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THE CAUSE(S) OF CONTINUED HYPOLIMNETIC ANOXIA IN LONG LAKE, WASHINGTON FOLLOWING ADVANCED WASTEWATER TREATMENT BY THE CITY OF SPOKANE

FINAL PROGRESS REPORT

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State of Washington
John Spellman
Governor

Department of Ecology
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ABSTRACT

Long Lake is an impoundment of the Spokane River downstream from Spokane, Wa. Prior to 1978, the reservoir was characterized by excessive summer algae growth, limited water clarity and extensive hypolimnetic anoxia.

Advanced wastewater treatment (AWT) by Spokane's sewage treatment plant began in the fall of 1977. Advanced treatment included at least 85 percent biochemical oxygen demand (B.O.D.) removal, 90 percent suspended solids removal and 85 percent phosphorus removal.

Investigations during post-AWT years (1978-1981) have shown significant reductions in phosphorus loading with corresponding declines in chlorophyll a, phytoplankton biovolume, primary productivity and increased water clarity. However, anoxia has continued to exist although the degree of anoxia has been considerably less.

The purpose of this study was to determine the cause(s) of continued hypolimnetic anoxia in Long Lake with AWT in operation. Biochemical oxygen demand, chemical oxygen demand (C.O.D.) and sediment oxygen demand (S.O.D.) were determined. Sediment oxygen demand was measured under stationary and dynamic conditions with a Gilson Differential Respirometer. In addition, the areal hypolimnetic oxygen demand (AHOD) for all study years (1972-1981) was determined. Chlorophyll a concentrations, phytoplankton biovolume, primary productivity and Secchi disk visibility were used as measures of phytoplankton standing crop.

The AHOD calculated for 1981 was less than those calculated for previous study years. Post-AWT mean AHOD was significantly less than pre-AWT mean AHOD. Chlorophyll a, phytoplankton biovolume and primary productivity were correlated with AHOD on a volume and areal basis. Reservoir and hypolimnetic B.O.D. and C.O.D. were considerably greater than influent B.O.D. and C.O.D. Correlations were found between chlorophyll a, phytoplankton biovolume and primary productivity versus B.O.D. and S.O.D.

The phytoplankton standing crop in Long Lake does affect oxygen demand both within the water column and at the sediment-water interface, and is a primary factor in the seasonal decline of dissolved oxygen levels in Long Lake.

INTRODUCTION

Long Lake is an impoundment of the Spokane River downstream from the City of Spokane, Washington. Prior to 1978 the reservoir was characterized by excessive summer algae growth, limited water clarity and extensive hypolimnetic anoxia (Soltero et al., 1973; 1974; 1975; 1976; 1978). At the height of stagnation, anoxia was evident in approximately the lower 25 km of reservoir and extended from the 15m depth to the bottom (up to 40% of the reservoir's volume could be anoxic, Soltero et al., 1974).

Advanced wastewater treatment (AWT) by the City of Spokane's sewage treatment plant went "on line" in the fall of 1977. Advanced treatment was defined as 85 percent or better biochemical oxygen demand removal, 90 percent or more suspended solids removal and 85 percent or greater phosphorus removal.

Investigations during post-AWT years (Soltero et al., 1979, 1980; 1981) have shown considerable decrease in phosphorus loading with corresponding declines in chlorophyll a, phytoplankton biovolume, primary productivity and increased water clarity. However, anoxia has continued to exist, although the degree of anoxia has been considerably less.

Cunningham and Pine (1969) and Soltero et al. (1974) attributed phytoplankton decomposition as the cause of oxygen depletion prior to AWT. The purpose of this study was to determine the cause(s) of continued hypolimnetic anoxia in Long Lake with AWT in operation.

DESCRIPTION OF STUDY AREA

Sampling stations were established on the Spokane River and its tributaries at the following locations (Fig. 1A):

Hangman Creek (H.C.)--lat. 47°39'10", long. 117°26'55", in NW¼ Sec. 24, T. 25N, R. 42E., Spokane County, at river km 1.3.

Spokane River, Fort Wright Bridge (F.W.)--lat. 47°40'50", long. 117°27'00", in NE¼ Sec. 11, T. 25N., R. 42E., Spokane County at river km 112.5.

Sewage Effluent, Spokane Advanced Wastewater Treatment Plant (S.E.)--lat. 47°41'40", long. 117°28'30", in NE¼ Sec. 3, T. 25N, R. 42E., Spokane County.

Spokane River, Nine Mile Dam (N.M.)--lat. 47°46'29", long. 117°32'35", in SE¼ Sec. 6, T. 26N., R. 42E., Spokane County, off left bank below Nine Mile powerhouse and at river km 93.2.

Little Spokane River (L.S.R.)--lat. 47°47'00", long. 117°31'44", in SE¼, NW¼ Sec. 5, T. 26N., R. 42E., Spokane County, at county road bridge and at river km 1.8.

Spokane River, Long Lake Dam (DAM)--lat. 47°50'12", long. 117°50'25", in NW¼, SW¼ Sec. 13, T. 27N., R 39E, Lincoln County, off left bank below Long Lake powerhouse and at river km 54.5.

Five sampling stations were established on the reservoir (Fig. 1B). Station 0 was located just behind the dam with the remaining stations located at approximately 8 km intervals up the reservoir for 32 km to station 4.

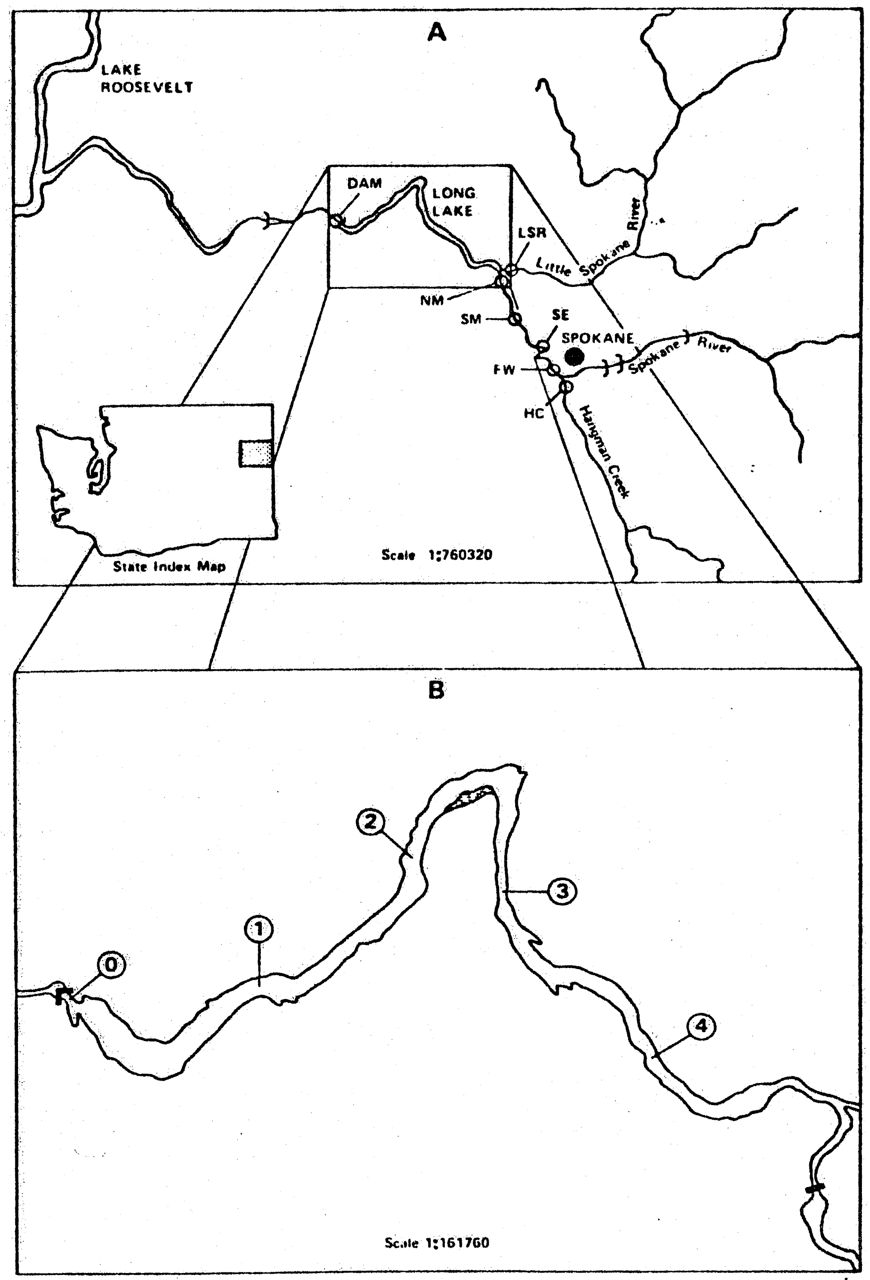

Figure 1. Map of the lower Spokane River system detailing the study area.

METHODS AND MATERIALS

Ten samplings were made from 22 June to 3 December, 1981. Sampling was biweekly for the period June through September and monthly for the period October through December.

Biochemical Oxygen Demand and Chemical Oxygen Demand

The following river and reservoir stations were sampled for biochemical oxygen demand ($B.O.D._5$ at 20^oC) and chemical oxygen demand (C.O.D.): H.C., F.W., L.S.R., N.M., DAM; station 0 (euphotic zone composite, 21m, 33m); station 1 (euphotic zone composite, 21m, 27m); station 2 (euphotic zone composite, 21m, 24m); station 3 (euphotic zone composite, 15m) and station 4 (euphotic zone composite, 6m). Data for sewage effluent B.O.D. and C.O.D. were taken from Spokane advanced wastewater treatment plant records. All B.O.D. and C.O.D. analyses were conducted by treatment plant personnel.

Sediment Oxygen Demand

At each reservoir station, two sediment cores were taken with a No. 217-WA200 Phleger corer and stored at 4^oC. Within twenty-four hours sediment oxygen demand (S.O.D.) was determined. Previous study of Long Lake (Thomas and Soltero, 1977) showed the yearly sedimentation rate to be approximately 26 mm yr^{-1}. Liu (1973) determined that the top sediment layer has a higher oxygen uptake rate than lower sediments. Therefore, in this investigation, the top 15 mm of each core was used to represent 1981 sedimentation at each site and to determine all S.O.D. values. Sediment samples for a given station were mixed and divided into two containers. One sample was suspended in 30 ml of filtered (0.45 micron) reservoir water taken near the bottom of each respective station., the other sample was suspended in 30 ml of distilled water. All samples were suspended using a magnetic stirring bar.

Duplicate Warburg flasks were set up for each suspension according to the method described by Gilson Medical Electronics (1976). A 7.5 ml aliquot was used from a given suspension in each flask. Oxygen consumption was measured at 14.0 ^{o}C in a Gilson Differential Respirometer, Model No. IGRP-14. The 14.0 ^{o}C temperature was used in all runs to simulate the average hypolimnetic temperature and to facilitate comparison between samplings. A temperature equilibration period of 45 minutes was used for all runs. During dynamic S.O.D. determinations, the Warburg flasks were shaken at a rate of 130-140 strokes per minute with a 2.75 cm amplitude. Long term (7 and 14-day) S.O.D. values were determined under stationary conditions (no shaking) for samples taken during the 10 August, 24 August and 6 November cruises.

After each run was completed the sediment samples were removed and analyzed for total dry weight, volatile residue and fixed residue as described by A.P.H.A. (1976).

The S.O.D. was expressed as μg O_2 consumed per gram of sediment weight (total dry weight, volatile residue weight, and fixed residue weight) per hour. The Gilson respirometer measures oxygen consumption in microliters of wet gas at approximately room temperature (manometer temperature). These values were converted to micrograms of oxygen according to the method described by Umbreit _et al_. (1972):

$$\mu g O_2 = \frac{\frac{P - P_{H_2O}}{760}\ (3200)\ (\Delta V)}{(0.08205)\ \ (273 + T)}$$

where, ΔV is the change in gas volume in μl, P is room pressure (mm Hg), P_{H_2O} is the vapor pressure of water (mm Hg) at temperature T (^oC), and T is the temperature at the manometer. A curvilinear regression (third degree) of elapsed time (hours) versus total oxygen consumption (micrograms) was calculated for each sample. Correlation coefficients above 0.99 were found for all samples.

Areal rates ($gO_2\ m^{-2}\ day^{-1}$) were also calculated for dynamic and stationary S.O.D. As each 7.5 ml aliquot represented a constant proportion of the total sediment sample (45 ml) used, its rate of oxygen consumption was assumed to be proportional to the oxygen consumption for the total sample. The units $\mu gO_2\ hr^{-1}$ described earlier were converted to $gO_2\ hr^{-1}$ according to the following equation:

$$\mu gO_2\ hr^{-1} \times \frac{1}{PA} \times \frac{1g}{10^6} \times \frac{24\ hr}{day} = gO_2\ m^{-2}\ day^{-1}$$

where, P is the proportion of sediment sample used (0.1667) and A is the surface area of the core tube ($9.932 \times 10^{-4}\ m^2$).

The surface area of the reservoir was assumed to represent the reservoir bottom surface area because of a relatively small mean depth of 14.6m compared to a mean width of 571.8m and a length of 35.4km. In addition, the surface area at a depth of 15m was used to represent the bottom surface area for the hypolimnion.

Chlorophyll *a*, Phytoplankton Biovolume, Primary Productivity, Secchi Disk Visibility and Hydrology

Chlorophyll *a* concentration, phytoplankton biovolume, primary productivity, temperature, dissolved oxygen and Secchi disk visibility data were taken from the project entitled "The Effect of Seasonal Phosphorus Removal by the City of Spokane's Advanced Wastewater Treatment Plant on the Water Quality of Long Lake, Wa." (Soltero *et al.*, 1982). Discharge measurements for the Little Spokane River at its mouth, Nine Mile Dam and Long Lake Dam were also taken from this report.

RESULTS AND DISCUSSION

Spokane River and Its Tributaries

Water temperatures for the Spokane River and its tributaries are presented in Table 1. Water temperatures ranged between 2.1^{o}C at H.C. at 3 December to 21.1^{o}C at the DAM on 10 and 24 August, respectively.

Dissolved oxygen concentrations for the river and its tributaries are presented in Table 2. Dissolved oxygen concentrations ranged between 7.2 mg l^{-1} at H.C. on 10 August to 12.0 mg l^{-1} at H.C. on 6 November and 3 December, respectively. The S.E. had the lowest mean dissolved oxygen during the study period at 8.4 mg l^{-1}. The lowest mean dissolved oxygen for all sites was 7.8 mg l^{-1} on 11 September.

Biochemical oxygen demand values are presented in Table 3. Biochemical oxygen demand was less than 0.1 mg l^{-1} at F.W. and L.S.R. on 20 July and reached 15.0 mg l^{-1} at S.E. on 20 July and 6 November, respectively. The S.E. had the highest mean B.O.D. of 9.0 mg l^{-1} during the study period. The L.S.R. had the lowest mean value of 1.9 mg l^{-1}.

Chemical oxygen demand values are presented in Table 4. Values of C.O.D. ranged between 0 mg l^{-1} at F.W. and N.M. on 22 June to 67 mg l^{-1} at S.E. on 22 June. Spokane River samples at F.W. and N.M. had the lowest mean C.O.D. of 12 mg l^{-1} during the study period, while the S.E. had the highest mean C.O.D. of 33 mg l^{-1}. The sewage effluent C.O.D. and B.O.D. values were usually two to three times that determined for the river stations.

Table 1. Temperature (^{o}C) for each of the established sampling stations on the Spokane River and its tributaries (1981).

Station	6/22	7/7	7/20	8/10	Date 8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
HC	15.0	15.4	18.6	19.2	17.7	14.2	8.7	7.2	4.0	2.1	12.2
FW	13.3	16.3	17.7	17.7	16.9	16.4	12.9	10.1	7.7	5.8	13.5
SE	15.8	16.9	18.0	18.9	18.9	18.5	16.4	15.1	13.7	11.9	16.4
SM	13.4	16.4	16.8	18.1	17.5	16.5	13.0	10.4	8.6	6.2	13.7
NM	13.3	16.3	17.5	19.1	17.9	16.9	12.6	10.2	8.5	6.1	13.8
LSR	12.4	13.3	14.4	13.8	13.2	11.7	9.2	8.2	6.9	5.4	10.9
DAM	14.7	15.8	18.5	21.1	21.1	18.9	16.7	12.5	10.1	6.6	15.6
$\bar{x}$	12.6	15.8	17.4	18.3	17.6	16.2	12.8	10.5	8.5	6.3	

Table 2. Dissolved oxygen (mg l^{-1}) concentrations for the established sampling stations on the Spokane River and its tributaries (1981).

	Date										
Station	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/6	11/6	12/3	$\bar{x}$
HC	9.7	8.5	7.3	7.2	7.3	7.8	9.8	10.5	12.0	12.0	9.2
FW	11.8	9.4	8.5	8.6	8.3	7.8	9.1	10.9	10.7	10.7	9.6
SE	9.4	8.8	8.3	8.7	8.5	8.1	8.8	5.6	9.3	8.9	8.4
SM	11.6	9.0	8.6	8.5	8.3	8.1	9.5	10.0	10.9	10.8	9.5
NM	11.3	9.1	8.2	8.8	9.0	8.4	9.8	9.9	10.4	10.6	9.5
LSR	9.6	8.8	8.3	8.6	8.6	8.5	9.6	9.7	10.4	9.8	9.2
DAM	10.3	9.3	8.7	9.1	8.0	5.8	7.0	8.2	9.5	9.3	8.5
$\bar{x}$	10.5	9.0	8.3	8.5	8.3	7.8	9.1	9.3	10.5	10.3	

Table 3. Biochemical oxygen demand (mg l^{-1}) for each of the established sampling stations on the Spokane River and its tributaries (1981).

Station	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
	Date										
HC	2.3	3.2	1.3	3.0	0.7	3.8	4.1	3.4	3.2	2.8	2.8
FW	2.5	2.4	<0.1	1.1	0.4	3.2	3.4	2.6	2.4	2.0	2.0
SE	7.5	14.0	15.0	6.0	4.0	5.0	8.0	6.0	15.0	9.0	9.0
NM	2.5	5.4	0.3	1.1	0.4	3.6	4.1	2.5	1.7	2.9	2.5
LSR	2.3	2.2	<0.1	0.8	0.3	3.0	3.9	2.0	2.6	1.5	1.9
DAM	2.4	2.4	0.8	1.3	0.3	3.0	3.5	2.1	2.0	1.8	2.0
$\bar{x}$	3.3	4.9	2.9	2.2	1.0	3.6	4.5	3.1	4.5	3.3	

Table 4. Chemical oxygen demand (mg l^{-1}) for each of the established stations on the Spokane River and its tributaries (1981).

	Date										
Station	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
HC	26	31	26	4	16	23	14	16	15	41	21
FW	0	10	17	13	12	19	9	16	8	19	12
SE	67	31	26	30	37	33	28	40	28	9	33
NM	0	26	9	4	37	5	9	4	11	19	12
LSR	26	31	13	21	33	5	14	12	11	25	19
DAM	21	26	13	30	20	5	19	12	15	25	19
$\bar{x}$	23	26	17	17	26	15	16	17	15	23	

Reservoir

Hydrology

Maximum inflow and discharge occurred during May (Table 5.) Inflow and discharge were minimal from July through December. Storage changes were minimal throughout 1981 with the exception of April and August. Monthly water retention times ranged from nine to approximately 65 days with a mean of 26 days (Table 6). Soltero et al. (1982) determined for the period of June through November there was no significant difference in mean retention times between 1981 and all other study years (Soltero et al., 1973; 1974; 1975; 1976; 1978; 1979; 1980; 1981).

Temperature

Temperature profiles for each of the Long Lake sampling stations are presented in Tables 7 through 11. The reservoir was essentially homothermal at the beginning of the sample period. The onset, duration and breakdown of thermal stratification was similar to that observed in previous investigations (Soltero et al., 1973; 1974; 1975; 1976; 1978; 1979; 1980; 1981). Thermal stratification was evident by 7 July. The greatest temperature difference between the surface and bottom was 10.3 ^{o}C at station 0 on 10 August. The maximum recorded temperature was a surface value of 27.3 ^{o}C at station 4 on 10 August. Fall turnover had begun by 25 September and the reservoir was essentially homothermal by 16 October.

Table 5. Monthly mean inflow, discharge and storage change for Long Lake, Wa. (1981).

Month	Inflow ($m^3 \times 10^6$)	Discharge ($m^3 \times 10^6$)	Storage Change ($m^3 \times 10^6$)
Jan.	851	845	+6
Feb.	832	832	0
Mar.	628	627	+1
Apr.	818	837	-19
May	1040	1034	+6
June	831	832	-1
July	346	347	-1
Aug.	190	144	+46
Sept.	174	175	-1
Oct.	216	216	0
Nov.	244	242	+2
Dec.	371	370	+1

Table 6. Monthly mean storage, discharge and water retention times for Long Lake, Wa. (1981).

Month	Mean Storage (m^3)	Mean Discharge (m^3 day^{-1})	Retention Time (days)
Jan.	300×10^6	273×10^5	11.0
Feb.	300×10^6	297×10^5	10.1
Mar.	300×10^6	202×10^5	14.8
Apr.	300×10^6	279×10^5	10.8
May	300×10^6	333×10^5	9.0
June	300×10^6	277×10^5	10.8
July	300×10^6	112×10^5	26.8
Aug.	300×10^6	46.4×10^5	64.7
Sept.	300×10^6	58.4×10^5	51.4
Oct.	300×10^6	69.7×10^5	43.1
Nov.	300×10^6	80.8×10^5	37.1
Dec.	300×10^6	119×10^5	25.1

Table 7. Temperature (^{o}C) profiles at station 4, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	13.6	17.0	20.6	27.3	23.8	22.2	16.0	12.6	9.2	6.5
3	13.3	17.0	18.9	22.1	22.9	19.9	13.7	10.6	9.0	6.5
6	13.4	16.8	18.2	19.3	18.2	17.5	13.2	10.6	9.0	6.5

Table 8. Temperature (^{o}C) profiles at station 3, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/11	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	14.2	18.3	23.0	25.4	23.7	21.9	17.7	13.4	10.0	5.6
3	14.0	18.1	21.8	22.4	23.1	20.2	17.4	13.0	9.9	5.6
6	14.0	18.0	19.2	19.3	19.5	19.3	17.3	13.0	9.8	5.6
9	13.9	18.0	18.3	18.7	18.6	17.8	16.9	12.7	9.8	5.6
12	13.8	17.9	17.5	18.5	18.3	17.3	15.9	11.4	9.7	5.5
15	13.8	17.2	16.8	18.1	18.0	16.7	14.2	11.1	9.6	5.5

Table 9. Temperature (^{O}C) profiles at station 2, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	14.9	19.3	21.3	20.8	22.0	19.8	17.3	13.3	10.4	6.1
3	14.9	19.2	21.1	20.7	20.6	19.8	17.3	13.3	10.4	6.1
6	14.9	19.2	18.3	20.6	19.5	19.7	17.2	13.3	10.4	6.2
9	14.6	18.3	16.8	19.4	18.7	18.1	17.1	13.3	10.4	6.2
12	14.4	16.8	16.6	18.4	18.6	17.1	16.7	13.1	10.4	6.2
15	14.2	15.9	16.3	17.8	17.7	16.8	16.0	12.0	9.8	6.1
18	14.1	15.1	16.1	17.2	16.6	16.3	15.8	11.3	9.6	6.1
21	14.0	14.3	15.5	16.2	15.9	16.1	15.5	11.2	9.6	6.1
24	14.0	14.2	14.6	15.7	15.4	15.8	15.6	11.2	9.5	5.9

Table 10. Temperature (^{o}C) profiles at station 1, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	15.3	18.7	21.6	23.3	22.9	20.1	17.2	13.3	10.5	6.5
3	15.2	18.6	21.2	22.4	22.7	20.0	17.1	13.3	10.5	6.6
6	15.2	18.4	18.0	21.5	21.8	19.9	17.1	13.3	10.5	6.6
9	15.0	17.8	17.6	19.3	19.2	18.6	17.2	13.3	10.5	6.6
12	14.6	17.4	17.0	18.3	18.6	17.4	16.8	13.2	10.5	6.6
15	14.3	16.4	16.6	17.6	17.7	16.9	16.6	12.7	10.5	6.5
18	14.3	15.6	16.2	16.5	16.7	16.3	16.1	12.1	10.4	6.5
21	14.2	15.1	15.9	15.8	15.7	16.0	15.9	11.6	10.2	6.5
24	14.2	14.4	15.5	15.5	15.1	15.8	15.6	11.4	10.0	6.4
27	14.2	14.3	14.9	14.7	14.8	14.3	15.3	11.3	9.8	6.2

Table 11. Temperature (^{o}C) profiles at station 0, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	15.4	19.0	21.8	24.6	23.6	20.6	17.1	13.3	10.5	7.1
3	15.4	18.5	19.4	22.4	23.5	20.3	17.0	13.3	10.6	7.1
6	15.4	16.9	18.4	19.6	23.4	19.7	17.0	13.2	10.5	7.2
9	15.3	16.5	17.6	18.3	19.2	18.0	17.0	13.3	10.5	7.1
12	15.2	16.3	16.9	17.6	18.5	17.3	16.9	13.2	10.5	7.1
15	15.1	15.9	16.4	16.5	18.1	16.4	16.9	12.6	10.5	7.1
18	15.1	15.0	16.1	15.7	17.2	16.0	16.1	12.2	10.5	7.2
21	15.0	14.2	15.1	15.0	15.8	15.7	15.7	12.0	10.5	7.1
24	14.9	14.1	14.6	14.8	15.1	15.2	15.3	12.0	10.3	7.1
27	14.9	14.0	14.3	14.4	14.7	14.6	14.7	12.0	10.2	7.1
30	14.8	14.0	14.2	14.3	14.3	14.4	14.3	12.0	10.1	7.1
33	14.7	14.0	14.2	14.3	14.3	14.4	14.1	12.0	10.1	7.1

Dissolved Oxygen

Dissolved oxygen profiles for each of the reservoir sampling stations are presented in Tables 12 through 16. Dissolved oxygen concentrations exceeded 10 mg l^{-1} throughout the water column on 22 June. Oxygen concentrations in the hypolimnion (depth below 15 m) declined throughout the summer and reached a minimum for stations 1, 2, and 3 on 24 August, and for station 0 on 25 September. The greatest difference in dissolved oxygen between the surface and bottom was 10.8 mg l^{-1} at station 1 on 24 August. Hypolimnetic oxygen depletion was most predominant at station 1 for the period of August through September. Oxygen depletion was also evident at station 2 during August and station 0 during September. Oxygen concentrations reached minimum levels on the reservoir bottom at stations 1, 2, and 3. However, minimum oxygen concentrations at station 0 occurred within the water column between the 15 and 27 m depths. Bottom dissolved oxygen concentrations at station 0 were approximately 3.0 mg l^{-1} or greater throughout the study period. This phenomenon suggests that oxygen depletion occurred while the water was on the bottom of the reservoir, up-reservoir from station 0, and the water mass preserved these characteristics as if moved down the reservoir toward the power penstocks.

The extent and duration of anoxia during 1981 appears to be less than that in other post-AWT years (Soltero _et al._, 1979; 1980; 1981). By 16 October, dissolved oxygen concentrations exceeded 7.9 mg l^{-1} throughout the water column. Surface concentrations exceeded 7 mg l^{-1} throughout the study period.

Table 12. Dissolved oxygen (mg l^{-1}) profiles at station 4, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	11.3	9.0	9.2	13.3	12.6	11.4	11.5	11.6	10.7	10.5
3	11.5	9.0	9.5	11.0	12.1	11.8	10.8	10.4	10.7	10.6
6	11.8	9.1	9.1	9.1	9.9	9.0	10.8	10.5	10.8	10.8

Table 13. Dissolved oxygen (mg l^{-1}) profiles at station 3, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	11.3	9.7	9.0	11.0	11.0	9.6	9.0	9.9	10.3	10.5
3	11.4	9.1	9.1	14.1	7.7	9.0	8.8	9.9	10.2	10.5
6	11.3	9.2	8.9	9.0	7.7	7.8	8.8	9.7	10.1	10.6
9	11.3	9.1	8.5	7.7	7.3	8.5	8.9	9.3	10.1	10.6
12	11.3	8.7	7.9	7.5	5.7	7.9	9.7	10.1	10.2	10.7
15	11.5	8.3	7.5	6.8	2.7	7.6	10.2	10.0	10.5	10.9

Table 14. Dissolved oxygen (mg l^{-1}) profiles at station 2, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	11.3	10.1	9.4	9.8	10.9	8.4	8.4	9.0	9.8	9.6
3	11.2	10.1	9.5	10.0	8.5	8.4	8.4	9.0	9.8	9.5
6	11.2	10.1	9.7	9.6	7.0	8.3	8.4	9.0	9.8	9.7
9	10.9	10.7	7.9	7.5	6.3	4.2	8.4	9.0	9.8	9.8
12	10.7	9.1	7.8	7.0	6.1	6.6	5.4	9.0	9.7	10.0
15	10.6	8.5	7.7	6.4	4.1	7.0	6.1	9.3	9.2	10.2
18	10.6	8.6	7.1	5.2	2.3	6.7	7.0	9.4	9.2	10.5
21	10.6	8.5	6.1	3.5	0.2	6.4	6.5	9.4	9.2	10.4
24	10.6	8.5	3.2	1.6	0.2	5.0	6.4	9.5	9.2	10.3

Table 15. Dissolved oxygen (mg l^{-1}) profiles at station 1, Long Lake, Wa. 1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	11.1	10.0	9.3	10.3	11.1	9.3	8.3	8.4	9.5	9.4
3	11.1	10.0	9.4	10.0	11.3	9.3	8.2	8.4	9.5	9.3
6	10.9	9.9	9.5	9.5	11.4	9.2	8.3	8.5	9.5	9.4
9	10.9	9.7	8.4	7.6	7.0	4.4	8.2	8.5	9.5	9.3
12	10.8	9.2	7.7	6.7	5.8	3.9	6.1	8.4	9.5	9.3
15	10.7	8.7	7.7	6.1	4.9	4.4	4.8	8.3	9.4	9.4
18	10.7	8.8	7.5	5.6	4.1	4.6	3.5	8.7	9.2	9.4
21	10.6	9.3	7.0	3.6	2.4	4.8	3.0	8.8	8.8	9.4
24	10.6	8.9	6.8	2.6	0.7	4.0	1.6	8.9	8.8	9.6
27	10.8	8.8	6.8	1.1	0.3	0.5	0.6	9.3	8.9	10.0

Table 16. Dissolved oxygen (mg l^{-1}) profiles at station O, Long Lake, Wa. (1981).

	Date									
Depth(m)	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	11.3	9.7	9.0	10.2	10.2	9.4	7.3	8.3	9.2	9.1
3	11.3	10.3	10.6	10.7	10.3	9.7	7.6	8.2	9.1	9.1
6	11.3	10.1	10.0	8.4	10.4	7.2	7.6	8.3	9.2	9.0
9	11.2	9.3	8.9	6.9	7.2	3.2	7.6	8.3	9.1	9.1
12	10.6	9.2	7.9	6.8	5.6	2.6	7.7	8.3	9.1	9.1
15	10.6	9.3	7.6	6.4	5.3	1.6	7.6	8.0	9.1	9.3
18	10.6	9.4	7.6	5.7	5.2	1.2	1.5	7.9	9.0	9.1
21	10.5	9.9	7.8	6.2	5.0	1.5	1.1	8.0	9.1	9.1
24	10.4	8.7	7.8	6.5	5.5	2.8	0.7	7.9	8.7	9.0
27	10.3	8.5	7.6	6.4	5.6	3.3	1.9	7.9	8.6	9.0
30	10.3	8.3	7.6	6.3	5.2	3.8	2.0	8.0	8.6	9.1
33	10.8	7.9	7.2	6.2	5.0	3.9	3.0	8.0	8.2	9.1

Dissolved oxygen concentrations were similar at the surface throughout the reservoir at the start of the study (Table 17). The maximum percent saturation was 176 at station 4 on 10 August. By late September, the surface dissolved oxygen concentration at stations 0, 1, 2 and 3 had dropped below saturation levels. This could have been due to a decrease in photosynthetic activity and declining surface temperatures at the initiation of fall turnover.

Areal Hypolimnetic Oxygen Demand

Many investigators have discussed the relationship between areal hypolimnetic oxygen demand (AHOD) and lake trophic status (Cornett and Rigler, 1979; 1980; Hutchinson, 1957; Lasenby, 1975; Mortimer, 1941; and Walker, 1979). Hutchinson and Mortimer developed trophic classification schemes using AHOD based on relative oxygen deficits. According to Hutchinson, oligotrophic lakes have an AHOD between 0.004 and 0.033 $mgO_2\ cm^{-2}\ day^{-1}$, eutrophic lakes between 0.05 and 0.14 $mgO_2\ cm^{-2}\ day^{-1}$, and lakes between these ranges are mesotrophic. Mortimer suggested somewhat different limits: 0.055 $mgO_2\ cm^{-2}$ day-1 as the lower limit for eutrophy, 0.025 to 0.055 $mgO_2\ cm^{-2}\ day^{-1}$ as mesotrophic and less than 0.025 $mgO_2\ cm^{-2}\ day^{-1}$ as oligotrophic. Both systems are based on lakes with maximum depths between 20 and 75 meters.

Cornett and Rigler (1979; 1980), Lasenby (1975) and Walker (1979) report that the classification systems of Hutchinson (1957) and Mortimer (1941) are biased due to differences in lake morphometry. Since the AHOD comparisons for Long Lake were for a short period of time, the comparisons should be valid as no known changes in gross hypolimnetic morphometry or volume have occurred.

Table 17. Dissolved oxygen percent saturation at the surface (elevation 468m.) Long Lake, Wa. (1981).

	Date									
Station	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3
0	119	110	107	128	126	110	80	83	87	80
1	117	113	110	127	135	108	90	85	90	80
2	118	115	111	115	131	97	91	91	93	84
3	116	108	110	140	136	112	99	103	97	88
4	114	98	107	176	156	137	123	115	99	90
$\bar{x}$	117	109	109	137	137	113	97	95	93	84

The AHOD for all study years (Table 18) were calculated according to Hutchinson (1957), using absolute oxygen deficits in order to facilitate comparison between study years, as spring dissolved oxygen concentrations were not available for all study years. A time period of 163 days between spring turnover and the height of summer stagnation was used based on the average number of Julian days between 15 March and the height of summer stagnation. The height of stagnation was determined by the lowest mean hypolimnetic dissolved oxygen concentration reached taking into account the volume of water represented at each three meter stratum below 15 meters. The maximum AHOD was 0.081 mgO_2 cm^{-2} day^{-1} occurring in 1973 while the minimum AHOD was 0.055 mgO_2 cm^2 day^{-1} occurring in 1981. Post-AWT mean AHOD (0.062 mgO_2 cm^{-2} day^{-1}) was signficantly less ($P = 0.05$) than pre-AWT mean AHOD (0.073 mgO_2 cm^{-2} day^{-1}). Apparently, advanced wastewater treatment has had a significant effect on the AHOD.

The classification scheme of Mortimer or Hutchinson is based on relative oxygen deficits using the difference between the dissolved oxygen present at the end of spring turnover and the height of summer stagnation. The absolute oxygen deficit is based on the difference between the dissolved oxygen saturation value at 4^oC and at the lake's surface elevation (12.0 mg 1^{-1} for Long Lake) and that present at the height of summer stagnation. Although the two methods are different the results should be comparable in the case of Long Lake as the dissolved oxygen concentration in the hypolimnion at spring turnover is approximately 11 to 12 mg 1^{-1} (Soltero et al., 1977; 1979; 1980; 1981). According to the classification scheme of Mortimer or Hutchinson Long Lake would be approaching the lower limit of eutrophy in 1981. Even more significant is the yearly decline observed in the AHOD since advanced wastewater treatment went into effect.

Table 18. Mean hypolimnetic dissolved oxygen (mg l^{-1}) at the peak of stagnation, absolute oxygen deficit (mg l^{-1}) and the areal hypolimnetic oxygen demand (mgO_2 cm^{-2} day^{-1}) for all study years, Long Lake, Wa. (1972-1981).

YEAR	Date of maximum stagnation	$\bar{x}$ Hypolimnetic D.O.	Absolute oxygen deficit	AHOD
1972	9/5	0.8	11.2	0.076
1973	8/21	0.0	12.0	0.081
1974	9/3	1.9	10.1	0.069
1975	8/25	3.3	8.7	0.059
1977	8/9	0.3	11.7	0.079
$\bar{x}$		1.3	10.7	0.073
1978	8/29	2.3	9.7	0.066
1979	9/4	2.3	9.7	0.066
1980	8/25	3.1	8.9	0.060
1981	8/24	3.9	8.1	0.055
$\bar{x}$		2.9	9.1	0.062

Correlation coefficients (Table 19) for chlorophyll a, phytoplankton biovolume and primary productivity versus AHOD showed that phytoplankton standing crop had a direct effect on the AHOD. Areal hypolimnetic oxygen deficits did not significantly correlate with mean retention times for the period June through November over all study years.

Sediment Oxygen Demand

Mean dynamic S.O.D. increased down-reservoir from 315 $\mu g O_2$ g total dry weight^{-1} hr^{-1} at station 4 to 747 $\mu g O_2$ g total dry weight^{-1} hr^{-1} at station 0 (Table 20). The maximum mean dynamic S.O.D. for the reservoir (988 $\mu g O_2$ g total dry weight^{-1} hr^{-1}) occurred on 3 December. Stational values ranged from 44 $\mu g O_2$ g total dry weight-1 hr^{-1} at station 4 on 10 August to 1548 $\mu g O_2$ g total dry weight^{-1} hr^{-1} at station 0 on 3 December. A considerable increase in dynamic S.O.D. at all stations occurred during the latter part of August coinciding with declining oxygen concentrations in the hypolimnion. This may have been the result of the accumulation of reduced substances in the sediment resulting in an oxygen debt. Starting in August, the color of the sediment darkened at about one to two cm in depth. This was thought to be the result of reduced iron compounds, probably ferrous sulfide, as the material stuck to a magnetic stirring bar. Another possible explanation might be an accumulation of oxidizable organic matter. However, sediment analyses (Table 29, page 42) does not support this as the percent organic matter did not increase correspondingly. Similar trends, as given above, were observed for dynamic S.O.D. g volatile residue^{-1} hr^{-1} (Table 21) and g fixed residue^{-1} hr^{-1} (Table 22).

Dynamic S.O.D. studies were made using two dilution media, filtered lake water and distilled water. Berg (1970) found that maximum oxygen uptake

Table 19. Correlation coefficients (n = 9) for mean chlorophyll *a*, phytoplankton biovolume, and primary productivity during the period June through November versus areal hypolimnetic oxygen demand for all study years, Long Lake, Wa. (1972-1981).

Variables	r	P
Chlorophyll *a* (mg m^{-3}) vs. AHOD (mgO_2 cm^{-2} day^{-1})	0.81	0.01
Chlorophyll *a* (mg m^{-2}) vs. AHOD (mgO_2 cm^{-2} day^{-1})	0.85	0.01
Phytoplankton biovolume (mm^3 l^{-1}) vs. AHOD (mgO_2 cm^{-2} day^{-1})	0.73	0.05
Phytoplankton biovolume (mm^3 m^{-2} x 10^3) vs. AHOD (mgO_2 cm^{-2} day^{-1})	0.88	0.01
Primary productivity (gC m^{-2} day^{-1}) vs. AHOD (mgO_2 cm^{-2} day^{-1})	0.82	0.01

Table 20. Range and mean of the dynamic sediment oxygen demand ($\mu g O_2$ g total dry weight^{-1} hr^{-1}) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	149-204 176	153-162 158	101-107 104	72-75 73	55-62 59	114
7/7	53-235 124	59-89 76	92-103 98	14-67 49	29-52 44	79
7/21	298-525 411	310-459 393	117-336 249	71-89 80	46-77 65	240
8/10	114-208 159	156-192 171	129-247 164	52-81 63	37-51 44	121
8/24	543-907 719	542-637 586	294-535 448	96-183 154	83-138 104	402
9/11	1157-1253 1211	727-863 791	739-1646 1126	726-1201 906	536-796 654	938
9/25	798-858 830	445-768 619	815-918 856	773-960 865	395-708 542	742
10/16	990-1492 1178	1043-1254 1138	1018-1176 1089	586-1007 780	518-700 603	958
11/6	792-1405 1117	920-1122 1045	638-1019 779	606-818 715	440-573 524	836
12/3	853-2253 1548	950-1681 1268	816-1058 921	416-971 688	473-565 514	988
$\bar{x}$	747	625	584	437	315	

Table 21. Range and mean of the dynamic sediment oxygen demand ($\mu g O_2$ g volatile residue^{-1} hr^{-1}) by station and date, Long Lake, Wa. (1981).

Date	Station 0	1	2	3	4	$\bar{x}$
6/22	1631-2491 2061	1827-2302 2065	1252-1614 1433	1258-1317 1288	1186-1202 1194	1608
7/7	785-3512 1873	555-1497 1156	1180-1554 1393	257-1186 924	610-988 890	1247
7/21	3079-6178 4603	4122-6386 5283	2685-4413 3652	1308-1499 1412	799-1309 1112	3212
8/10	1304-2327 1833	1961-2384 2150	1805-3554 2360	877-1512 1110	727-1029 885	1668
8/24	6889-11030 8790	7695-9275 8420	4521-8702 7069	1559-3372 2766	1694-2885 2076	5824
9/11	15620-26130 22230	12460-14910 13670	10960-26510 17860	11500-21010 15320	13410-18040 15590	16930
9/25	9867-13360 11310	7379-15470 12180	12910-16550 14930	15370-19300 17770	8742-15850 12910	13820
10/16	11150-17480 13260	15560-18990 16730	17060-19350 18360	11230-19340 15110	15260-21650 18480	16390
11/6	9823-16940 13580	12100-15870 14680	10250-17580 13460	11940-15870 13580	10300-13060 12110	13480
12/3	10180-28000 18650	13570-23970 18510	13240-20260 16740	7510-19360 13760	11450-13490 12270	15990
$\bar{x}$	9819	9484	9726	8304	7752	

Table 22. Range and mean of the dynamic sediment oxygen demand ($\mu g O_2$ g fixed residue^{-1} hr^{-1}) by station and date, Long Lake, Wa. (1981).

Date	Station 0	1	2	3	4	$\bar{x}$
6/22	164-222 193	164-177 171	110-114 112	76-79 78	58-66 62	123
7/7	57-252 132	66-95 82	104-111 107	15-71 52	31-55 48	84
7/21	330-574 451	335-494 425	190-364 284	75-94 84	48-82 69	263
8/10	125-228 174	169-209 186	139-265 177	55-86 67	39-53 47	130
8/24	590-995 783	583-684 630	314-570 478	102-193 163	87-145 109	433
9/11	1216-1362 1285	772-915 840	792-1755 1202	775-1274 964	558-832 682	995
9/25	861-940 896	473-808 652	865-979 981	814-1008 908	414-741 566	786
10/16	1087-1631 1293	1114-1342 1221	1083-1256 1158	619-1062 823	536-723 623	1024
11/6	861-1532 1217	995-1208 1125	678-1082 827	638-863 755	495-599 548	894
12/3	931-2450 1689	1022-1808 1362	870-1116 977	492-1022 724	492-590 537	1058
$\bar{x}$	811	669	623	462	329	

rates were not changed when different dilution media were used. In this study a comparison was made of filtered lake water S.O.D. versus distilled water S.O.D. No significant difference was found in the mean S.O.D. for these dilution media. Therefore, all values, regardless of dilution medium, were used in calculating the range and mean for S.O.D.

Stationary S.O.D. values (Table 23) increased down-reservoir with a mean value of 6.5 μgO_2 g total dry weight^{-1} hr^{-1} at station 4 to 13.3 μgO_2 g total dry weight^{-1} hr^{-1} at station 0. Berg (1970) reported that dynamic suspension can increase the quiescent oxygen uptake by more than a multiple of 10. Similar results were found in this study; dynamic S.O.D. values were ten to one hundred times greater than stationary S.O.D. values.

Areal dynamic S.O.D. values are presented in Table 24. Mean areal dynamic S.O.D. varied little between stations during the study period. However, mean areal dynamic S.O.D. values by date over all stations increased from June to December. This is probably due to the same reasons mentioned earlier for the similar increase observed in the dynamic S.O.D. Fluctuations in mean areal S.O.D. corresponded to fluctuations in dynamic S.O.D. (Figure 2, page 48). A strong correlation ($r = 0.99$, $P = 0.01$) by date over all stations existed between log dynamic S.O.D. and log areal dynamic S.O.D. Dynamic S.O.D. and areal dynamic S.O.D. were not correlated by station over all dates.

Although there was considerable change in the areal dynamic S.O.D. during the study period, the areal stationary S.O.D. (Table 25) was relatively constant. This was probably due to a limit in the rate at which oxygen would diffuse into the sediment sample in the Warburg flask.

Table 23. Range and mean of the stationary sediment oxygen demand ($\mu g O_2$ g total dry weight^{-1}, g volatile residue^{-1}, g fixed residue^{-1} hr^{-1}), Long Lake, Wa. (1981).

Date	Station 0	1	2	3	4	$\bar{x}$
Units = $\mu g\ O_2$ g total dry weight^{-1} hr^{-1}						
8/10*	12.7-14.8 13.7	8.5-9.8 9.2	7.6-10.1 8.9	6.7-10.6 8.7	6.4-8.4 7.4	9.6
8/24	14.8-15.4 15.1	8.8-11.6 10.2	8.4-8.4 8.4	7.3-8.6 8.0	6.9-7.9 7.4	9.8
11/6	10.6-11.6 11.1	8.2-9.3 8.7	6.6-6.7 6.6	6.0-6.0 6.0	4.2-5.0 4.6	7.4
$\bar{x}$	13.3	9.4	8.0	7.5	6.5	
Units = $\mu g\ O_2$ g volatile residue^{-1} hr^{-1}						
8/10*	158.3-193.0 175.7	94.6-113.0 103.8	101.7-145.1 123.4	114.8-179.8 147.3	120.6-156.8 138.7	137.8
8/24	177.3-184.3 180.8	129.9-166.2 148.0	129.0-129.3 129.2	132.7-175.5 154.1	172.5-196.0 184.3	159.3
11/6	145.2-145.5 145.4	130.0-136.5 133.2	116.2-122.8 119.5	118.2-131.0 124.6	125.8-148.1 137.0	131.9
$\bar{x}$	167.3	128.3	124.0	142.0	153.3	
Units = $\mu g\ O_2$ g fixed residue^{-1} hr^{-1}						
8/10*	13.8-16.1 14.9	9.3-10.7 10.0	8.2-10.8 9.5	7.2-11.3 9.2	6.8-8.9 7.9	10.3
8/24	16.1-16.7 16.4	9.4-12.5 10.9	8.9-9.0 9.0	7.8-9.0 8.4	7.2-8.3 7.7	10.5
11/6	11.4-12.6 12.0	8.7-9.4 9.3	6.9-7.1 7.0	6.2-6.3 6.3	4.3-5.2 4.8	7.9
$\bar{x}$	14.4	10.1	8.5	8.0	6.8	

* 8/10/81 was a 7-day run, 8/24/81 and 11/6/81 were 14-day runs.

Table 24. Range and mean of the areal dynamic sediment oxygen demand ($gO_2\ m^{-2}\ day^{-1}$) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	15-24 19	14-20 17	12-15 14	11-12 11	11-13 12	15
7/7	8-43 21	10-14 11	14-16 15	2-11 9	7-11 9	13
7/20	29-41 35	27-47 38	16-42 29	9-13 11	7-12 10	25
8/10	5-14 10	16-19 17	14-25 17	6-9 7	7-7 7	12
8/24	37-72 56	63-80 72	40-75 62	14-34 25	16-23 19	47
9/11	103-107 104	123-133 127	81-167 134	105-166 127	113-173 141	127
9/25	91-97 94	94-127 114	114-122 119	119-167 143	83-159 135	121
10/16	112-139 121	131-146 142	134-155 143	90-141 124	156-162 159	138
11/6	87-128 108	131-146 136	93-146 122	84-143 113	101-134 120	120
12/3	106-183 144	122-157 140	145-171 155	91-178 132	113-169 139	142
$\bar{x}$	71	81	81	70	75	

Table 25. Range and mean of the areal stationary sediment oxygen demand (gO_2 m^{-2} day^{-1}) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
8/10*	0.80-0.92 0.85	0.90-1.01 0.96	0.85-1.11 0.98	0.85-1.31 1.08	1.07-1.34 1.15	1.01
8/24	1.09-1.12 1.11	1.01-1.31 1.16	1.10-1.12 1.11	1.13-1.30 1.22	1.22-1.35 1.29	1.18
11/6	1.05-1.15 1.10	1.07-1.20 1.14	1.05-1.08 1.06	0.92-0.96 0.94	0.96-1.15 1.06	1.06
$\bar{x}$	1.02	1.09	1.05	1.08	1.17	

* 7-day run

Sediment Analyses

The mean and range of sediment dry weights, volatile residues and fixed residues are given in Tables 26, 27 and 28, respectively. Mean percent organic matter for the study period decreased up-reservoir from 7.98 at station 0 to 4.61 at station 4 (Table 31). However, there was little change in mean percent organic matter between sampling dates. Several investigators (Hargrave, 1972a; Liu, 1973; and Pamatmat et al., 1973) have found a relationship between S.O.D. and percent organic matter in the sediments. Similar results were found in this study as a strong correlation ($r = 0.99$, $P = 0.001$) existed between mean percent organic matter and mean dynamic S.O.D. ($\mu g O_2$ g tdw^{-1} hr^{-1}) by station over all dates.

Biochemical Oxygen Demand and Chemical Oxygen Demand

Mean B.O.D. ranged from 0.1 mg l^{-1} at stations 1 and 0 on 20 July to 4.3 mg l^{-1} at station 3 on 11 September (Table 30). Mean B.O.D. for the study period tended to decrease down-reservoir from 2.6 mg l^{-1} at station 4 to 1.8 mg l^{-1} at station 0. Maximum mean B.O.D. for the reservoir was 3.5 mg l^{-1} on 25 September.

Table 31 shows the B.O.D. (metric tons day^{-1}) influent to and effluent from the reservoir, as well as that in the reservoir and hypolimnion. Reservoir B.O.D. was 20 to 100 times greater than influent B.O.D. during the summer months. Hypolimnion B.O.D. was four to 30 times greater than influent B.O.D. Retention times during the summer months ranged from 10 to 65 days. These results along with the lack of anoxia at stations 3 and 4 support the conclusion that influent B.O.D. did not contribute significantly to the oxygen depletion observed in Long Lake for the period of study. Effluent B.O.D. was approximately equal to influent B.O.D. throughout the study period.

Table 26. Mean and range of the sediment mass (grams total dry weight) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22*	0.451-0.544 0.498	0.398-0.585 0.492	0.553-0.647 0.600	0.677-0.743 0.710	0.937-0.946 0.942	0.648
7/7*	0.671-0.832 0.733	0.510-0.779 0.684	0.662-0.714 0.689	0.676-0.904 0.788	0.815-1.151 0.973	0.773
7/20	0.537-0.660 0.603	0.610-0.707 0.663	0.637-0.868 0.754	0.848-1.007 0.921	1.053-1.085 1.066	0.801
8/10	0.332-0.460 0.400	0.676-0.695 0.685	0.703-0.774 0.732	0.655-0.910 0.772	0.974-1.274 1.129	0.744
8/24	0.471-0.600 0.537	0.806-0.870 0.842	0.932-0.963 0.949	0.924-1.271 1.109	1.165-1.327 1.264	0.940
9/11	0.567-0.620 0.595	1.017-1.169 1.111	0.707-0.977 0.835	0.952-0.995 0.973	1.395-1.592 1.486	1.000
9/25	0.760-0.800 0.784	1.138-1.461 1.390	0.906-1.026 0.965	1.062-1.216 1.137	1.402-2.055 1.733	1.182
10/16	0.644-0.782 0.716	0.806-0.957 0.864	0.875-0.960 0.909	0.964-1.215 1.109	1.537-2.146 1.853	1.090
11/6	0.620-0.760 0.680	0.869-0.942 0.901	0.991-1.189 1.092	0.933-1.234 1.085	1.534-1.610 1.575	1.067
12/3	0.553-0.859 0.706	0.644-0.887 0.751	1.110-1.239 1.162	1.266-1.387 1.324	1.651-2.069 1.858	1.160
$\bar{x}$	0.625	0.828	0.869	0.993	1.389	

* 5.0ml samples

Table 27. Mean and range of the sediment mass (grams volatile residue) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22*	0.041-0.044 0.043	0.035-0.039 0.037	0.043-0.045 0.044	0.038-0.042 0.040	0.043-0.050 0.046	0.042
7/7*	0.046-0.056 0.049	0.032-0.081 0.052	0.041-0.049 0.045	0.037-0.046 0.042	0.043-0.056 0.049	0.047
7/20	0.046-0.064 0.054	0.046-0.051 0.049	0.042-0.065 0.054	0.046-0.058 0.052	0.061-0.064 0.062	0.054
8/10	0.029-0.045 0.035	0.054-0.055 0.054	0.048-0.055 0.052	0.041-0.050 0.044	0.048-0.065 0.057	0.048
8/24	0.037-0.051 0.044	0.057-0.062 0.059	0.056-0.066 0.061	0.060-0.072 0.063	0.056-0.072 0.064	0.058
9/11	0.027-0.046 0.034	0.059-0.068 0.064	0.044-0.064 0.053	0.054-0.063 0.058	0.057-0.067 0.062	0.054
9/25	0.050-0.068 0.058	0.057-0.088 0.067	0.050-0.064 0.056	0.051-0.060 0.055	0.063-0.081 0.072	0.062
10/16	0.055-0.073 0.064	0.053-0.064 0.059	0.049-0.058 0.054	0.050-0.062 0.057	0.050-0.073 0.061	0.059
11/6	0.051-0.061 0.056	0.062-0.072 0.064	0.057-0.070 0.063	0.049-0.067 0.057	0.065-0.071 0.068	0.062
12/3	0.045-0.072 0.059	0.045-0.062 0.052	0.058-0.076 0.065	0.063-0.084 0.068	0.063-0.087 0.078	0.064
$\bar{x}$	0.050	0.056	0.055	0.054	0.062	

* 5.0 ml samples

Table 28. Mean and range of the sediment mass (grams fixed residue) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22*	0.410-0.499 0.455	0.363-0.546 0.455	0.508-0.604 0.556	0.638-0.701 0.670	0.894-0.897 0.896	0.606
7/7*	0.624-0.776 0.683	0.478-0.737 0.632	0.616-0.673 0.644	0.637-0.860 0.746	0.772-1.096 0.924	0.726
7/20	0.491-0.602 0.548	0.564-0.655 0.614	0.595-0.803 0.700	0.802-0.950 0.869	0.989-0.021 1.004	0.733
8/10	0.303-0.418 0.365	0.622-0.639 0.631	0.655-0.719 0.686	0.615-0.860 0.728	0.925-1.210 1.072	0.696
8/24	0.433-0.557 0.493	0.749-0.808 0.783	0.876-0.903 0.889	0.874-1.199 1.047	1.019-1.256 1.200	0.882
9/11	0.522-0.589 0.561	0.958-1.103 1.047	0.663-0.913 0.782	0.897-0.932 0.915	1.337-1.525 1.424	0.946
9/25	0.704-0.750 0.726	1.081-1.373 1.223	0.855-0.976 0.909	1.009-1.160 1.082	1.339-1.974 1.661	1.120
10/16	0.590-0.710 0.652	0.753-0.896 0.805	0.824-0.903 0.855	0.914-1.152 1.052	0.487-2.073 1.793	1.031
11/6	0.569-0.699 0.624	0.808-0.870 0.837	0.933-1.123 1.028	0.882-1.169 1.028	1.469-1.539 1.507	1.005
12/3	0.505-0.787 0.647	0.599-0.825 0.699	1.048-1.163 1.097	1.203-1.324 1.256	1.586-1.983 1.779	1.096
$\bar{x}$	0.576	0.773	0.815	0.904	1.326	

* 5.0 ml samples

Table 29. Percent organic matter (ratio of volatile residue to total dry weight x 100) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	8.60	7.55	7.30	5.69	4.92	6.81
7/7	6.69	7.53	6.53	5.29	5.05	6.22
7/20	9.03	7.45	7.14	5.64	5.84	7.02
8/10	8.78	7.96	7.03	5.74	5.02	6.91
8/24	8.18	6.97	6.38	5.64	5.05	6.44
9/11	5.65	5.79	6.38	5.95	4.18	5.59
9/25	7.42	5.22	5.77	4.87	4.17	5.49
10/16	8.94	6.81	5.94	5.16	3.28	6.03
11/6	8.19	7.14	5.82	5.27	4.33	6.15
12/3	8.30	6.87	5.58	5.17	4.21	6.03
$\bar{x}$	7.98	6.93	6.39	5.44	4.61	

Table 30. Biochemical oxygen demand (mg l^{-1}) by station and date, Long Lake, Wa. (1981).

Station	Date 6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
EZ-4	2.4	1.9	0.4	5.8	1.1	4.1	5.0	2.5	2.3	1.5	
6m-4	2.5	1.4	1.0	1.4	0.7	3.6	3.4	2.4	5.8	2.6	
$\bar{x}$	2.5	1.7	0.7	3.6	0.9	3.9	4.2	2.5	4.1	2.1	2.6
EZ-3	2.5	2.2	0.8	2.4	0.9	4.6	4.2	3.3	2.8	2.4	
15m-3	2.3	1.6	0.3	1.1	0.7	4.0	3.9	2.1	2.9	1.4	
$\bar{x}$	2.4	1.9	0.6	1.8	0.8	4.3	4.1	2.7	2.9	1.9	2.3
EZ-2	3.3	2.3	0.7	2.1	1.2	3.4	3.7	2.3	2.2	1.7	
21m-2	2.4	1.6	0.1	0.6	1.0	3.9	3.4	2.2	2.4	1.4	
24m-2	2.4	1.3	0.2	0.5	1.0	3.0	4.1	2.2	2.8	1.8	
$\bar{x}$	2.7	1.7	0.3	1.2	1.1	3.4	3.7	2.2	2.5	1.6	2.1
EZ-1	2.9	2.2	0.1	1.8	0.9	2.9	4.3	2.4	2.4	1.5	
21m-1	2.5	1.5	<0.1	0.9	0.1	3.3	3.0	2.0	2.1	1.3	
27m-1	2.8	1.5	0.2	0.9	1.0	2.7	2.0	2.1	2.0	1.9	
$\bar{x}$	2.7	1.7	0.1	1.2	0.7	3.0	3.1	2.2	2.2	1.6	1.9
EZ-0	2.6	2.1	0.2	2.1	0.9	3.7	3.9	2.4	2.4	1.8	
21m-0	2.5	2.0	0.1	1.6	0.1	2.0	2.1	2.5	2.0	1.4	
33m-0	2.4	2.2	<0.1	1.4	0.1	2.5	2.3	2.6	2.0	1.3	
$\bar{x}$	2.5	2.1	0.1	1.7	0.4	2.7	2.8	2.5	2.1	1.5	1.8
$\bar{x}$	2.6	1.8	0.3	1.7	0.7	3.4	3.5	2.4	2.6	1.7	

Table 31. Biochemical oxygen demand (metric tons day^{-1}) for the influent, effluent, reservoir and hypolimnion by date, Long Lake, Wa. (1981).

	Date										
	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
influent B.O.D.	14	6.1	0.6	1.1	0.5	3.9	4.6	3.4	3.0	6.6	4.4
effluent B.O.D.	13	5.4	1.8	1.2	0.3	3.5	4.1	2.9	3.2	4.3	4.0
reservoir B.O.D.	160	110	18	98	44	200	220	140	160	100	130
hypolimnion B.O.D.	53	36	2.1	21	13	66	64	47	49	32	38

Mean C.O.D. ranged from 5 mg l^{-1} at all stations on 11 September, station 4 on 7 July and station 1 on 22 June to 32 mg l^{-1} at stations 3 and 4 on 3 December (Table 32). Maximum mean C.O.D. for the reservoir was 26 mg l^{-1} on 3 December.

Chemical oxygen demands (metric tons) for the reservoir, hypolimnion, influent and effluent are presented in Table 33. Reservoir C.O.D. ranged from 10 to 140 times the influent C.O.D. during the summer months. Hypolimnetic C.O.D. was five to 40 times the influent C.O.D. during the summer months. Effluent C.O.D. was usually higher than influent C.O.D. through the study period with the exception of 22 June (N.M. C.O.D. on 22 June was zero, substantially decreasing influent C.O.D.).

A comparison of B.O.D., C.O.D., dynamic S.O.D. and areal dynamic S.O.D. by date over all stations is presented in Figure 2. Fluctuations in B.O.D. and C.O.D. appear to be inversely related and not related to dynamic S.O.D. or areal dynamic S.O.D.

Biochemical oxygen demand, C.O.D., dynamic S.O.D. and areal dynamic S.O.D. by station for the period June through November are presented in Figure 3. Areal dynamic S.O.D. was relatively constant between stations; dynamic S.O.D. decreased from station 0 to station 4; C.O.D. increased slightly from station 0 to 2 and was relatively constant between stations 2 and 4. The B.O.D. increased from station 0 to station 4. For the study period an inverse correlation ($r = -0.96$, $P = 0.01$) existed between mean B.O.D. (mg l^{-1}) and mean dynamic S.O.D. ($\mu g O_2$ g total dry weight^{-1} hr^{-1}) by station over all dates.

Table 32. Chemical oxygen demand (mg l^{-1}) by station and date, Long Lake, Wa. (1981).

Station	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
					Date						
EZ-4	26	5	9	17	16	5	14	12	23	31	
6m-4	21	5	13	38	8	5	19	12	23	33	
$\bar{x}$	24	5	11	28	12	5	17	12	23	32	17
EZ-3	26	15	17	17	8	5	23	12	30	39	
15m-3	10	15	13	13	20	5	14	16	28	25	
$\bar{x}$	18	15	15	15	14	5	19	14	29	32	18
EZ-2	5	10	17	26	25	5	14	16	15	22	
21m-2	10	15	9	17	29	5	14	16	11	28	
24m-2	26	15	17	13	37	5	14	12	23	39	
$\bar{x}$	14	13	14	19	30	5	14	15	16	30	17
EZ-1	5	21	17	26	29	5	9	8	11	25	
21m-1	5	15	17	21	25	5	5	12	15	19	
27m-1	5	10	13	17	25	5	9	12	15	19	
$\bar{x}$	5	15	16	21	26	5	8	11	14	21	14
EZ-0	10	10	26	17	33	5	14	12	11	19	
21m-0	5	10	9	4	29	5	14	16	8	19	
33m-0	5	10	13	4	25	5	5	12	15	22	
$\bar{x}$	7	10	16	8	29	5	11	13	11	20	13
$\bar{x}$	12	12	15	18	24	5	13	13	18	26	

Table 33. Chemical oxygen demand (metric tons) for the influent, effluent, reservoir and hypolimnion by date for Long Lake, Wa. (1981).

	Date										
	6/22	7/7	7/20	8/10	8/24	9/11	9/25	10/16	11/6	12/3	$\bar{x}$
influent C.O.D.	33*	310	110	40	220	29	57	35	90	230	120
effluent C.O.D.	580	290	150	140	93	29	110	84	120	300	190
reservoir C.O.D.	3600	3600	4500	5400	7200	1500	3900	3900	5400	7800	4700
hypolimnion C.O.D.	1000	1400	1400	1400	2900	530	1200	1500	1700	2600	1600

* N.M. C.O.D. was 0 mg l^{-1} on 6/22

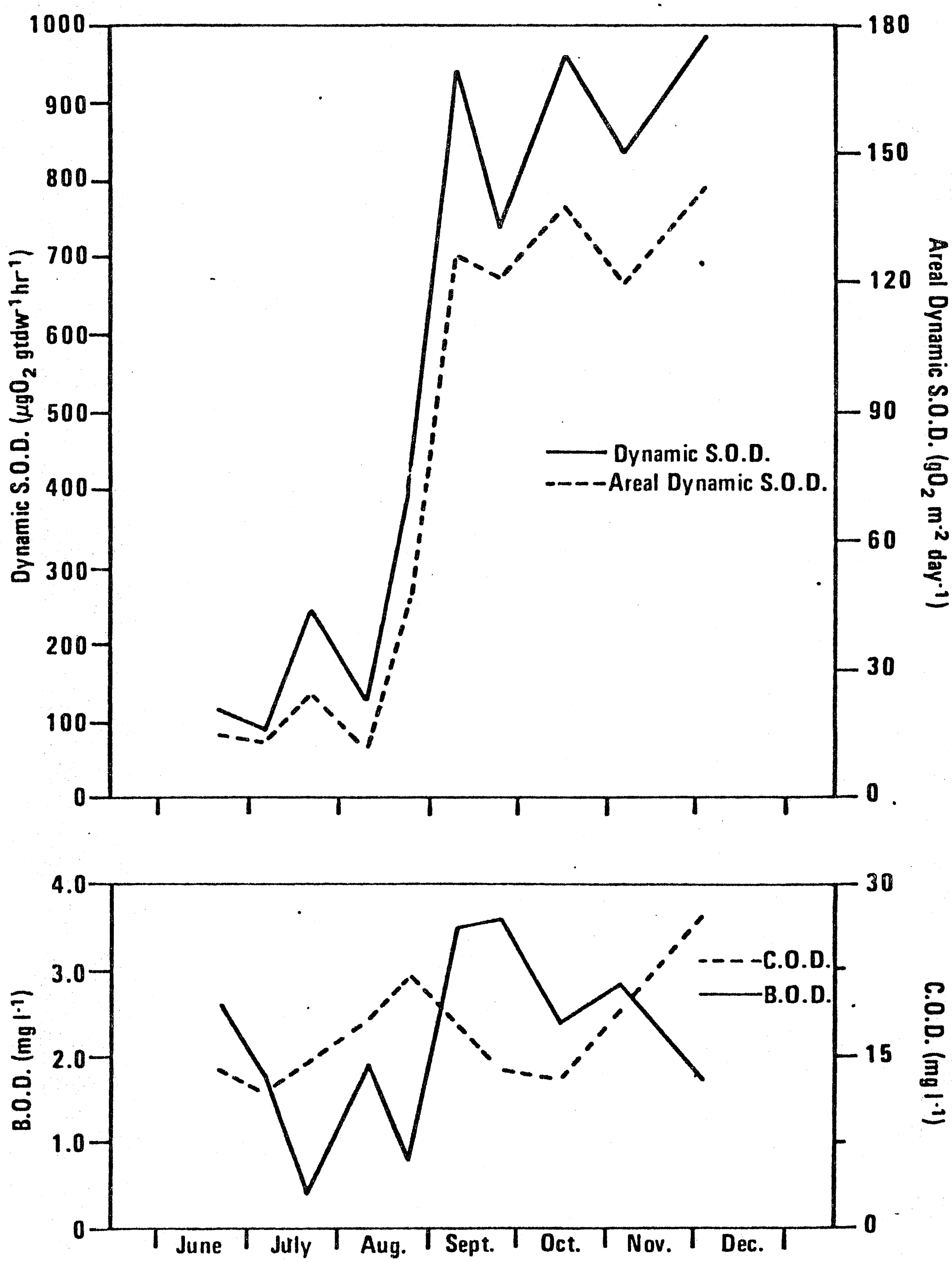

Figure 2. Biochemical oxygen demand (mg l^{-1}), chemical oxygen demand (mg l^{-1}), dynamic sediment oxygen demand (μgO_2 g total dry weight^{-1} hr^{-1}) and areal dynamic sediment oxygen demand (gO_2 m^{-2} day^{-1}) by date over all stations, Long Lake, Wa. (1981).

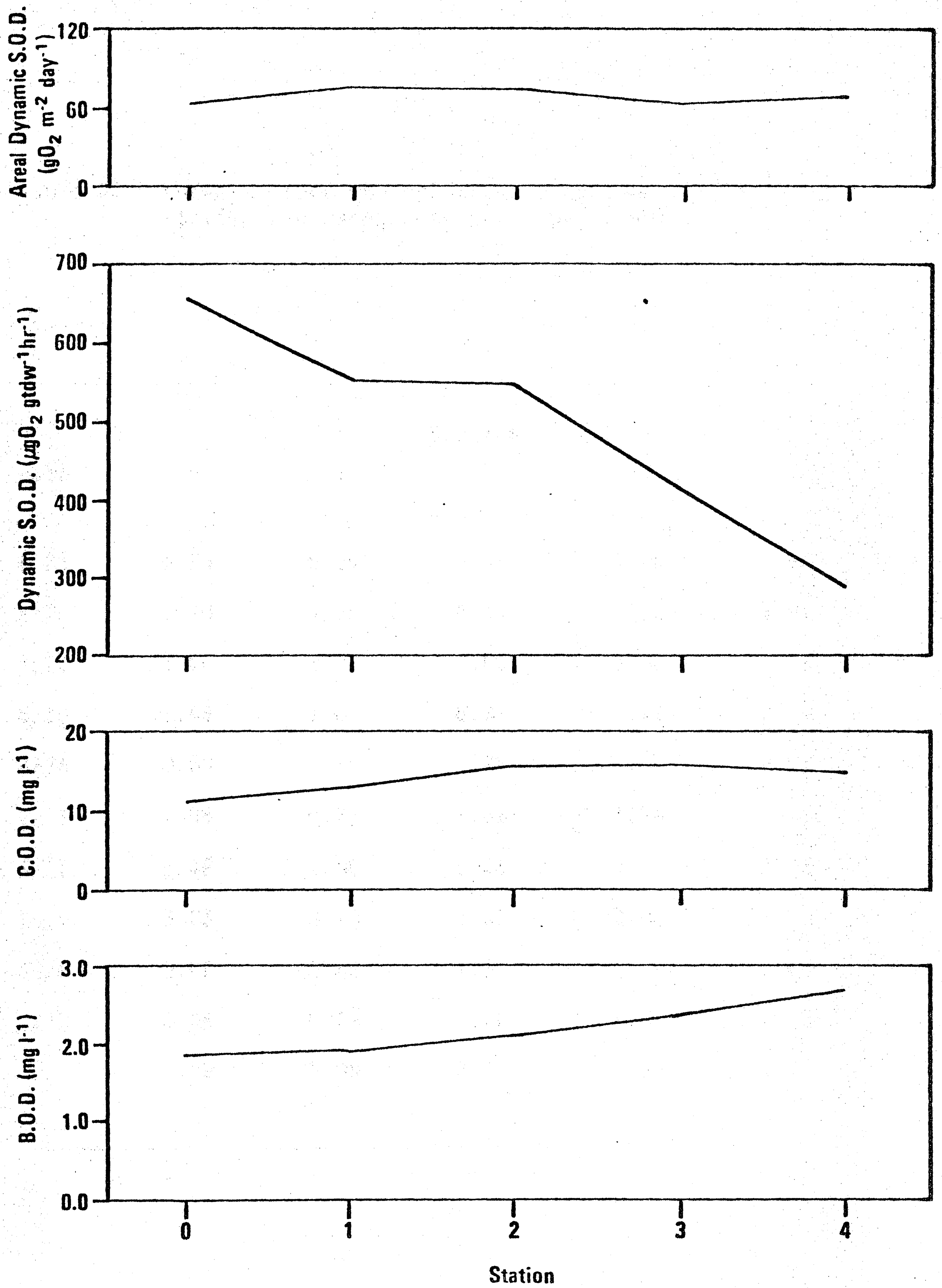

Figure 3. Biochemical oxygen demand (mg l^{-1}), chemical oxygen demand (mg l^{-1}), dynamic sediment oxygen demand (μgO_2 g total dry weight^{-1} hr^{-1}) and areal dynamic sediment oxygen demand (gO_2 m^{-2} day^{-1}) by station for the period June through November, Long Lake, Wa. (1981).

Phytoplankton Biovolume, Chlorophyll a, Primary Productivity and Secchi Disk Visibility

Total phytoplankton biovolume ranged between 0.22 $mm^3 l^{-1}$ at station 2 on 3 December to 6.35 $mm^3 l^{-1}$ at station 2 on 10 August (Table 34). Station 2 had the highest mean phytoplankton biovolume of 2.70 $mm^3 l^{-1}$ during the study period. The highest mean phytoplankton biovolume for the reservoir (4.45 $mm^3 l^{-1}$) occurred on 22 June.

Areal phytoplankton biovolume tended to increase down-reservoir (Table 35). The minimum mean areal phytoplankton biovolume for the study period was 10.36 $mm^3 m^{-2} \times 10^3$ at station 4, while the maximum was 19.05 $mm^3 m^{-2} \times 10^3$ at station 2. The highest mean areal phytoplankton biovolume for the reservoir (24.43 $mm^3 m^{-2} \times 10^3$) occurred on 22 June.

Mean chlorophyll a concentrations tended to decrease down-reservoir from 7.49 mg m^{-3} at station 4 to 5.22 mg m^{-3} at station 0 (Table 36). Chlorophyll a concentrations ranged from a maximum of 23.57 mg m^{-3} at station 4 on 10 August to 0.78 mg m^{-3} at station 1 on 3 December.

Areal mean chlorophyll a was relatively constant throughout the reservoir for the study period (Table 37). The seasonal maximum value (141.4 mg m^{-2}) occurred at station 4 on 10 August, while the minimum value (8.6 mg m^{-2}) occurred at station 1 on 3 December.

Mean daily primary productivity for the study period tended to increase up-reservoir from 0.62 gC m^{-2} day^{-1} (1.65 gO_2 m^{-2} day^{-1}) at station 0 to 0.99 gC m^{-2} day^{-1} (2.64 gO_2 m^{-2} day^{-1}) at station 4 (Table 38). A photosynthetic quotient of one was used to convert carbon units to oxygen. Reservoir mean values of primary productivity increased during the summer months and then declined during the fall. The maximum reservoir mean value was 2.23 gC m^{-2} day^{-1} (5.95 gO_2 m^{-2} day^{-1}), occurring on 10 August. A maximum value (4.81 gC m^{-2} day^{-1}, 12.8 gO_2 m^{-2} day^{-1}), occurred at station 4 on 10 August.

Table 34. Euphotic zone phytoplankton biovolume ($mm^3 \ l^{-1}$) by station and date, Long Lake, Wa. (1981).

			Station			
Date	0	1	2	3	4	$\bar{x}$
6/22	5.70	5.30	5.37	3.06	2.80	4.45
7/7	4.20	4.26	5.13	1.28	1.95	3.37
7/20	1.66	2.32	1.55	1.58	1.46	1.71
8/10	1.43	1.03	6.35	3.11	2.39	2.86
8/24	0.88	3.75	1.74	4.04	2.24	2.53
9/11	1.05	0.71	1.63	1.16	1.63	1.24
9/25	1.42	1.80	1.16	2.41	3.11	1.98
10/16	3.26	0.73	2.51	0.89	1.26	1.73
11/6	0.82	0.68	1.33	2.02	0.64	1.10
12/3	0.34	0.22	0.22	0.27	0.23	0.26
$\bar{x}$	2.08	2.08	2.70	1.98	1.77	

Table 35. Euphotic zone phytoplankton biovolume (mm^3 m^{-2} x 10^2) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	34.19	31.79	26.83	15.30	14.02	24.43
7/7	33.63	29.83	35.90	6.41	11.71	23.50
7/20	18.26	20.86	12.40	12.65	8.77	14.59
8/10	15.70	11.30	44.47	18.64	14.31	20.88
8/24	9.68	30.03	13.91	28.28	13.45	19.07
9/11	10.47	6.33	11.42	8.14	9.80	9.23
9/25	11.37	14.40	8.10	14.45	18.67	13.40
10/16	32.58	6.55	25.13	5.33	7.58	15.43
11/6	6.54	6.83	10.62	14.16	3.85	9.96
12/3	3.37	2.44	1.75	2.92	1.39	2.37
$\bar{x}$	17.58	16.04	19.05	12.63	10.36	

Table 36. Euphotic zone chlorophyll *a* concentrations (mg m^{-3}) by station and date, Long Lake, Wa. (1981).

Date	Station 0	1	2	3	4	$\bar{x}$
6/22	14.56	14.51	13.09	6.78	4.42	10.67
7/7	7.73	9.71	9.80	7.34	3.08	7.53
7/20	2.65	3.26	3.04	4.25	5.54	3.75
8/10	3.42	3.74	8.00	15.35	23.57	10.82
8/24	4.56	4.73	6.99	6.88	9.85	6.60
9/11	4.08	6.95	8.22	9.69	10.50	7.89
9/25	5.43	5.05	4.87	5.10	10.00	6.09
10/16	4.30	3.89	5.37	7.15	4.46	5.03
11/6	2.94	3.97	4.63	5.52	2.01	3.81
12/3	2.44	0.78	1.34	2.18	1.47	1.64
$\bar{x}$	5.22	5.66	6.54	7.03	7.49	

Table 37. Euphotic zone chlorophyll a (mg m^{-2}) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	87.4	87.1	65.5	33.9	22.1	59.2
7/7	61.8	67.9	68.6	36.7	18.5	50.7
7/20	29.2	29.3	24.3	34.0	33.2	30.0
8/10	37.6	41.1	64.0	92.1	141.4	75.3
8/24	50.2	37.8	55.9	48.2	59.1	50.2
9/11	40.8	62.6	57.5	67.8	62.9	58.3
9/25	43.4	40.4	34.1	30.6	60.1	41.7
10/16	43.0	35.0	53.7	42.9	26.8	40.3
11/6	23.5	39.7	37.0	38.6	12.1	30.2
12/3	24.4	8.6	10.7	24.0	8.8	15.3
$\bar{x}$	44.1	44.9	47.1	44.9	44.5	

Table 38. Primary productivity (gC m^{-2} day^{-1}) by station and date, Long Lake, Wa. (1981).

Date	Station 0	1	2	3	4	$\bar{x}$
6/22	0.86	0.80	0.64	0.28	0.17	0.55
7/7	1.04	1.29	1.38	0.62	0.29	0.92
7/20	0.62	0.63	0.53	0.91	0.79	0.70
8/10	0.90	1.04	1.40	3.01	4.81	2.23
8/24	1.44	1.12	1.27	1.53	1.88	1.45
9/11	0.66	1.10	0.98	1.25	1.28	1.05
9/25	0.49	0.44	0.39	0.36	0.53	0.44
10/16	0.17	0.15	0.22	0.17	0.10	0.16
11/6	0.04	0.07	0.12	0.06	0.02	0.06
12/3	0.01	<0.01	0.01	0.01	0.01	0.01
$\bar{x}$	0.62	0.66	0.69	0.82	0.99	

Secchi disk visibility ranged between 1.4m at station 4 on 10 August to 4.9m at stations 0 and 2 on 20 July (Table 39). Mean Secchi disk visibility tended to increase down-reservoir from 2.7m at station 4 to 3.9m at station 0. The minimum mean Secchi disk visibility for the reservoir was 1.7m on 22 June. The maximum value for the reservoir was 4.0m on 3 December.

Fluctuations in chlorophyll a coincided with changes in primary productivity, phytoplankton biovolume and Secchi disk visibility on both a volume and areal basis (Figures 4 and 5). Correlations between these parameters by station for June through November and by date over all stations are presented in Tables 40 and 41, respectively.

Relationship of Chlorophyll a, Phytoplankton Biovolume, Primary Productivity and Secchi Disk Visibility to Sediment Oxygen Demand, Biochemical Oxygen Demand and Chemical Oxygen Demand

Several investigators have discussed the relationship of trophic status and phytoplankton standing crop to various measures of oxygen demand (Burns and Ross, 1972; Hargrave, 1972b; and Welch, 1969). Cunningham and Pine (1969) concluded that phytoplankton in Long Lake moved horizontally as well as vertically and eventually settled to the bottom down-reservoir, the decomposition of the phytoplankton causing the observed hypolimnetic anoxia. Soltero *et al.* (1974) also attributed hypolimnetic oxygen depletion in Long Lake to phytoplankton decomposition. In this report chlorophyll a, phytoplankton biovolume, primary productivity and Secchi disk visibility were used as measures of phytoplankton standing crop.

Correlations between phytoplankton biovolume versus dynamic S.O.D.

Table 39. Secchi disk visibility (m) by station and date, Long Lake, Wa. (1981).

	Station					
Date	0	1	2	3	4	$\bar{x}$
6/22	1.8	1.6	1.8	1.6	1.7	1.7
7/7	3.0	2.1	2.2	1.8	2.2	2.3
7/20	4.9	4.7	4.9	3.7	2.4	4.1
8/10	4.2	3.8	3.6	2.0	1.4	3.0
8/24	4.7	3.9	3.7	3.2	2.8	3.7
9/11	3.6	3.5	3.4	2.7	2.6	3.2
9/25	4.2	4.3	3.9	2.5	2.8	3.5
10/6	4.0	3.6	3.3	2.5	3.0	3.3
11/6	4.2	4.4	3.4	3.9	3.7	3.9
12/3	3.9	4.3	3.0	4.2	4.7	4.0
$\bar{x}$	3.9	3.6	3.3	2.8	2.7	

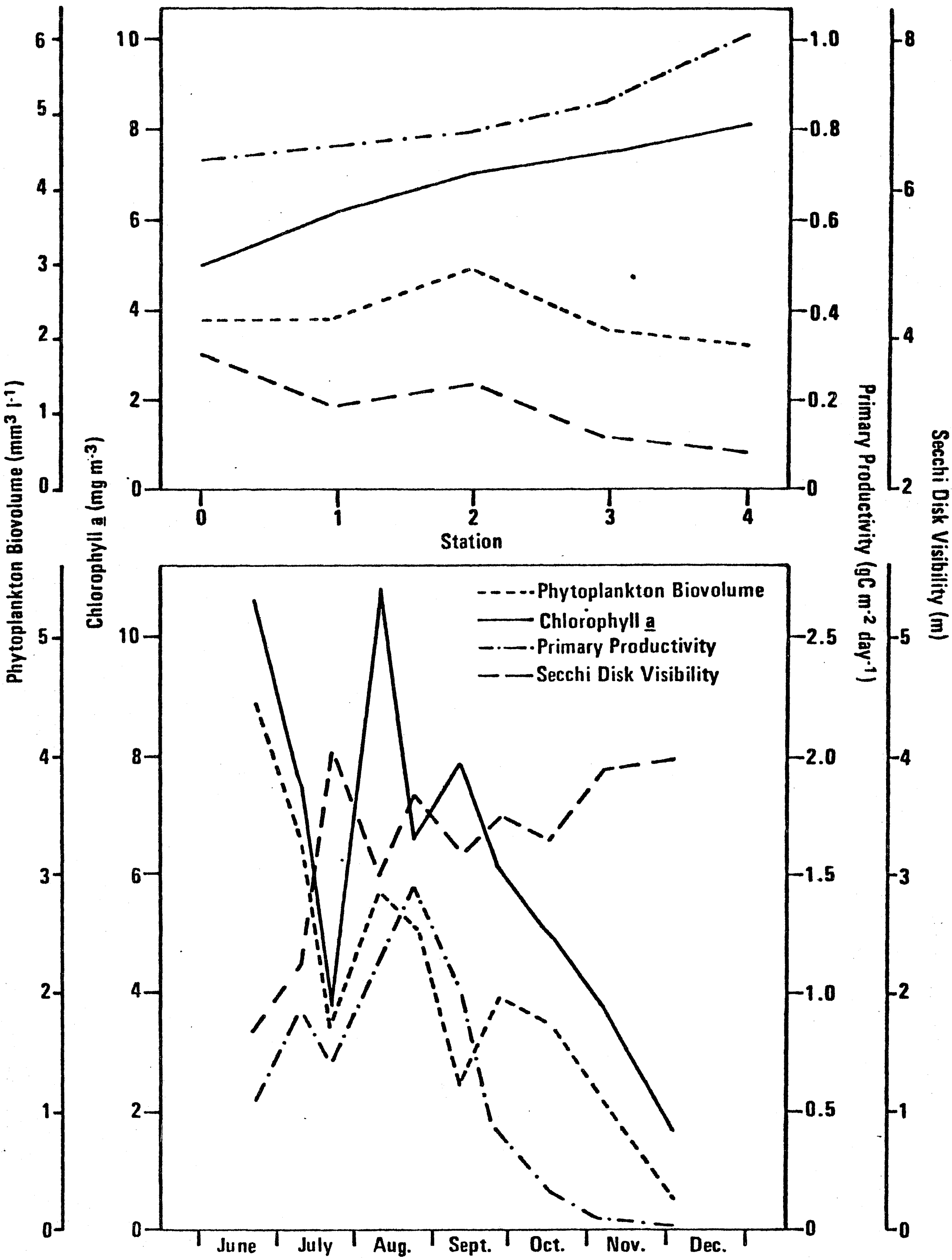

Figure 4. Phytoplankton biovolume (mm^{-3} l^{-1}), chlorophyll a (mg m^{-3}), primary productivity (gC m^{-2} day^{-1}) and Secchi disk visibility (m) by station for the period June through November and by date over all stations, Long Lake, Wa. (1981).

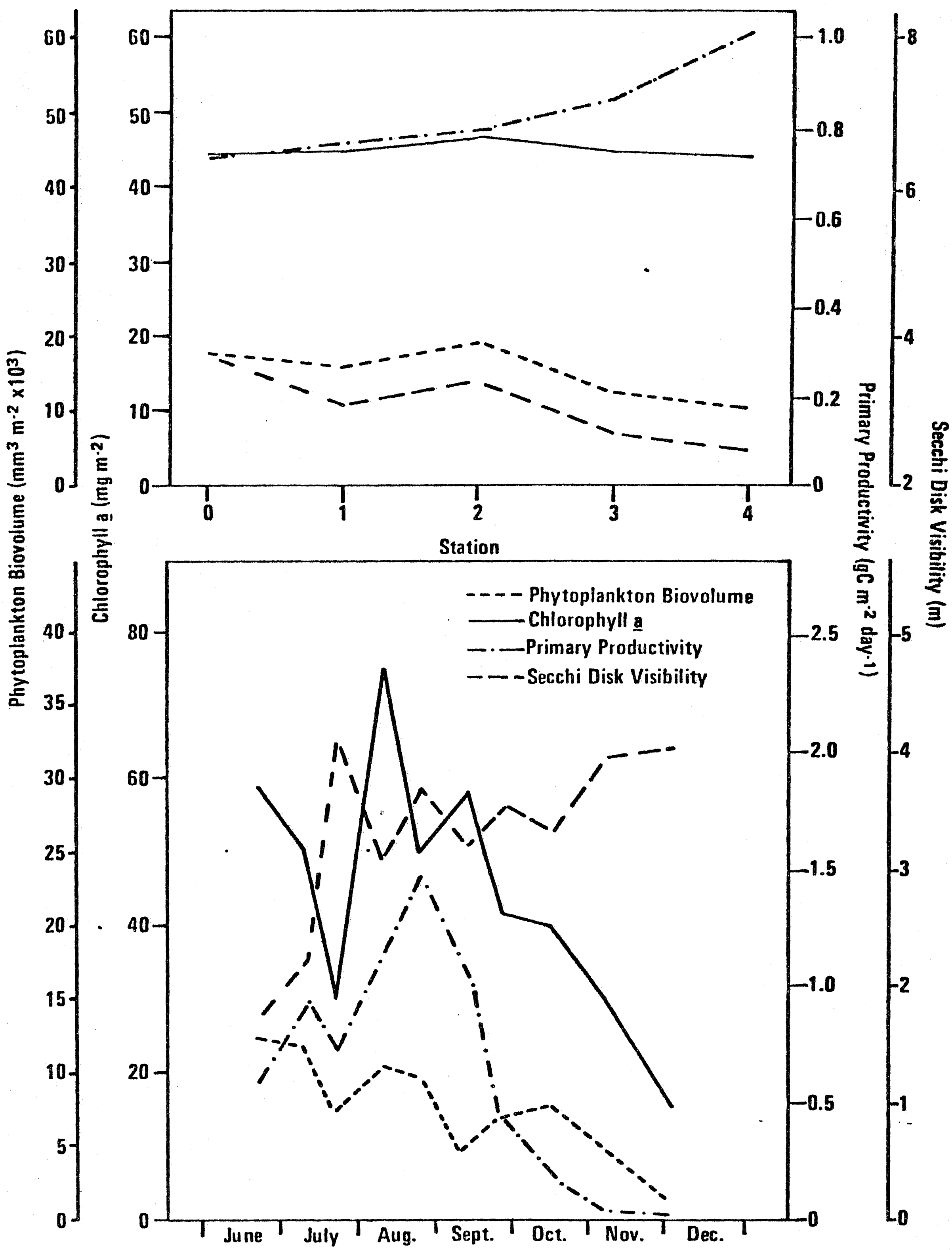

Figure 5. Phytoplankton biovolume (mm^3 m^{-2} x 10^3), chlorophyll a (mg m^{-2}), primary productivity (gC m^{-2} day^{-1}) and Secchi disk visibility (m) by station for the period June through November and by date over all stations, Long Lake, Wa. (1981).

Table 40. Correlation coefficients, (n = 5), for phytoplankton biovolume versus primary productivity versus Secchi disk visibility and for chlorophyll a versus primary productivity and Secchi disk visibility by station for the period June through November, Long Lake, Wa. (1981).

Variables	r	P
Phytoplankton biovolume (mm^3 m^{-2} x 10^3) vs Primary productivity (gC m^{-2} day^{-1})	-0.90	0.05
Phytoplankton biovolume (mm^3 m^{-2} x 10^3) vs Secchi disk visibility (m)	0.89	0.05
Chlorophyll a (mg m^{-3}) vs Primary productivity (gC m^{-2} day^{-1})	0.91	0.05
Chlorophyll a (mg m^{-3}) vs Secchi disk visibility (m)	-0.88	0.05
Primary productivity (gC m^{-2} day^{-1}) vs Secchi disk visibility (m)	-0.88	0.05

Table 41. Correlation coefficients, (n = 10), for phytoplankton biovolume versus chlorophyll *a* and Secchi disk visibility and for chlorophyll *a* versus primary productivity and Secchi disk visibility by date for all stations, Long Lake, Wa. (1981).

Variables	r	P
Phytoplankton biovolume ($mm^3\ l^{-1}$) vs Chlorophyll *a* ($mg\ m^{-3}$)	0.81	0.01
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Chlorophyll *a* ($mg\ m^{-2}$)	0.71	0.05
Phytoplankton biovolume ($mm^3\ l^{-1}$) vs Secchi disk visibility (m)	-0.85	0.01
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Secchi disk visibility (m)	-0.74	0.02
Chlorophyll *a* ($mg\ m^{-3}$) vs Primary productivity ($gC\ m^{-2}\ day^{-1}$)	0.70	0.05
Chlorophyll *a* ($mg\ m^{-2}$) vs Primary productivity ($gC\ m^{-2}\ day^{-1}$)	0.81	0.01
Chlorophyll *a* ($mg\ m^{-3}$) vs Secchi disk visibility (m)	-0.79	0.01
Chlorophyll *a* ($mg\ m^{-2}$) vs Secchi disk visibility (m)	-0.66	0.05

on a volume and areal basis by date over all stations are presented in Table 42. All correlations between phytoplankton biovolume and dynamic S.O.D. were negative ($r \geq -0.80$). This negative relationship probably represents a time lag between phytoplankton production and when it eventually settles to the bottom effecting an increased S.O.D. Chlorophyll _a_, primary productivity and Secchi disk visibility were not significantly correlated with dynamic S.O.D., areal dynamic S.O.D., B.O.D. OR C.O.D. by date over all stations.

Table 43 shows correlations between chlorophyll _a_, phytoplankton biovolume, primary productivity and Secchi disk visibility versus B.O.D. and dynamic S.O.D. by station for the period June through November. As might be expected chlorophyll _a_, and primary productivity were positively correlated ($r \geq 0.93$) with B.O.D. Areal phytoplankton biovolume was positively correlated ($r = 0.92$) with areal B.O.D. Secchi disk visibility was negatively correlated ($r = -0.85$) with B.O.D. Chlorophyll _a_ and primary productivity were negatively correlated ($r \geq -0.94$) with dynamic S.O.D. Areal phytoplankton biovolume was positively correlated ($r = 0.93$) with dynamic S.O.D.

Areal measures of phytoplankton standing crop with the exception of primary productivity were greater in the lower part of the reservoir whereas volume measures of phytoplankton standing crop were greater in the upper part of the reservoir. This corresponds to a higher B.O.D. in the upper reservoir and a higher areal B.O.D. in the lower reservoir. Dynamic S.O.D. is greater in the lower reservoir perhaps indicating a settling area for organic material. These results suggest

Table 42. Correlation coefficients, (n = 10), for phytoplankton biovolume versus dynamic sediment oxygen demand and areal dynamic sediment oxygen demand by date over all stations, Long Lake, Wa. (1981).

Variables	r	P
Phytoplankton biovolume ($mm^3\ l^{-1}$) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	-0.83	0.01
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	-0.85	0.01
Phytoplankton biovolume ($mm^3\ l^{-1}$) vs Areal dynamic S.O.D. ($gO_2\ m^{-2}\ day^{-1}$)	-0.80	0.01
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Areal dynamic S.O.D. ($gO_2\ m^{-2}\ day^{-1}$)	-0.83	0.01

Table 43. Correlation coefficients, (n = 5), for chlorophyll a, phytoplankton biovolume, primary productivity, and Secchi disk visibility versus biochemical oxygen demand and dynamic sediment oxygen demand by station for the period June through November, Long Lake, Wa. (1981).

Variables	r	P
Chlorophyll a ($mg\ m^{-3}$) vs Biochemical oxygen demand ($mg\ l^{-1}$)	0.93	0.05
Chlorophyll a ($mg\ m^{-3}$) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	-0.94	0.02
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Areal B.O.D. ($mg\ m^{-2} \times 10^3$)	0.92	0.05
Phytoplankton biovolume ($mm^3\ m^{-2} \times 10^3$) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	0.93	0.05
Primary productivity ($gC\ m^{-2}\ day^{-1}$) vs Biochemical oxygen demand ($mg\ l^{-1}$)	0.98	0.01
Primary productivity ($gC\ m^{-2}\ day^{-1}$) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	-0.97	0.01
Secchi disk visibility (m) vs Biochemical oxygen demand ($mg\ l^{-1}$)	-0.85	0.05
Secchi disk visibility (m) vs Dynamic S.O.D. ($ugO_2\ gtdw^{-1}\ hr^{-1}$)	0.95	0.02

that the phytoplankton standing crop does effect an oxygen demand in Long Lake both within the water column and at the sediment-water interface and is a primary factor in the seasonal decline of dissolved oxygen levels in Long Lake. To further support this conclusion additional study including sedimentation traps, hypolimnetic chlorophyll a determinations and a differentiation of S.O.D. into a biological and a chemical S.O.D. would be helpful.

SUMMARY AND CONCLUSIONS

1. The S. E. and DAM had the lowest mean dissolved oxygen concentrations of all Spokane River and tributary stations during the study period.
2. Sewage effluent B.O.D. and C.O.D. was approximately three times that of any other Spokane River or tributary station.
3. Maximal inflow and discharge from Long Lake in 1981 occurred in May. A maximum retention time of 65 days occurred in August.
4. Thermal stratification in the reservoir was evident from July to late September.
5. Dissolved oxygen concentrations declined throughout the summer and minimum values occurred by the end of August. The extent and duration of anoxia during 1981 appears to be less than that in other post-AWT years.
6. The AHOD calculated for 1981 was less than those calculated for previous study years. Post-AWT mean AHOD was significantly ($P = 0.05$) less than pre-AWT mean AHOD. Chlorophyll *a*, phytoplankton biovolume and primary productivity were positively correlated ($r \geq 0.73$) with AHOD on a volume and areal basis.
7. Mean dynamic S.O.D. increased down-reservoir from station 4 to station 0. Dynamic sediment oxygen demand also increased with time attaining maximal values on 3 December. Stationary S.O.D. was relatively constant throughout the study period. Dynamic S.O.D. values were 10 to 100 times greater than those of stationary S.O.D.
8. Mean percent organic matter correlated ($r = 0.99$) with mean dynamic S.O.D. Mean percent organic matter increased down-reservoir.

9. Mean B.O.D. decreased down-reservoir. Maximum B.O.D. for the reservoir occurred in late September. Influent B.O.D. made a small contribution to the total reservoir B.O.D. Reservoir B.O.D. was 20 to 100 times greater than influent B.O.D. Hypolimnetic B.O.D. was four to 30 times greater than influent B.O.D. Effluent B.O.D. was approximately equal to influent B.O.D.

10. Chemical oxygen demand was relatively constant throughout the reservoir. Reservoir C.O.D. was 10 to 140 times the influent C.O.D. during the summer months. Hypolimnetic C.O.D. was five to 40 times the influent C.O.D. during the summer months. Effluent C.O.D. usually exceeded influent C.O.D. throughout the study period.

11. Fluctuations in B.O.D. and C.O.D. appeared to be inversely related and not related to dynamic S.O.D. or areal dynamic S.O.D. by date over all stations. However, by station over all dates, an inverse correlation ($r = -0.96$) existed between B.O.D. and dynamic S.O.D.

12. Correlations were found between chlorophyll a, phytoplankton biovolume and primary productivity, on a volume and areal basis, versus B.O.D., dynamic S.O.D. and areal dynamic S.O.D. These results suggest that phytoplankton standing crop does effect an oxygen demand in Long Lake both within the water column and at the sediment water interface and is a primary factor in the seasonal decline of dissolved oxygen levels in Long Lake.

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