

Response of Physical and Chemical Parameters to Eliminating Thermal Stratification in a Reservoir

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**RESPONSE OF PHYSICAL AND CHEMICAL PARAMETERS TO ELIMINATING
THERMAL STRATIFICATION IN A RESERVOIR¹**

Robert T. Lackey²

ABSTRACT. The effects of maintaining a 19 ha Colorado montane reservoir in a thermally destratified condition for one year were evaluated. Water temperatures were kept nearly vertically and horizontally isothermal throughout the year. The weighted mean temperature of the lake was 1-4 °C colder in winter and 1-2°C warmer in summer than normal. Deep water in summer was up to 6°C warmer than typical hypolimnion temperatures, but summer surface temperature was unaltered. Without destratification dissolved oxygen depletion develops in summer and winter, but by eliminating stratification, oxygen was kept near saturation throughout the year. Alkalinity, pH, conductivity, and total residue were not significantly affected. Seston decreased which was probably due to declines in planktonic diatom populations. Increases in iron and manganese did not occur in deep water during destratification. Calcium concentrations increased slightly. Magnesium and most anions (chloride, nitrate-N, and silica) were not greatly altered, but sulfate concentration was reduced. Artificial destratification, as a reservoir management tool, will be very useful in altering chemical problems; particularly increasing oxygen and decreasing iron and manganese concentrations. (KEY TERMS: stratification; destratification; recirculation; aeration; compressed air; thermal; reservoir)

INTRODUCTION

Thermal stratification in reservoirs can cause or accentuate many water management problems. Fish mortality, habitat deterioration, limited commercial and domestic water use, lessened recreational use, and high evaporation rates have been directly or indirectly identified with thermal stratification. A number of approaches to solving these problems have been employed, but water quality deterioration caused by thermal stratification is usually difficult to treat. One solution used with increasing frequency is controlling or eliminating thermal stratification.

Fisheries scientists have often attempted aeration of lakes to eliminate fish mortality caused by winter oxygen loss. Results have not been uniformly successful, but Hemphill [1954], Rasmussen [1960], and Halsey [1968], to cite a few, were reasonably successful in preventing winterkill. On the other hand, Patriarche [1961], Woods [1961], and Seaburg [1966] found their attempts unsuccessful with small scale aeration.

Plankton blooms and warm epilimnion water may lessen the aesthetic appeal of lakes. Wirth, Dunst, Uttormark, and Hilsenhoff [1970] demonstrated reduction in plankton blooms

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by eliminating thermal stratification in a popular Wisconsin recreational lake. The opposite approach, increasing primary production, has been attempted by eliminating thermal stratification [Hooper, Ball, and Tanner, 1953, Johnson, 1966]. Both efforts dealt with increasing production of fish by stimulating phytoplankton growth.

Industrial or domestic consumption of water is sometimes limited by thermal stratification. Hydrogen sulfide can build up in the hypolimnion and/or plankton blooms develop in the epilimnion. Derby [1956], Riddick [1957], Nickerson [1961], Koberg and Ford [1965], Bernhardt [1967], and Symons, Carswell and Robeck [1970] reported successful results with lake destratification in solving these kinds of management problems. Evaporation in lakes is a significant management problem in many arid areas of the world [Streiff, 1955]. Koberg and Ford [1965] showed significant reduction in evaporation rate from a California reservoir by cooling surface water with thermal destratification.

The purpose of this paper is to evaluate response of several important physical and chemical parameters to eliminating thermal stratification in a small reservoir throughout the year. Changes in these physical and chemical parameters should provide an indication of potential use of destratification in lake management and water quality improvement.

STUDY AREA

Parvin Lake, Colorado, is a 19 ha mesotrophic reservoir. It was constructed in 1927 and has a maximum depth of 10 m and mean depth of 4.4 m. This dimictic lake is located at an elevation of 2500 m in the Rocky Mountains of northern Colorado and has served as an experimental lake for fishery and limnological research since 1949. Summer surface temperature usually does not exceed 21°C. Oxygen deficiency occurs in the hypolimnion and in deep water in winter. Ice cover lasts from November to April and reaches 20-50 cm thickness.

METHODS

Destratification System

Aerators used during this study were manufactured by the Polcon Corporation, Montreal, Canada. Each aerator consists of a one-piece polyethylene tube 46 cm in diameter containing a helix, which divides the tube into two longitudinal sections. Air is released at the bottom of the aerator through several small holes and upwelling is created by rising water in the tube. Two aerators were used in Parvin Lake. Anchored polyethylene pipe (3.8 cm diameter) connected aerators with a shore-based compressor. Maximum displacement of this compressor was rated at 2.1 m³/min, maximum operating pressure at 4.2 kg/cm², and operating equilibrium pressure at 1.0-1.4 kg/cm². Design, installation, and operation of this destratification system is described more fully by Lackey [1972].

Sampling

A standard sampling program was carried out at five stations (three lake stations and the inlet and outlet) in Parvin Lake during a control year (November, 1968-October, 1969) and a treatment year (November, 1969-October, 1970). During the treatment year the destratification system was in continuous operation. Samples and measurements at each station were taken on a single day near the middle of each month.

Analytical Methods

Physical and chemical parameters were estimated, unless otherwise noted, by standard methods [Amer. Pub. Health Assoc., 1965] at 2 m intervals at lake stations and the inlet and outlet on unfiltered water. Temperatures were taken with an Applied Research Associates Model FT-2 electronic thermometer (1 m intervals). Dissolved oxygen was determined with the Alsterberg modification of the Winkler method. Hydrogen ion concentration was determined with a Beckman Electromate 1009 pH meter. Conductivity was determined at 25°C with a Beckman Model RC-16B2 conductivity bridge. Total residue was estimated by evaporation to constant weight at 100-106°C. An estimate of seston concentration was made by filtration through a Whatman GF/C glass fiber filter [Reed and Reed, 1970]. Cation (calcium, magnesium, iron, and manganese) concentrations were determined on a Perkin-Elmer Model 303 atomic absorption spectrophotometer. All cation samples were preserved in 1% HCl or HNO₃ solution [Fed. Water Pol. Contr. Admin., 1969] and stored for a maximum of 6 months. Anion (chloride, nitrate nitrogen, silica, and sulfate) concentrations were determined by wet chemical techniques. Chloride was estimated with the mercuric nitrate method with pH adjustment to 3.1 [Golterman, 1969]. Nitrate nitrogen was determined by the phenoldisulfonic acid method. Silica was determined with the colorimetric molybdo-silicate method. Sulfate was determined with the turbidimetric method [Fed. Wat. Pol. Contr. Admin., 1969].

RESULTS

Water Temperature

All data were analyzed by weighting the parameter value obtained for each stratum in proportion to that stratum's volume of the total lake volume. Temperature data from the control year (no aeration) are similar to previous years and 1968-69 can be taken as a normal annual temperature cycle (Table 1 and Fig. 1). Stratification during summer months was nearly eliminated during treatment (continuous aeration). Control winter temperatures were up to 3°C different between lake top and bottom, but this difference was completely eliminated during treatment.

Changes in absolute temperatures at certain times of the year were very marked. During ice covered months (November-April), the weighted mean temperature of the lake was 3.7°C during control and 2.0°C during treatment. The opposite relationship (12.0°C vs 12.9°C) developed during months of open water (May-October) and is reflected in the run test ($P < 0.07$). A run test measures the randomness of the order of data and a significant test indicates that high and low data values are probably occurring systematically. These deviations (cooler winter water, warmer summer water) from the typical thermal cycle nearly balanced to yield a treatment annual average temperature of 7.4°C compared to 7.8°C for control year.

During the treatment winter, an ice-free area of 200-300 m diameter was maintained above each aerator. These areas of open water would fluctuate with air temperature and amount of wind, but were rarely less than 200 m in diameter.

Dissolved Oxygen

Weighted lake means (Table 1) and oxygen profiles (Fig. 2) for the control year are similar to past years at Parvin Lake. Mean monthly dissolved oxygen in Parvin Lake during treatment increased significantly. Dissolved oxygen depletion did not develop during treatment year (Fig. 2), but the slight decrease in deep water oxygen content during summer resulted from

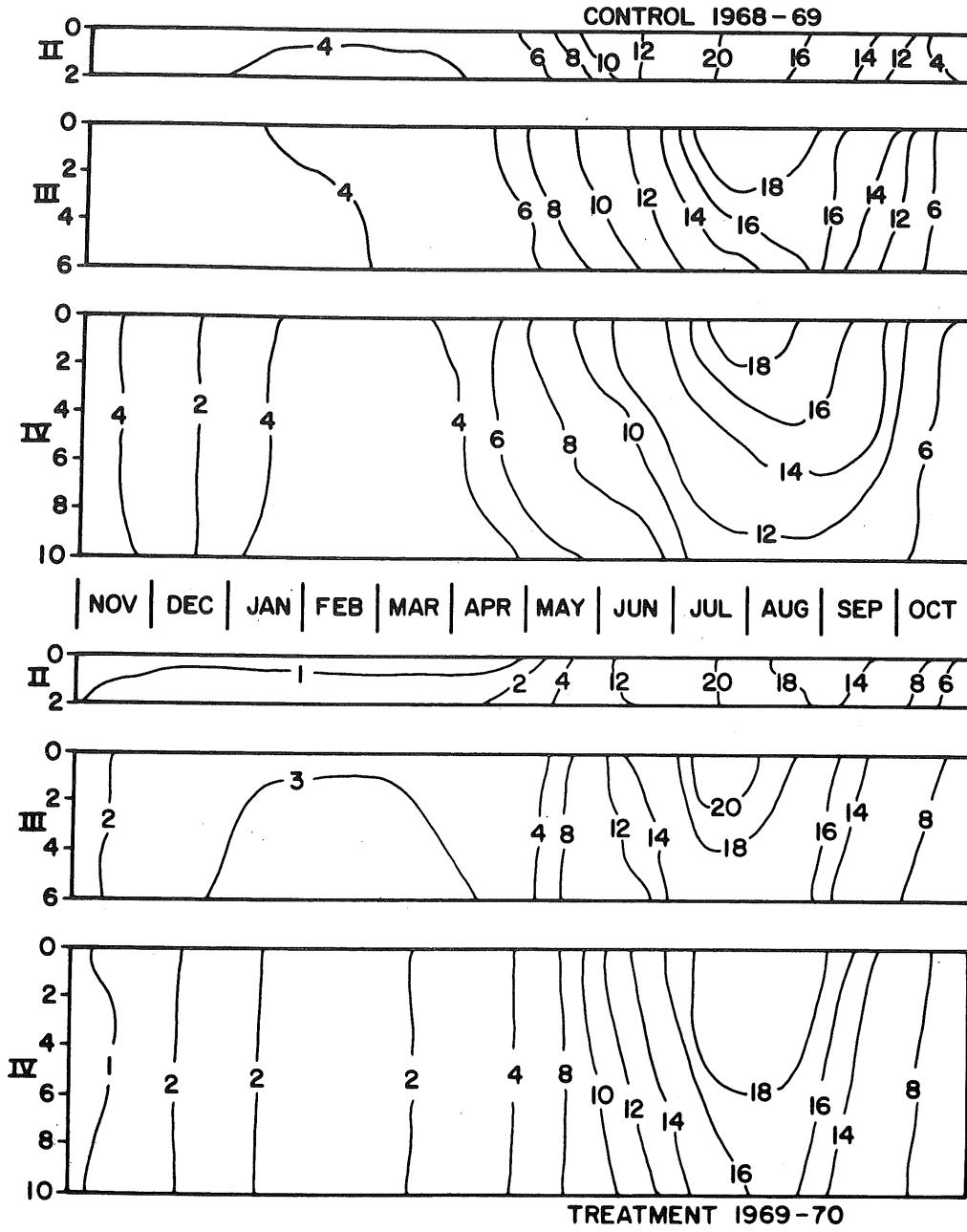


Fig. 1. Water temperature.

TABLE 1. Weighted Lake Means of Physical and Chemical Parameters (Temperature, °C; Dissolved Oxygen, mg/liter; Hydrogen Ion, pH; Alkalinity, mg/liter; Conductivity, micromhos/cm; Total Residue and Seston, mg/liter; Cations and Anions, mg/liter) in Parvin Lake During Control Year (C) and Treatment Year (T)

Parameter	Year	Weighted Mean												P of Run Test	Paired t Test	
		Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.			Mean
Temperature	C	4.0	1.6	4.2	3.6	3.3	5.7	8.8	11.3	16.4	16.6	13.6	5.0	7.8	0.07	0.70
	T	1.5	2.0	2.2	1.9	2.2	1.9	7.5	13.0	12.7	17.8	13.5	7.1	7.4		
Dissolved Oxygen	C	7.1	8.1	5.6	7.3	7.4	9.7	8.2	6.6	6.0	6.4	6.2	8.2	7.3	0.07	2.95*
	T	10.0	9.4	8.7	9.4	9.1	9.5	11.5	7.4	6.3	7.5	6.3	7.1	2.5		
Hydrogen Ion (pH)	C	-	-	6.9	6.9	6.8	7.0	7.2	6.9	6.6	6.9	7.0	6.9	6.9	0.20	0.86
	T	6.8	6.8	7.0	6.9	6.8	7.1	6.8	7.1	6.7	7.2	7.0	7.0	6.9		
Alkalinity	C	-	29.7	30.0	24.8	28.0	24.0	28.4	22.8	23.2	26.0	26.3	25.6	26.3	0.26	0.08
	T	27.2	27.9	29.1	29.2	31.1	30.6	29.0	21.6	20.9	24.1	23.2	23.4	26.4		
Conductivity	C	-	56.4	-	58.5	63.2	63.8	61.1	55.0	20.5	28.4	64.1	61.3	65.2	0.36	0.45
	T	63.4	65.9	70.3	70.7	66.7	68.4	73.0	62.6	52.3	61.5	53.8	56.0	63.7		
Total Residue	C	54.4	56.4	-	58.8	61.2	58.8	34.1	60.4	57.2	61.8	31.3	44.0	57.1	0.91	0.76
	T	48.7	61.2	78.0	66.2	60.4	65.3	68.2	68.8	58.5	52.6	54.8	50.1	61.1		
Seston	C	-	1.9	2.6	-	5.7	5.5	4.4	2.8	1.4	3.8	2.8	1.9	3.3	0.52	3.12*
	T	1.2	1.2	1.5	1.4	0.8	2.5	3.5	2.5	0.7	1.2	2.9	0.7	1.7		
Cations	C	6.5	6.9	7.0	7.0	6.6	6.6	6.5	6.3	5.8	6.7	6.5	6.4	6.6	0.91	3.85**
	T	7.0	7.1	7.7	7.2	7.3	7.5	7.5	6.5	6.0	7.7	6.3	6.4	7.0		
Calcium	C	1.7	1.8	1.8	1.8	1.6	1.8	1.9	1.6	1.6	1.8	1.8	1.8	1.8	0.02	1.49
	T	1.9	2.0	2.1	2.0	2.1	2.2	1.9	1.6	1.6	1.7	1.6	1.6	1.8		
Magnesium	C	.83	.87	.96	.99	1.05	.77	.57	.48	.54	.72	.86	.60	.77	0.07	5.39**
	T	.69	.62	.62	.50	.42	.47	.59	.35	.47	.61	.32	.29	.48		
Iron	C	0.1	0.0	0.1	0.0	0.1	0.0	0.0	0.0	0.0	0.1	0.1	0.0	0.0	---	2.85*
	T	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0		
Manganese	C	0.7	1.2	1.2	-	0.7	0.7	1.1	1.1	0.3	0.7	0.7	0.9	0.8	0.52	0.74
	T	0.8	1.0	1.0	1.1	0.8	1.2	1.5	0.8	0.7	0.9	0.5	0.8	0.9		
Anions	C	0.4	0.5	0.4	-	1.0	0.4	0.4	0.6	0.3	0.2	0.2	0.2	0.4	0.88	1.57
	T	0.2	0.2	0.0	0.1	0.1	0.2	0.2	0.2	0.2	0.2	0.6	0.6	0.2		
Nitrate-N	C	11.3	10.5	10.4	8.3	9.9	6.8	7.9	11.2	13.6	13.0	10.8	11.5	10.4	0.18	1.84
	T	12.5	12.0	12.8	11.2	15.8	13.3	11.0	10.5	9.6	11.0	13.5	11.3	12.0		
Silica	C	4	4	4	9	5	6	6	6	3	3	3	3	5	0.28	4.86**
	T	3	3	3	3	3	4	4	0	0	2	1	0	2		
Sulfate	C	4	4	4	9	5	6	6	6	3	3	3	3	5	0.28	4.86**
	T	3	3	3	3	3	4	4	0	0	2	1	0	2		

* Significant at $\alpha = 0.05$.
 ** Significant at $\alpha = 0.01$.

minor thermal gradients hindering circulation. Greatest increases in oxygen concentration were during winter (run test, $P < 0.07$).

Cations

Calcium did not follow a definite annual cycle in either control or treatment year, but the treatment year was consistently higher (Table 1). The mean increase was, however, only 0.4 mg/liter. Vertical stratification or horizontal gradients were not observed for calcium. Magnesium exhibited little annual variation in control or treatment years except that winter changes were generally increases and summer changes decreases (run test, $P < 0.02$). Vertical stratification or horizontal gradients were not observed.

Iron normally follows a definite seasonal cycle in Parvin Lake with deep water increases in winter and summer (Table 1). Winter weighted means are highest and reach a maximum in March. Iron remains fairly low during spring and early summer, but rises somewhat in late summer. Weighted means in the treatment year did not follow such a pronounced cycle, although concentrations were highest in winter. There was significantly less iron in the

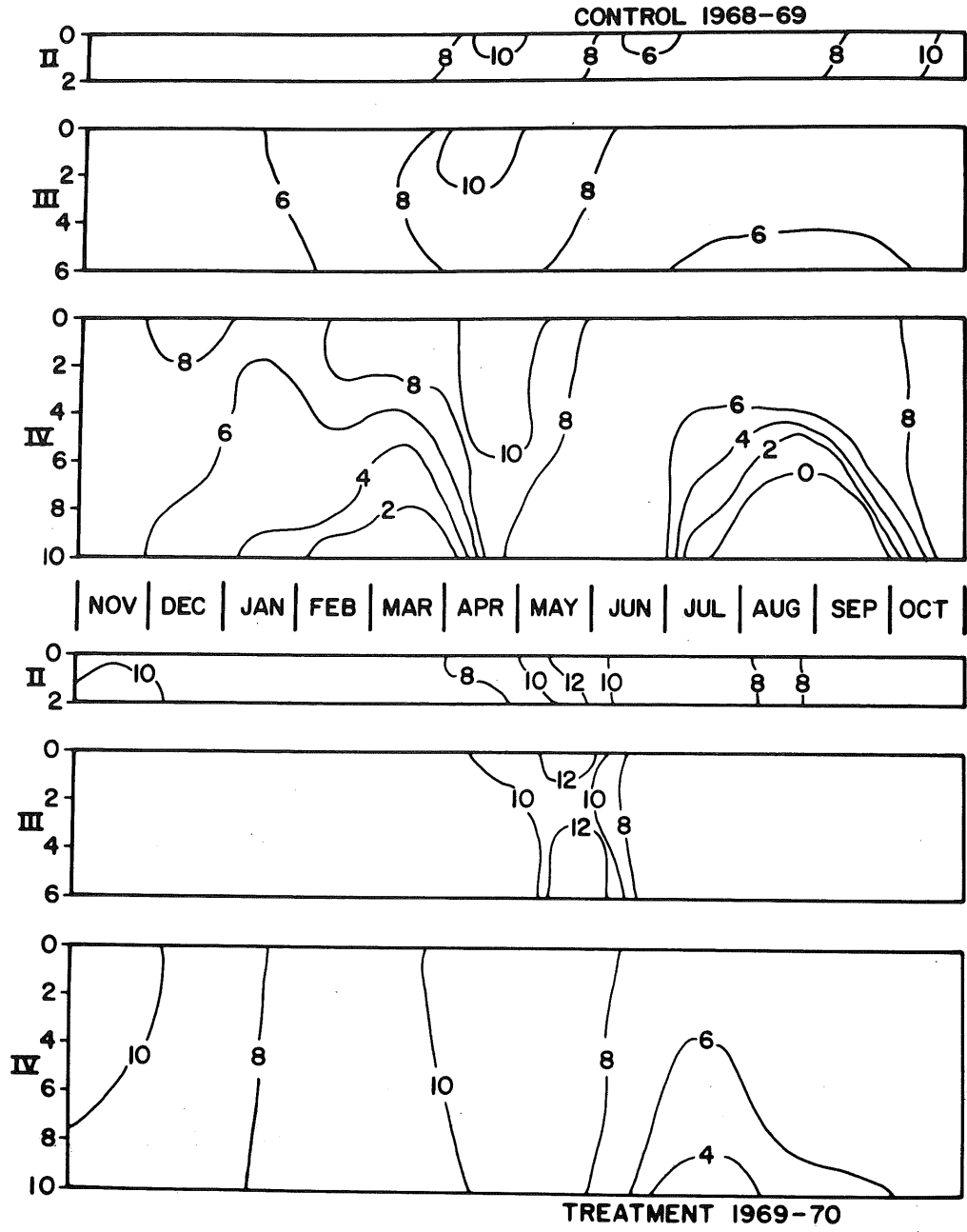


Fig. 2. Dissolved oxygen.

treatment year. Vertical stratification of iron was pronounced (Fig. 3). During the control year, iron increased in deep water during both winter and summer. Only a slight increase in iron was detected in deep water during winter and summer of the treatment year.

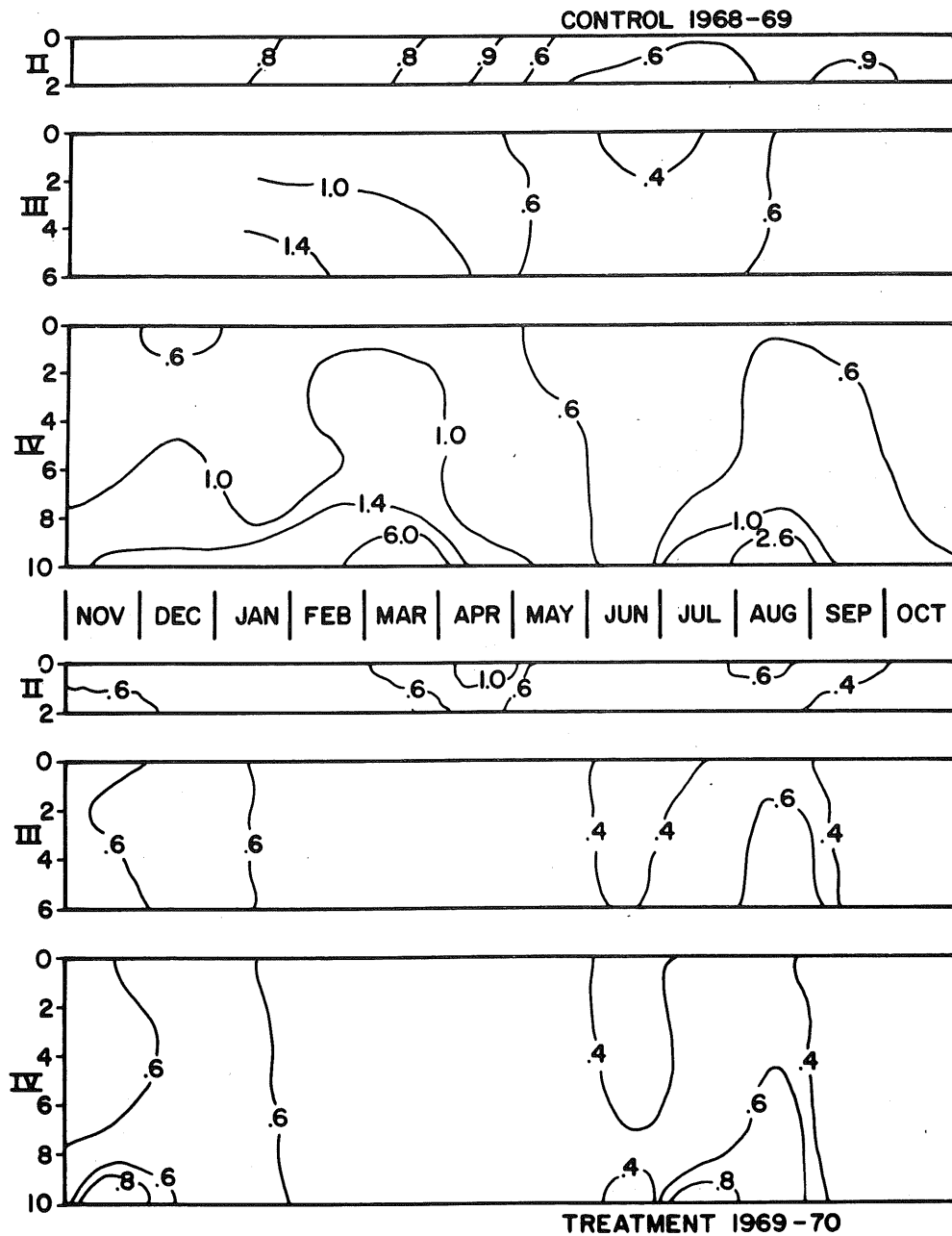


Fig. 3. Iron.

Manganese in Parvin Lake was detectable only during summer and winter during the control year and rarely during the treatment year and was significantly lower during treatment (Table 1). The most pronounced increases occurred in deep water in winter and summer of the control year. Concentrations reached 0.9 mg/liter at 10 m in March and 0.8 mg/liter at 10 m in August.

Anions

Chloride followed no clear annual pattern in either year and vertical stratification or horizontal gradients were not observed (Table 1). Nitrate nitrogen concentration during treatment was slightly lower than those during control, but there was much variability within a given month and no indication of vertical or horizontal gradients. During the control year silica concentration was low during late winter and higher and fairly uniform during the other seasons. During the treatment year, silica was at fairly high levels all year. Silica was much more stratified during the control year than during the treatment year (Fig. 4). Lower concentrations tended to be uppermost in the water column, but with little horizontal gradients. Within month sulfate concentrations were highly variable and followed no clear vertical or horizontal distribution pattern. Concentrations during the treatment year were lower than during control year, which was probably due to decreased sulfate concentration of inflow water during the treatment year. Seasonal differences were not appreciable in either year except for lower concentrations in summer and early autumn during treatment.

Other Parameters

Hydrogen ion concentration varied little (pH range: 6.5-7.5) in either year (Table 1). Vertical gradients did not develop nor was a seasonal cycle apparent. The annual alkalinity cycle generally showed higher levels in winter than summer and both years followed a similar pattern. Conductivity showed little difference between control and treatment years except for slightly higher treatment winter values and lower summer values. The range of conductivity during control year was 53-102 micromhos/cm and during treatment, 51-84 micromhos/cm with vertical stratification apparent only during July and August of the control year. Horizontal conductivity gradients sometimes developed and were associated with higher concentration near the inlet. Variations in total residue were large in both years (control: 21-117 mg/liter; treatment: 37-012 mg/liter), but weighted lake means were similar. Vertical stratification and horizontal gradients were not observed in either year. Seston concentration significantly decreased. Within month variation was great, but most concentrations were between 0 and 4 mg/liter with no evidence of horizontal gradients.

DISCUSSION

Deep water in summer in Parvin Lake during destratification was markedly (4-6°C) warmer than typical for Parvin Lake. This phenomenon will likely develop in an artificially destratified lake. The metalimnion normally insulates hypolimnion water from warming taking place at the air-water interface. The importance, if any, of a warmer hypolimnion can only be inferred, but effects on biological processes may be very important. Species adapted to certain temperature regimes may be displaced by other species.

Summer surface water temperatures during Parvin Lake destratification were not changed, but most destratification studies have shown a slight decline in surface water temperatures [Koberg and Ford, 1965; Irwin, Symons, and Robeck, 1968; Fraser and Halsey, 1969].

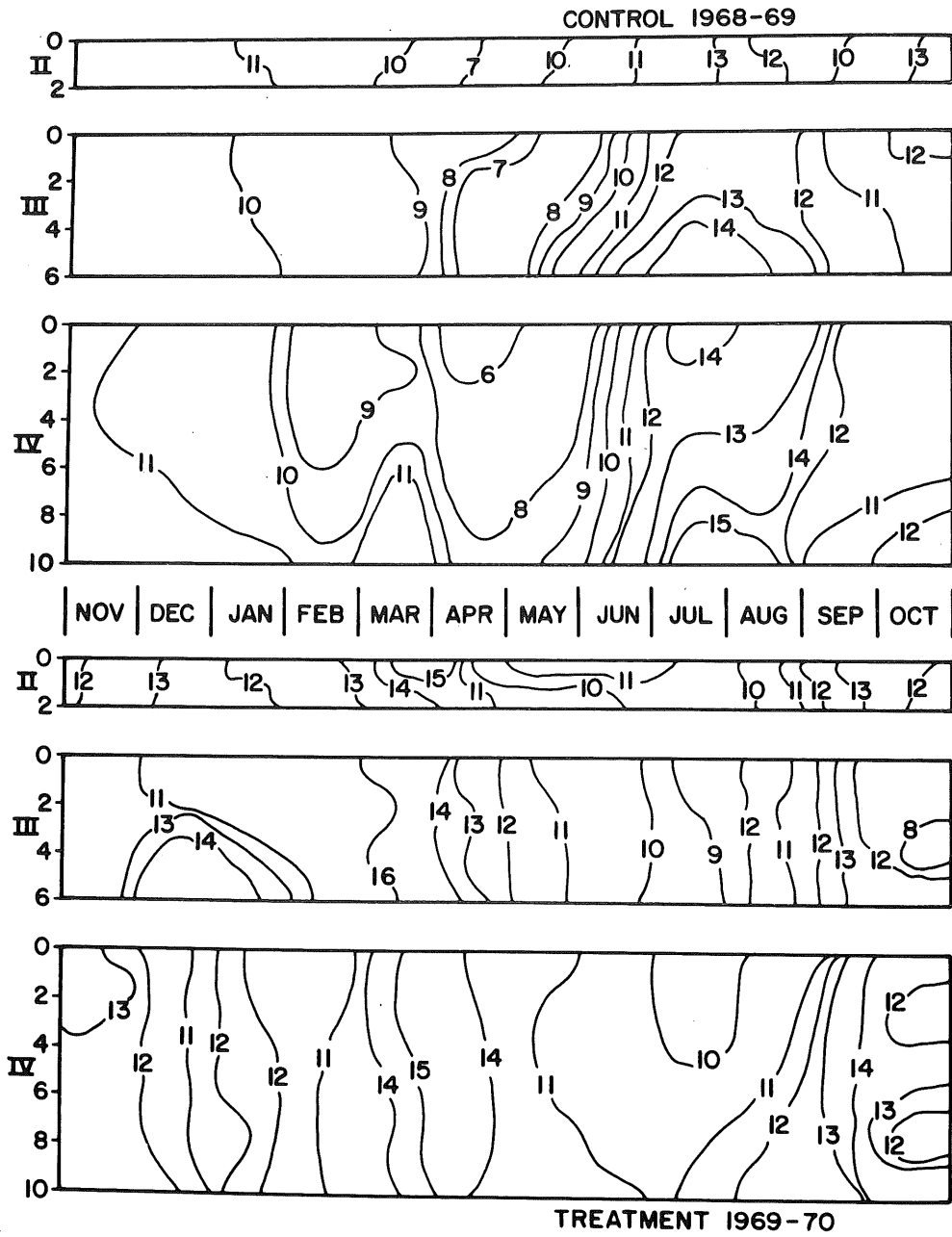


Fig. 4. Silica.

Operation of these destratification systems was limited to summer. When a highly stratified lake is quickly destratified, mixing tends to equalize temperature difference between epilimnion and hypolimnion. In Parvin Lake, however, stratification did not develop during the treatment year and the entire water mass was perpetually circulated. Streiff [1955] and others have reviewed the benefits of lowering surface water temperatures by reducing thermal stratification. In reservoirs with a large portion of relatively deep water, surface water temperature reduction is possible. Constant circulation of most reservoirs will probably not affect summer surface temperature greatly.

Winter water temperatures during destratification were lower than normally found in Parvin Lake and this result is typical in artificially destratified lakes [Schmitz and Hasler, 1958; Patriarche, 1961; Wirth, Dunst, Uttormark, and Hilsenhoff, 1970]. Lowering of winter water temperature is due to continued cooling at the air-water interface, when ice cover normally provides a degree of insulation.

Oxygen concentration during summer in Parvin Lake during forced circulation remained near saturation except for slight decreases in deep water. Maintenance of high concentrations of dissolved oxygen in mesotrophic and eutrophic lakes is very sensitive to thermal stratification and decreases in oxygen develop with slight thermal stratification. Other destratification projects have been able to maintain high summer dissolved oxygen concentrations by continuous mixing, but rapid oxygen loss takes place when aeration is curtailed [Koberg and Ford, 1965; Irwin, Symons, and Robeck, 1968; Wirth, Dunst, Uttormark, and Hilsenhoff, 1970]. From a water management standpoint, this means that during summer, constant or at least frequent operation of a destratification system is needed. Developing a substantial reserve of dissolved oxygen by aeration for either summer or winter is not promising.

Calcium concentration in Parvin Lake was slightly higher during the destratification year, but annual cycles, vertical gradients, or horizontal differences were not observed. Increased calcium concentration is not readily explained because forced circulation might be expected to keep more material suspended and result in increased calcium concentrations. Total residue did not increase and seston actually decreased during forced circulation. Further, treatment year inflow water generally contained less calcium than the control year.

Maintaining high dissolved oxygen concentration in deep water during winter and summer had important effects on chemical equilibria in Parvin Lake. Iron normally follows an annual cycle with distinct increases in deep water in winter and summer but destratification eliminated these increases. Iron decrease in lake water has been clearly correlated with oxygen depletion [Strum and Lee, 1960]. This was the situation in Parvin Lake where relatively abundant dissolved oxygen kept iron concentrations low. Such a decrease in deep water iron in summer during destratification has been observed and may be one of the most important uses of aeration in water management [Riddick, 1957; Wirth, Dunst, Uttormark, and Hilsenhoff, 1970; Irwin, Symons, and Robeck, 1968].

Manganese followed the same annual pattern as iron and destratification nearly eliminated manganese in winter and summer deep water. Eliminating reducing conditions at the mud-water interface in Parvin Lake prevented manganese from going into solution. Reduction of manganese in summer during destratification has been observed by Bernhardt [1967], Irwin, Symons, and Robeck [1968], Fast [1968], and Brezonik, Delfino, and Lee [1969]. However, Brezonik, Delfino, and Lee [1969] found a slight buildup of manganese in winter during destratification.

Parvin Lake, like most reservoirs, is very effectively buffered as an aquatic environment. Hydrogen ion concentration was very insensitive to artificial destratification and did not show a seasonal cycle during either year. Other research [Koberg and Ford, 1965] found little pH

change during summer under destratified conditions. Irwin, Symons, Robeck [1968], however, found that surface pH during summer months declined, but pH in deep water was unaffected. Evidence of buffering in Parvin Lake was also found in the behavior of alkalinity on which destratification had little or no effect.

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