LIMNOLOGIC CONDITIONS IN THREE EXISTING NEVADA PIT LAKES: OBSERVATIONS AND MODELING USING CE-QUAL-W2

David Atkins
Senior Hydrologist

J. Houston Kempton
Senior Geochemist

Todd Martin
Geochemist

PTI Environmental Services
4940 Pearl East Circle, Suite 300
Boulder, Colorado 80301
Tel: (303) 444-7270
Facsimile: (303) 444-7528
E-Mail: atkinsd@boulder.pti-enviro.com

Patrick Maley
Environmental Manager

Santa Fe Pacific Gold Corporation
Twin Creeks Mine
Golconda, Nevada 89414

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David Atkins, Senior Hydrologist; J. Houston Kempton, Senior Geochemist;
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Patrick Maley, Environmental Manager
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Twin Creeks Mine
Golconda, Nevada 89414

ABSTRACT

Limnologic processes that influence the evolution of mine pit lakes include the production of biomass and hydrodynamic mixing. Biological productivity may influence wildlife use, and when combined with lake hydrodynamics, affects the dissolved oxygen distribution and the corresponding chemical reactions within the lake.

Limnologic parameters (temperature and dissolved oxygen profiles, plankton speciation and abundance, and nutrient concentrations) were measured in three existing pit lakes in Nevada to develop a database to support predictions of limnologic conditions in future mine pit lakes. Two of the lakes were thermally stratified during summer sampling and completely vertically mixed during winter, whereas the third lake was completely mixed in summer and winter. The first lake formed when an open-pit copper mine was flooded by rebounding groundwater; it has a maximum depth of 110 m, and is seasonally stratified, well oxygenated, and oligotrophic. The second lake formed in an open-pit gold mine, has a maximum depth of 17 m, and is a seasonally stratified, mesotrophic lake that develops an anoxic hypolimnion at the end of the summer stratified period. The third lake also formed in an open-pit gold mine, has a maximum depth of 7 m, and is an isothermal, saline, well-oxygenated, oligotrophic lake.

Data from the field study were used to develop limnological models of the lakes using the U.S. Army Corps of Engineers hydrodynamic and water quality model CE-QUAL-W2. The model sufficiently describes major limnologic processes, including seasonal variations in temperature and dissolved oxygen concentration, supporting the use of this model to simulate hydrodynamic conditions and biological productivity in mine pit lakes. Information from the field and modeling study is being used to simulate future limnologic conditions in lakes such as the Twin Creeks mine pit lake, which have not yet formed.

Keywords: Pit lake, limnology, hydrodynamics, biological productivity, turnover, geochemical stability, models

INTRODUCTION

Many current and historical open-pit mine excavations in the United States extend below the regional groundwater table. Following cessation of dewatering activities at these mines, the water table rebounds, forming lakes in the open pits. To date, 17 mine pit lakes have formed in the state of Nevada (where much of the current U.S. metal mining is conducted), and 19 additional lakes are likely to form in the future (Nevada Bureau of Mines and Geology 1995).

Although these lakes are significant long-term features that may be used by humans and wildlife, very little site-specific data have been collected on their limnology. Consequently, recent pit-lake ecological risk assessments have relied on data collected from natural lakes and reservoirs, which may not accurately represent pit lakes. We studied three existing mine pit lakes in Nevada, generating data that can be compared to natural lakes, and will be useful in validating the hydrogeochemical models that are used to predict the limnology and chemical composition of these lakes.

LIMNOLOGIC PROCESSES

The important limnologic processes that influence water quality in pit lakes are hydrodynamic mixing and biological productivity (Wetzel 1983). Hydrodynamic mixing is influenced by wind speed and direction, morphology of the pit lake, length of the lake surface (fetch), and water density, which is a function of thermal and chemical gradients in the water column. Depending on site-specific conditions, these gradients may induce either relatively complete vertical mixing of the water column (e.g., the annual "turnover" of water that occurs in most lakes in temperate climates, termed holomixis), or relatively stable stratification of lake waters in which vertical mixing processes are strongly suppressed.

In some environments, lakes develop a salinity gradient at depth (a chemocline), which permanently inhibits mixing of the entire water column (meromixis). Meromixis can occur when large salinity differences exist between inflowing water and lake water (e.g., freshwater surface inflow into a saltwater lake, or saltwater intrusion into a freshwater lake) or when sediments release dissolved constituents from organic matter. Nevada pit lakes typically do not exhibit the conditions necessary to develop a chemocline. The primary source of inflow is groundwater that is uniformly distributed throughout the lake. Outflow from the lake is dominated by evaporation, which concentrates salts at the surface. These salts mix completely with the water column as the heavier surface water sinks. In addition, biological inputs to the lakes are typically low, which precludes buildup of organic matter in bottom sediments.

Nevada is in a temperate zone, where lakes generally exhibit isothermal conditions in the winter, followed by stratification in the spring and summer, with a corresponding peak in productivity. During the period of stratification, the warmer, less dense water near the surface defines the epilimnion, and the cold, more dense water near the bottom defines the hypolimnion (usually with a temperature 1–2° above 4 °C, the maximum density for pure water). The depth interval over which the water temperature changes from the epilimnion temperature to the hypolimnion temperature is termed the metalimnion, and the depth of the maximum rate of temperature change is termed the thermocline.

The surface water cools in the fall, and when its temperature reaches 4°C, the lake may undergo complete vertical mixing, or turnover, returning hypolimnetic nutrients to surface waters, which receive enough light to support biological productivity (the euphotic zone). Lakes that mix completely are termed holomictic, whereas lakes that exhibit a permanent chemical density gradient (chemocline) do not mix completely and are termed meromictic. Temperate-zone lakes may develop ice cover in mid-winter, and when this ice cover breaks up in the spring, the lake may turn over again. Lakes that turn over once per year, in the fall, are termed monomictic, and lakes that turn over in the fall and spring are termed dimictic.

Biological productivity is determined by light intensity, nutrient availability, and types of plankton present, and temperate-zone lake productivity is most dependent on nutrient availability. In most lakes, the level of productivity corresponds to the total phosphorus loading rate and corresponding water-column concentration. Highly productive (eutrophic) lakes generally have total water-column phosphorus concentrations greater than 0.03 mg/L, while lakes that exhibit low productivity (oligotrophic) generally have total water-column phosphorus concentrations below 0.01 mg/L (Wetzel 1983). Productivity of an individual lake, however, also depends on lake morphometry, chemistry, and local climate, leading to a relatively large range in trophic status for a given total phosphorus concentration, as is evidenced by the study lakes.

Together, the processes of hydrodynamic mixing and biomass production will influence the distribution of oxygen in the water column. Hence, a thorough understanding of these processes is necessary for predicting chemical interactions and attenuation mechanisms that are influenced by the dissolved oxygen concentration and corresponding oxidation state of iron (e.g., sorption of metals to amorphous ferrous hydroxides) in the pit lake.

DESCRIPTION OF THE STUDY AREA

Nevada mine pit lakes exhibit unique morphology and hydrology, which distinguish them from natural lakes and reservoirs. These characteristics also have a profound effect on geochemistry and limnology:

- The lakes lie in highly mineralized zones, so their geochemical characteristics are highly site specific, and metals and acid loading from pit walls can influence the chemistry and toxicity of lake water.
- The hydrology is dominated by groundwater inflow, so organic carbon inputs are primarily autochthonous.
- Lake outflow often occurs primarily through evaporation, and the lakes can be highly alkaline and/or saline.
- The lakes have large relative depths (large depth-to-surface-area ratios), which can affect lake hydrodynamics.
- The steep pit walls allow only minimal shoreline development of poor-quality sediment, so the lakes exhibit little littoral-zone habitat and shore-zone vegetation (typically <1% of shore zone).

The three Nevada lakes studied represent a range of size and biological productivity. The Anaconda lake, near Yerington, began filling in an open-pit copper mine in 1977 and currently has a surface area of 175 hectares and a maximum depth of 100 m; it is a seasonally stratified, well-oxygenated, oligotrophic lake. The Aurora lake, near Hawthorne, began forming in an open-pit gold mine in 1993 and has a surface area of 1 hectare and a maximum depth of 20 m; it is a seasonally stratified lake, seasonally anoxic at depth, and mesotrophic. The Boss lake, near Tonopah, began forming in an open-pit gold mine in 1989 and has a surface area of 0.25 hectares and a maximum depth of 7 m; it is an isothermal, saline (TDS=12,000 mg/L), well-oxygenated, low-productivity lake.

METHODS

Physical parameters were measured *in situ* throughout the water column using a calibrated Hydrolab multiparameter water quality instrument. At each sampling location, the instrument was lowered through the water column, measuring temperature, specific conductivity (SC), dissolved oxygen (DO), pH, and Eh approximately every 2 m depth. The data were used to identify temperature zones (e.g., the thermocline, epilimnion, and hypolimnion) and distinct geochemical zones (e.g., anoxic zones and chemically stratified zones).

Water samples for chemical analyses from each distinct zone were collected using weighted Tygon tubing and a peristaltic pump. Samples were collected for total and dissolved (<0.45 μm) silica. In addition, water was passed through a 1-μm glass fiber filter, and the filter was collected for determination of total particulate phosphorus. The filtrate was collected and frozen for determination of total dissolved phosphorus, nitrate, and ammonia. This process was repeated, and the filter was collected, placed in ethanol, and submitted for determination of chlorophyll-a content.

The extent of the photic zone (the zone with sufficient light for photosynthesis to occur) was measured by lowering a Secchi disk until it was no longer visible (i.e., the Secchi depth). Phytoplankton samples were collected at both discrete and composite depth intervals. Bulk water samples were collected from discrete sampling points using the peristaltic pump, and composite samples were collected using a weighted 1/8th-inch Tygon tube lowered to the desired depth, pinched at the top, and withdrawn from the water column. Zooplankton samples were collected by lowering a 37-μm plankton net to a specific depth and pulling the net up through the water column to the surface. All plankton samples were placed in amber glass jars and preserved with Lugol's solution (buffered iodine; 2% for phytoplankton and 4% for zooplankton).

Nutrient samples were submitted to the Center for Limnology at the University of Colorado (CU) for analysis of silica, total dissolved phosphorus, and ammonia (spectrophotometric techniques) and nitrate (ICP). Filter material also was submitted to CU for analysis of total particulate phosphorus (pyrolosis technique) and chlorophyll-a by hot ethanol extraction correcting for phaeophyton.

The phytoplankton and zooplankton samples were analyzed using standard limnological analytical techniques (Wetzel and Likens 1991). The samples were placed in a sedimentation chamber fitted with a slip cover at the bottom and placed in an inverted microscope. The iodine in the Lugol's preservative stained the cells and organisms and increased their weight to enhance sedimentation. Following settling, the number of cells and/or organisms, size of cells, and species were determined visually using an inverted optical microscope.

FIELD SAMPLING RESULTS

The Anaconda and Aurora lakes are seasonally stratified, and the Boss lake is isothermal year-round (Figure 1). None of the three lakes exhibits a salinity gradient (chemocline), which would inhibit complete mixing at turnover. The seasonal DO profiles of the Anaconda lake are typical of low-productivity lakes with large relative depths, while the DO profile for the Aurora lake reflects the seasonal variation that occurs in shallow, productive lakes (Wetzel 1983). The Boss lake is well oxygenated year-round, because of its low productivity and small size, which allow complete mixing year-round. The increase in DO at depth in winter in all three lakes, together with the uniform density profile, indicate that the lakes are holomictic. All three lakes are near neutral (pH=7 to 8.5) and moderately alkaline (80–140 mg/L as $CaCO_3$).

Phytoplankton concentrations correlate well with nutrient concentrations (total phosphorus <10 µg/L; Table 1) in the Anaconda pit lake, and the population shifted from predominantly green algae in summer to predominantly blue-green algae in winter and spring (Figure 2; Table 2). The positive heterograde DO profile (peak in DO at the thermocline) in the spring can be explained by the large population of blue-green algae at this depth (Figure 3). Zooplankton were limited in number and in species diversity, with Bdelloid rotifers making up nearly 100% of the samples in each season. Chlorophyll-a concentrations (~ 0.1µg/L) indicate that total pelagic-zone biomass is low.

The Aurora lake also showed seasonal population shifts in phytoplankton, with a large bloom of green algae in summer, and low concentrations of all species in winter and spring (Figure 2; Table 2). In lakes with nitrogen-to-phosphorus ratios greater than 10, phosphorus controls productivity (Thomann and Mueller 1987). Aurora lake nutrient concentrations indicate severe phosphorus limitation (total P ~20 µg/L; NO_3-N ~5,000 µg/L) and that the lake should be mesotrophic. The lower phytoplankton concentration in this lake vs. Anaconda is probably due to the sample depth interval. The Secchi depth in this lake is 1–2 m, whereas integrated samples were collected to a depth of 8 m, beyond which phytoplankton are unlikely to grow. In addition, the chlorophyll-a concentration is five times higher than that measured in the Anaconda lake, indicating that the lake is more productive. The summer dissolved oxygen profile indicates that the large bloom of green algae in summer is causing a large oxygen demand in deep water during the stratified period. The Aurora lake zooplankton concentration is 20 times larger than those measured in the Anaconda lake and 100 times larger than those measured in the Boss lake. Species diversity was also much higher.

Boss lake nutrient concentrations are extremely high (total P ~500 µg/L; NO_3-N ~25,000 µg/L) (Table 1), but phytoplankton and zooplankton concentration and diversity do not indicate that the lake is productive (Tables 2 and 3). Productivity in this lake is probably limited by water chemistry and potential metals toxicity (TDS = 12,000 mg/L; dissolved arsenic = 1 mg/L).

LIMNOLOGICAL MODELING

Mine pit-lake permitting investigations often require predictions of the composition and behavior of lakes that have not yet formed. To evaluate the ability of models to predict limnologic conditions in pit lakes, the U.S. Army Corps of Engineers limnological model CE-QUAL-W2 (Cole and Buchak 1995) was configured to replicate temperature and DO conditions in the Anaconda and Aurora lakes. The Boss lake was not included in this study, because it appears to exhibit chemical effects that inhibit phytoplankton productivity, which limnological models cannot simulate.

CE-QUAL-W2 simulates mixing that occurs within a water body because of wind, density gradients within the water column, and biological productivity (e.g., plankton population, nutrient utilization, photosynthesis, and respiration). The bathymetric profile of each lake, meteorological data, and measured nutrient concentrations were incorporated into models of the two lakes. Physical constants are used in the model to simulate the hydrodynamic mixing that results from density gradients and chemical coefficients. These constants, used to simulate organic matter decay and nutrient transformations, were set to default values (Cole and Buchak 1995; Environmental Laboratory 1986). Biological coefficients are used to predict growth of the phytoplankton community, and values for these coefficients were selected based on literature values (Cole and Buchak 1995; Environmental Laboratory 1986; Environmental Research Lab 1985).

Model results indicated that CE-QUAL-W2 is able to describe hydrodynamic conditions (e.g., thermal stratification and turnover) and DO conditions (e.g., peaks in DO due to phytoplankton photosynthesis, and reduction in DO due to phytoplankton decay; Figures 4 and 5) in both lakes.

CONCLUSION

Although the lakes studied are morphologically very different from natural lakes and reservoirs, temperature, specific conductivity, pH, and dissolved oxygen profiles indicate that the physical and biological characteristics of the lakes are consistent with those of natural lakes. For example:

- Temperature, specific conductivity, and DO profiles indicate that the lakes mix completely at turnover.
- DO profiles are consistent with those measured in lakes containing pelagic-zone phytoplankton.

Consequently, the unique setting of the lakes does not appear to greatly affect pelagic-zone behavior, and model results indicate that pit-lake limnology can be simulated provided geochemical conditions do not limit biological productivity.

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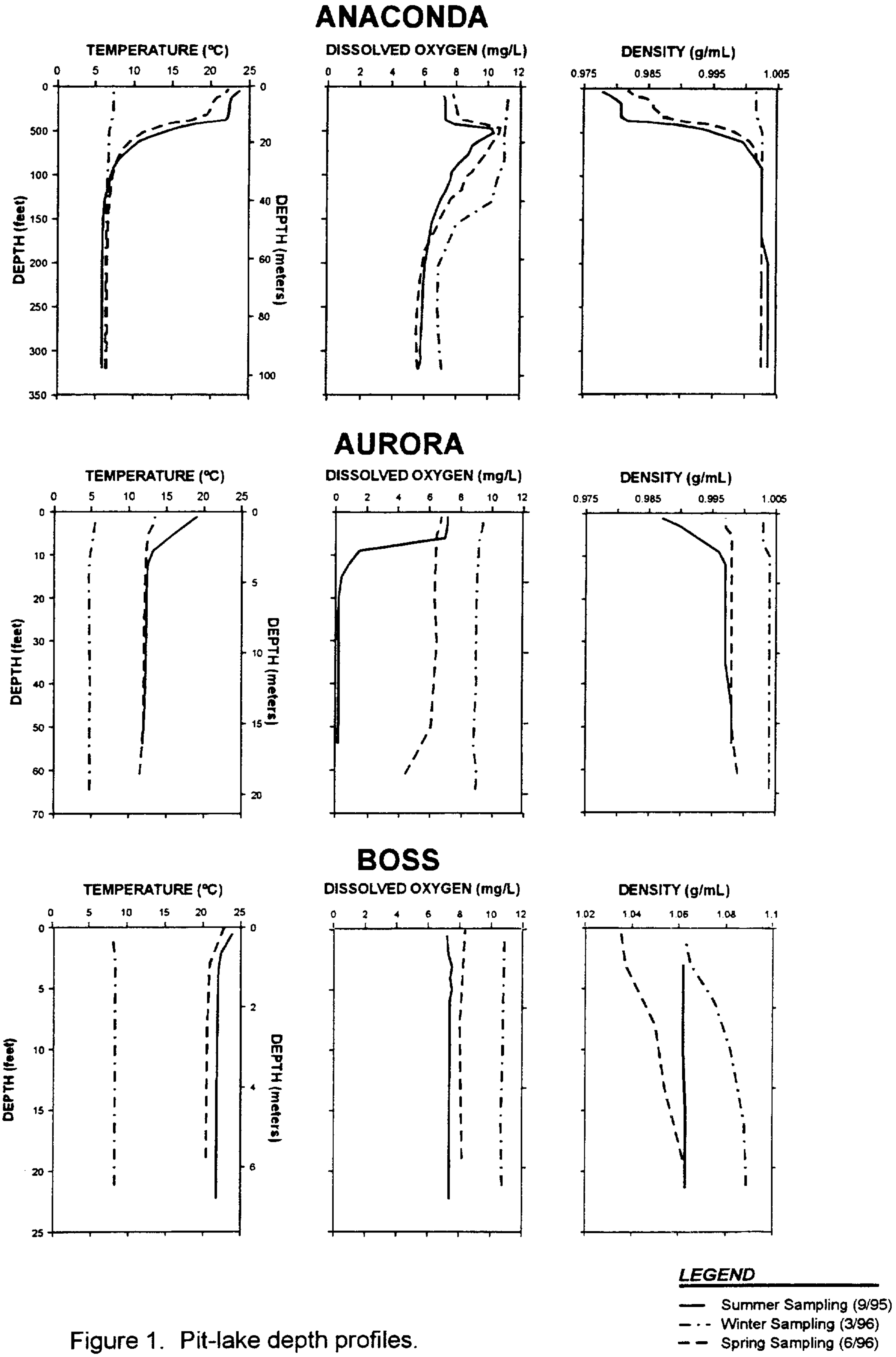

Figure 1. Pit-lake depth profiles.

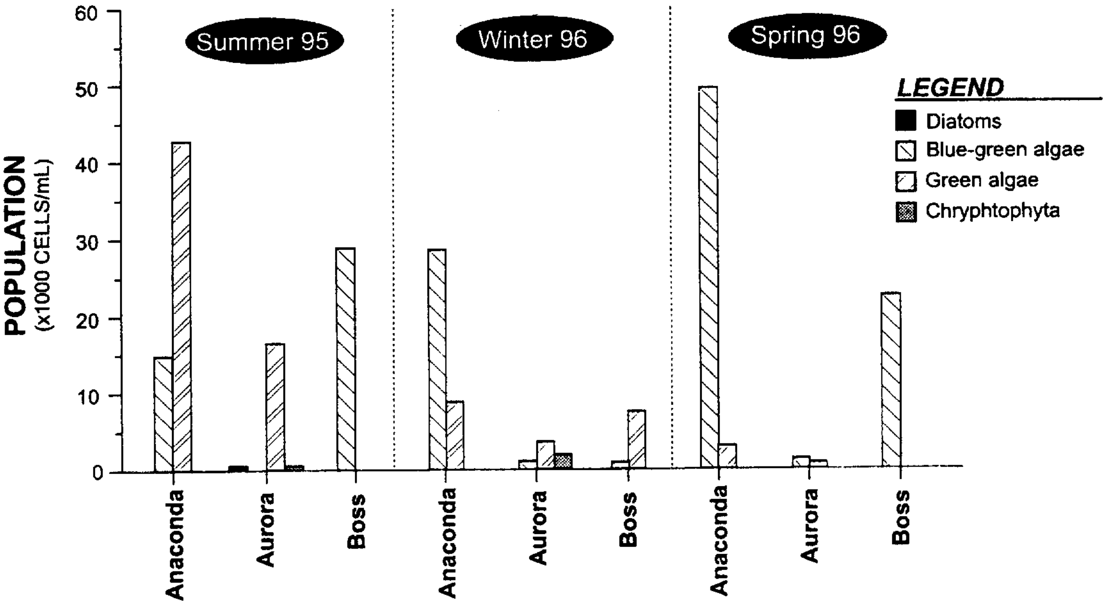

Figure 2. Seasonal phytoplankton concentrations.

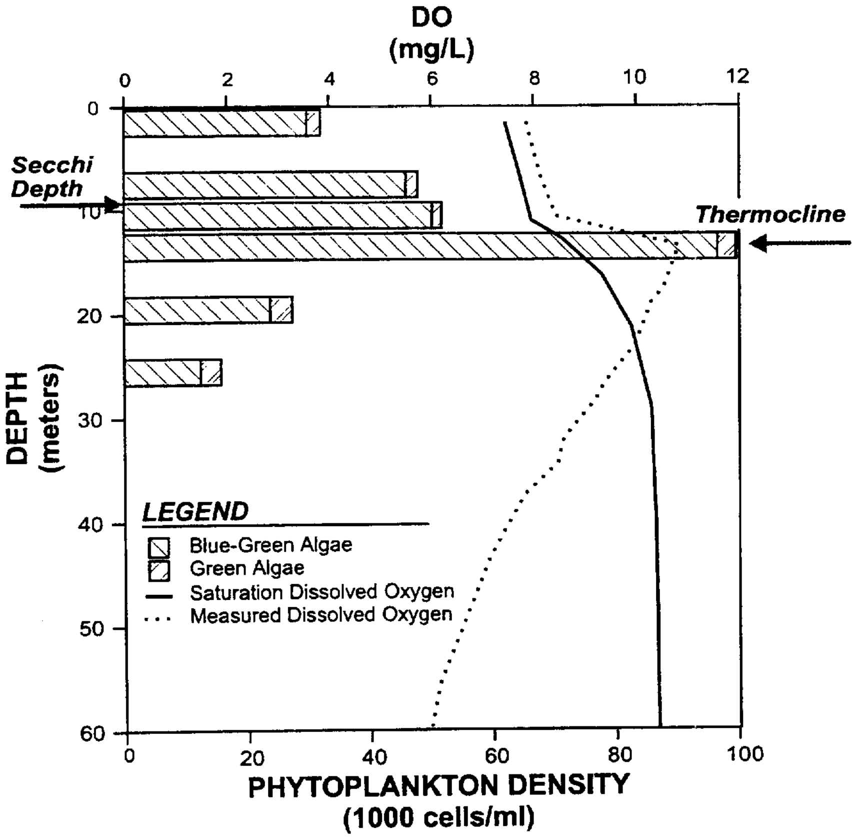

Figure 3. Anaconda pit lake phytoplankton and dissolved oxygen profile.

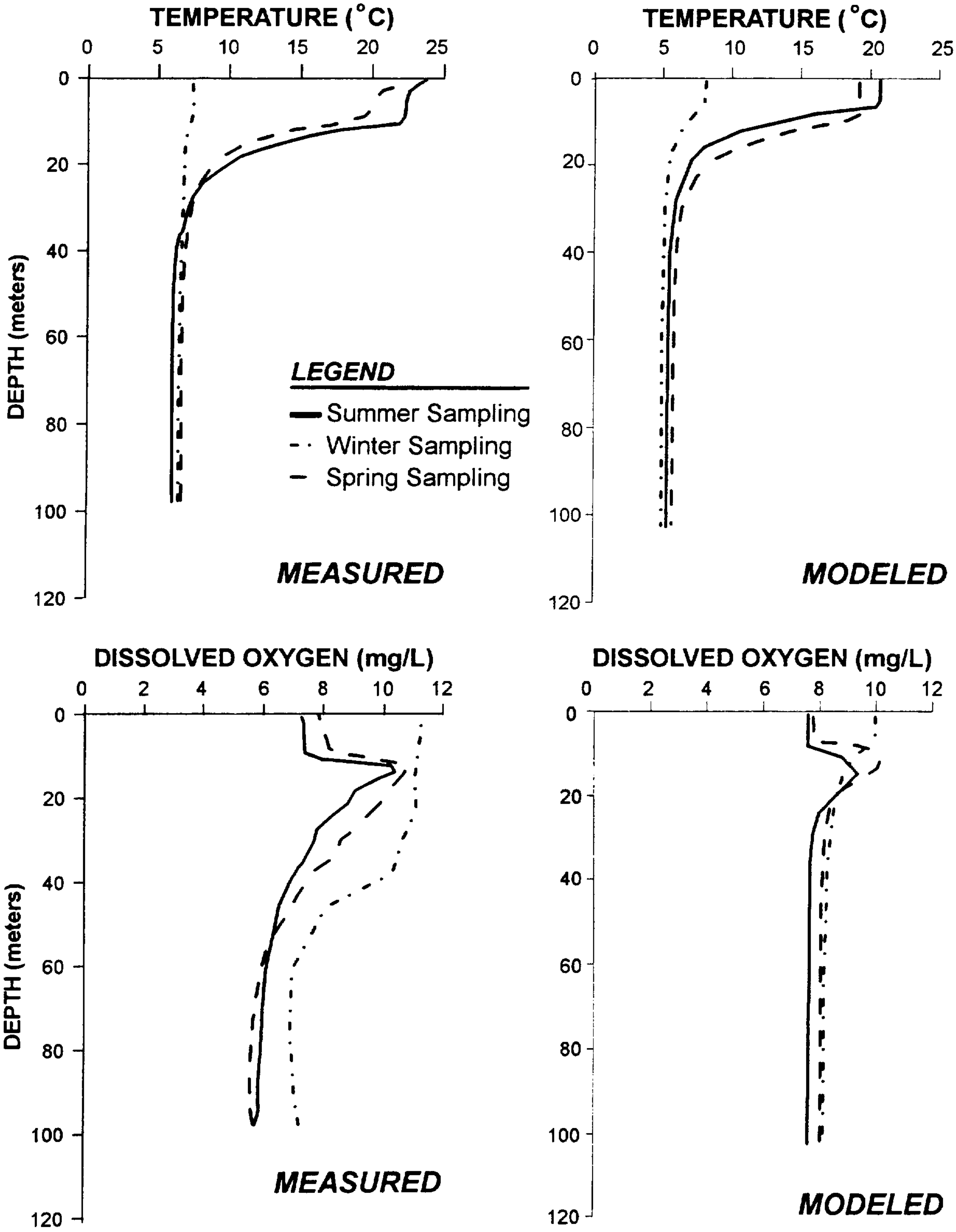

Figure 4. Anaconda lake measured and modeled results.

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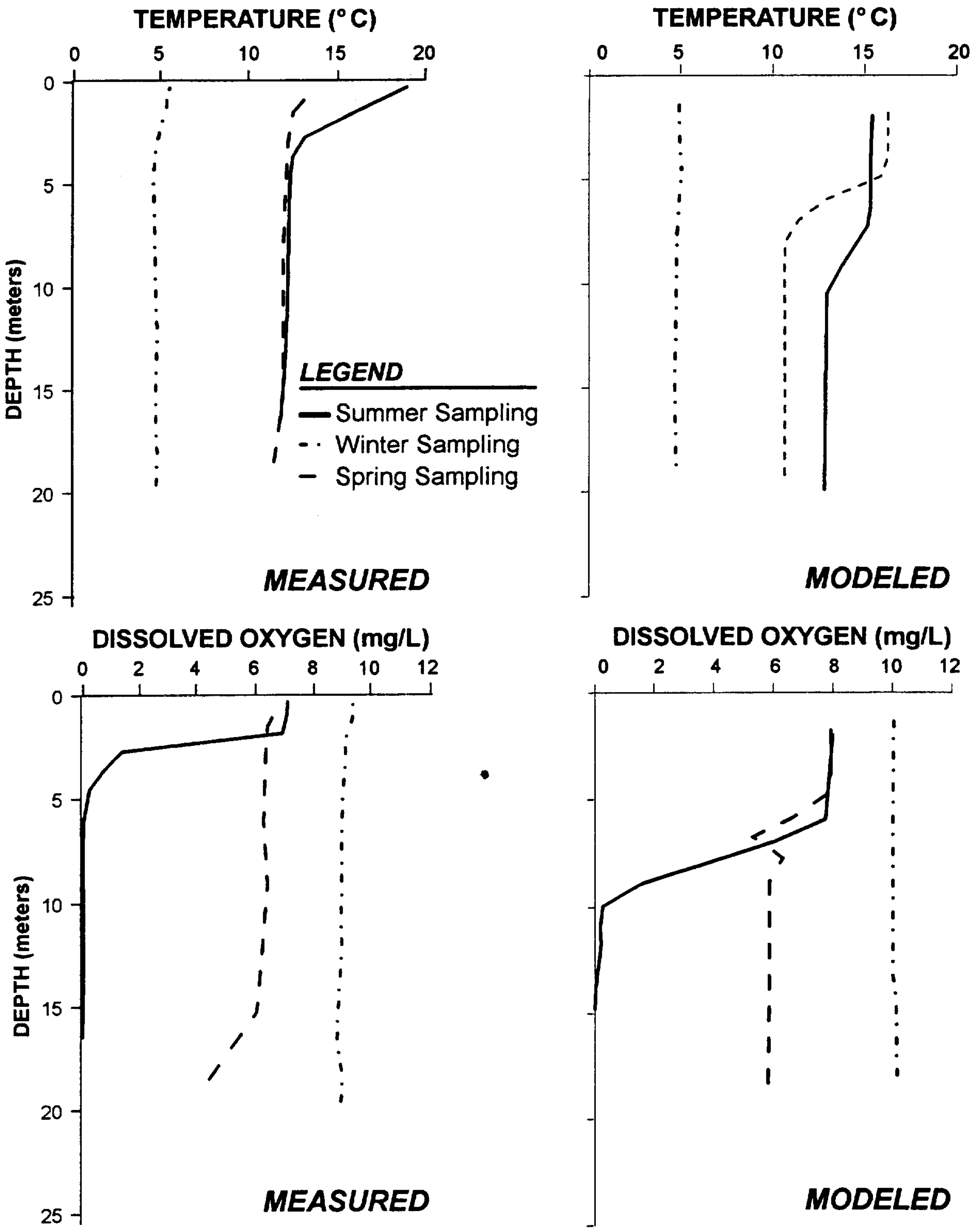

Figure 5. Aurora lake measured and modeled results.

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TABLE 1. NUTRIENT CONCENTRATIONS

	Total Phosphorus (µg/L)	Particulate Phosphorus (µg/L)	NO_3 (µg/L)	NH_3 (µg/L)	SiO_2 (mg/L)
ANACONDA PIT LAKE					
EPILIMNION					
Summer (9/95)	<5	--	80	<10	35.6
Winter (3/96)	8.9	5.0	100.5	14.5	32.3
Spring (6/96)	7.4	1.4	98	8.0	40.2
HYPOLIMNION					
Summer (9/95)	<5	--	80	10	33.4
Winter (3/96)	8.8	3.0	125	11	31.5
Spring (6/96)	6.6	1.2	122	6.0	35.7
AURORA PIT LAKE					
EPILIMNION					
Summer (9/95)	20	--	3,860	<10	19.6
Winter (3/96)	15.1	6.1	5,148	14	16.3
Spring (6/96)	22.6	8.3	3,978	16	15.3
HYPOLIMNION					
Summer (9/95)	30	--	4,640	<100	17.4
Winter (3/96)	46.4	15	5,290	21	16.7
Spring (6/96)	29.2	12.8	4,110	16	15.5
BOSS PIT LAKE					
Summer (9/95)	520	--	24,800	15	17.9
Winter (3/96)	440	3.0	25,676	11	17.8
Spring (6/96)	472	1.2	20,823	5	18.9

TABLE 2. PHYTOPLANKTON

(All units cells/mL)

	Summer 95	Winter 96	Spring 96
ANACONDA PIT LAKE (0-15 m)			
Chlorophyta (green algae)			
Chlamydomonas globosa	--	--	188
Chlamydomonas snowii	--	172	--
Chlamydomonas sp. 1	94	32	--
Chlamydomonas sp. 2	31	110	--
Chlorella ellipsoidea	--	8	--
Chlorella minutissima	41,551	--	--
Chlorella sp.	--	1,063	875
Choricystis minor	--	--	16
Choricystis sp.	--	6,813	--
Cylindrocystis brebissonii	--	--	656
Mesotaenium sp.	--	--	1,250
Oocystis lacustris	1,009	--	--
Oocystis solitaria	--	563	--
Scenedesmus ecornis	--	--	8
Percent of total	74%	22%	6%
Cyanophyta (blue-green algae)			
Aphanothece delicatissima	--	8	--
Aphanothece nidulans	--	--	813
Aphanothece sp.	376	--	--
Jaaginema geminatum	149	--	28,500
Jaaginema subtilissimum	14,304	28,500	20,000
Percent of total	26%	79%	94%
Total density	57,513	37,267	52,306
AURORA PIT LAKE (0-8 m)			
Bacillariophyta (diatoms)			
Cyclotella sp.	--	16	--
Fragilaria tenera	438	--	--
Nitzschia palea	31	--	--
Percent of total	3%	0.27%	--
Chlorophyta (green algae)			
Chlamydomonas angulosa	--	125	--
Chlamydomonas globosa	--	--	156
Chlorella minutissima	15,875	--	--
Chlorella sp.	--	3,188	16
Chloricystis minor	--	--	375
Monoraphidium convolutum	--	63	--
Oocystis solitaria	--	31	--
Percent of total	95%	58%	34%
Cryphtophyta			
Chroomonas acuta	--	1,625	--
Cryptomona marsonii	--	125	--
Cryptomonas sp.	438	--	--
Percent of total	3%	30%	--

TABLE 2. (cont.)
(All units cells/mL)

	Summer 95	Winter 96	Spring 96
AURORA PIT LAKE (cont.)			
Cyanophyta (blue-green algae)			
Aphanothece nidulans	--	--	1,000
Synechococcus sp.	--	750	--
Percent of total	--	13%	63%
Euglenophyta			
Euglena sp.	--	--	47
Percent of total	--	--	3%
Total density	16,782	5,923	1,594
BOSS PIT LAKE (0-6 m)			
Bacillariophyta (diatoms)			
Achnanthes minutissima	1.5	--	--
Cymbella cesatii	49.5	--	--
Cymbella gracilis	--	--	6
Percent of total	0.2%	--	0%
Chlorophyta (green algae)			
Chlamydomonas snowii	--	6,875	--
Chlamydomonas sp. 3	188	--	--
Chlorococcum sp.	1.5	--	--
Monoraphidinium minutum	2.5	--	--
Percent of total	0.2%	93%	--
Cyanophyta (blue-green algae)			
Aphanothece sp.	3,750	--	26,875
Jaaginema subtilissimum	--	500	--
Rhabdoglosa sp.	25,469	--	--
Synechococcus sp.	125	--	--
Percent of total	98.8%	6.8%	100%
Pyrrophyta (dynoflagellate)			
Gymnodinium palustre	8	--	--
Percent of total	0.02%	--	--
Total density	29,595	7,375	26,881

TABLE 3. ZOOPLANKTON

(All units organisms/m^3)

	Summer 95	Winter 96	Spring 96
ANACONDA PIT LAKE (0-30 m)			
Copepoda			
Eucyclops agilis (male)	0.038	--	--
Paracyclops fimbriatus poppei (female)	0.23	0.17	--
Paracyclops fimbriatus poppei (male)	0.04	--	--
Cyclopoid nauplius	1.7	6.8	0.91
Percent of total	0.3%	12%	0.3%
Rotifera			
Bdelloid rotifer	547	52	144
Cephalodella sp.	0.45	0.17	0.91
Colurella sp.	62	1.7	86
Lecane (L.) sp.	0.076	--	--
Lecane (M.) sp.	0.72	--	1.6
Lepadella sp.	70	8.6	92
Unknown rotifer sp. 1	--	--	14
Unknown rotifer sp. 2	--	--	0.91
Percent of total	100%	88%	100%
Total Density	682	69	340
AURORA PIT LAKE (0-9 m)			
Cladocera			
Alona sp.	--	0.29	--
Daphnia pulex (female)	2,736	385	767
Daphnia pulex (male)	--	1.5	--
Daphnia schodleri (female)	921	2,761	1,008
Daphnia schodleri (male)	--	5.3	--
Daphnia spp. (male)	118	--	--
Cladoceran juvenile	--	102	149
Percent of total	33%	98%	20%
Copepoda			
Acanthocyclops vernalis (female)	4.1	1.8	1.5
Acanthocyclops vernalis (male)	12	0.59	--
Eucyclops agilis (female)	1.5	4.4	3.8
Eucyclops agilis (male)	--	0.59	2.3
Cyclopoid juvenile	1,618	13	2,050
Cyclopoid nauplius	489	35	5,817
Percent of total	20%	2%	80%
Rotifera			
Asplanchna sp.	--	--	22
Bdelloid rotifer	--	1.2	0.76
Epiphanes senta	0.37	--	--
Filinia longiseta	6,809	--	--
Polyarthra vulgaris	208	--	--
Percent of total	47%	0.04%	0.01%
Total Density	12,917	3,312	9,821
BOSS PIT LAKE (0-6 m)			
Copepoda			
Eucyclops agilis (female)	--	--	0.57
Cyclopoid juvenile	--	--	9.7
Cyclopoid nauplius	--	--	34
Percent of total	--	--	25%
Rotifera			
Bdelloid rotifer	--	4.7	0.57
Brachionus urceolaris	4.1	1.6	6.9
Hexarthra sp.	--	--	--
Lecane (M.) sp.	82	--	86
Lepadella sp.	--	--	1.1
Unknown rotifer sp. 1	2.3	--	43
Percent of total	100%	100%	75%
Total Density	89	6.2	182