water transparency is a primary amenity, artificial circulation should be applied cautiously to avoid resuspension of bottom sediments (see recommendation A-3 above) and algal blooms (see section C below).

C. Control of Nuisance Algae

Although aeration/circulation techniques cannot be considered a "cure-all" for algal problems, the following recommendations should increase the likelihood of bloom control while reducing the risk of undesirable results.

1. Hypolimnetic aeration should be considered as a method for bloom control only in cases where internal loading of nutrients is high relative to external loading, and blooms occur following natural destratification in autumn or during early spring as a result of prior recycling of hypolimnetic nutrients.

2. Mixing techniques are recommended when the nuisance species is known to be sensitive to disruption of its vertical profile and variable hydrostatic pressures. Usually these are buoyant blue-green algae, such as *Anabaena* spp. and *Oscillatoria* spp., with depth-specific light and nutrient requirements.

3. When a lasting reduction of algal standing crop is desired, an evaluation of limiting mechanisms should preceed treatment (cf. Lorenzen and Mitchell 1975; Lorenzen and Fast 1977). Mixing techniques should be applied only in lakes where algal biomass is limited by low light levels or could be limited by reduced light availability resulting from an increase in mixed depth. Although a temporary reduction in algal biomass and a shift in species composition may follow mixing of a shallow lake, artificial circulation will probably not control total algal growth in shallow lakes.

D. Enhancement of Fisheries

1. Artificial circulation is appropriate for northern lakes where surface waters would remain below 22°C during summer allowing distribution of both cold-water and warm-water fishes throughout the lake.

2. Hypolimnetic aeration is recommended for southern lakes where high water temperatures in the epilimnion and metalimnion along with anoxic conditions in the hypolimnion otherwise preclude establishment of a cold-water fisheries.

3. Hypolimnetic aeration is recommended when improvement of fisheries is the only consideration, e.g. when control of algal blooms is unnecessary.

E. Future Research

1. Observational methods and experimental designs could be greatly improved. Ideally, at least two years of pretreatment data are required for proper evaluation of the effects of any perturbation on biological communities in lakes. Within-lake controls such as large enclosures or unaffected stations are also desirable. Chemical observations should focus on the flux of nutrients between various compartments of the system, especially sediment-water exchange, in addition to standing quantity within each compartment.

2. A team research approach is desirable in assessing the impact of aeration/circulation on lake ecology.

3. Integration of mathematical models predicting peak algal biomass (e.g. Lorenzen and Mitchell 1975) with conceptual models explaining shifts in algal species composition (Shapiro et al. 1975; Shapiro 1979) could form a basis for a priori hypotheses about community responses amenable to experimental testing. A systems analysis approach to lake ecosystems could provide a holistic view necessary to understand the complex response mechanisms operating during aeration/circulation treatment.

4. Long-term responses of lake systems to treatment need to be examined. Organisms with long generation times and slow turnover rates (e.g. fishes) may require up to five years or more to reach equilibrium growth and carrying capacity.

5. A general area requiring additional research concerns how trophic structure and species composition of communities determines responses to aeration/circulation.

6. The possibility that nitrogen supersaturation resulting from aeration could induce gas-bubble disease in fish needs to be investigated further.

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