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Technical Article

The Limnology of Summer Camp Pit Lake: A Case Study

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Abstract. Surface water bodies are expected to form in several pits at the Getchell Open Pit Mine after mining has ceased due to inflowing surface and ground water. Predicting the long-term geochemical behavior of the pit water is important in assessing potential environmental effects. One of the pits, the Summer Camp Pit, began to develop a pit lake in 1991 when dewatering ceased and the pit was used to store water pumped from underground operations. This provided a field-scale opportunity to identify the controls on lake water chemistry and determine the effects of seasonal mixing events on long-term chemical behavior. During a five-year period (1996-2001), a number of physical, chemical and mineralogical characteristics of the lake were monitored with the intent of using this information as a basis for predicting long-term geochemical behavior of future lakes in the other pits. Seasonal and multi-year cycles were identified within the water column. These cycles were influenced by climatic changes and element and sediment loadings of inflow to the lake. Stratification occurred, with the metalimnion or active layer of the lake evolving from a low total dissolved solids (TDS), alkaline water to a high TDS, neutral to mildly acidic water, until turnover occurred due to density variations between the metalimnion and epilimnion, completely mixing the layers. A hypolimnion that formed has the potential to stabilize metals in the basal sediments as sulfide minerals below a chemolimnion in the lake. Longer-term events also appear to involve the hypolimnion.

The monitoring program demonstrated the dynamic nature of a pit lake and how the complex limnology can affect seasonal water quality. Such considerations are important in interpreting water quality from pit lakes and in selecting monitoring data to use when constructing mathematical models for predicting changes in water quality.

Key words: geochemistry; limnology; pit lake

Introduction

After final closure of the Getchell Gold Corporation (GGC) Mine in northern Nevada (Figure 1), surface water bodies are expected to form in four pits. As these pits will be permanent surface features, their chemical composition is an important aspect in evaluating their potential environmental impact. The chemical composition of pit lakes varies widely, from the highly acidic metal-sulfate-rich waters of Butte Mine, Montana, to the near-neutral, low salinity pit lake at Tuscarora, Nevada (Davis and Ashenberg 1989; Price et al. 1995; Gannon et al. 1996; Miller et al. 1996; Eary 1999; Bowell 2002). Due to this wide range in water quality, each pit requires individual assessment and study.

The Summer Camp Pit (SCP) began filling in 1991 when mining ceased. Initially, only a small sump in the SW corner was filled, but this changed when water was pumped to the SCP from the Main Pit and the Getchell underground mine in 1993. The average TDS of the inflow water was about 800-900 mg/L and its inflow rate from the Getchell underground mine was about 25 L/sec (Bowell 2001). The winter of 1996-97 had an extremely high snowfall and the snowmelt was accompanied by high rainfall. A major flood event occurred January 1, 1997, and for three days thereafter, water with a TDS of about 2,000 mg/L was pumped into the SCP at a rate of about 125 L/sec. This increased the volume of the pit water by about 4% and brought the pit to its 1997-1998 average depth of about 24 m. Sometime between January 1 and late February 1997, a portion of high wall containing relatively pyrite-rich hornfels collapsed into the pit. For the next five years, approximately 38 L/sec of water from the Turquoise Ridge underground mine (average TDS about 450 mg/L) were pumped into the pit., while flow from the Getchell underground mine decreased to about 400-600 mg/L (Bowell 2002). The mine waters were pumped to the pit for settling of suspended solids before being returned either to the mill for beneficial use or to the water treatment plant for treatment and infiltration back into the ground. Over time, water levels tended to vary seasonally ±2 m in the pit lake.

During a 5-year period (1996-2000), the authors were involved in assessing pit water quality and limnology of the SCP. Although this is only one of several pits at the mine, it is the still the only one flooded. This paper summarizes the work conducted on the SCP from 1996-1998 and is a follow up to other publications (Bowell et al. 1998; Bowell 2002;

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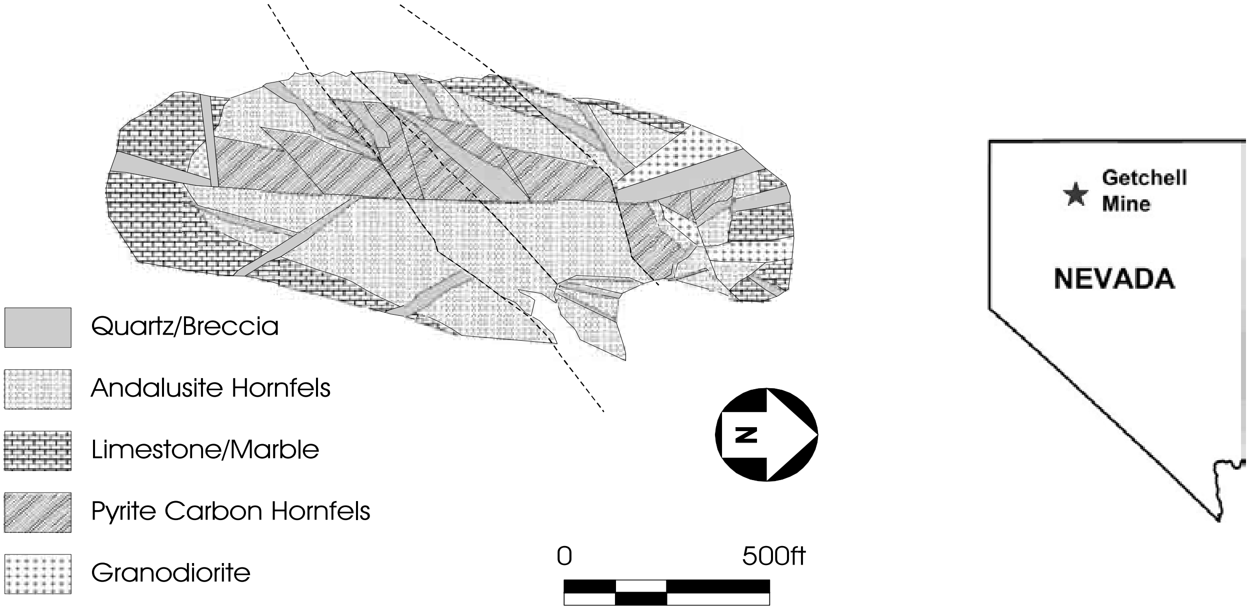


Figure 1: Simplified geology of Summer Camp Pit

Bowell and Parshley, in review). Underground mine water is no longer being pumped to the SCP and the lake water is being removed for use elsewhere on site.

Geology of Summer Camp Pit

The Getchell property comprises Palaeozoic sedimentary rocks, which have been extensively thrust faulted, intruded by a granodiorite stock and related hypabyssal intrusives, and undergone further faulting during Basin and Range tectonism (Joralemon 1951; Hotz and Willden 1964; Berentsen et al. 1996). Colluvial and alluvial deposits cover the Getchell valley and the flanks of the Osgood Mountains adjacent to the Getchell mine.

The primary lithologies in the SCP are shales, carbonates, and quartzites that were intensely silicified and metamorphosed to low to medium grade adjacent to the granodiorite stock. High-angle normal faulting that bound the range to the east with principal fracture sets trending N-S and N 40-600 E has fractured the brittle, silicified meta-sedimentary rocks. It is likely that the major fracture sets are connected, at least hydraulically, by minor cross-cutting NW to E-W fracture sets. Exposed geology in the SCP is dominated by andalusite and pyrite-bearing hornfels, marble, and a series of breccias and veins (Figure 1).

The gold mineralization mined from the SCP consist of a number of discrete high grade zones (breccias) linked by lower grade zones in hydrothermally altered wallrock. Throughout the pit, the upper 8-10 m of pit wall has been completely oxidised. The breccias and veins contain quartz, carbonates, sericite, carbon, and electrum and up to 20% sulfides comprising pyrite, pyrrhotite, marcasite, realgar, orpiment, sphalerite, galena, chalcopyrite and arsenopyrite. Secondary minerals include pararealgar, goethite, jarosite and Fe-Ca-Zn-Cu arsenates, carbonates, and sulfate minerals (Bowell et al. 1998). The disseminated mineralization (maximum sulfide content of 5 wt %) typically consist of quartz, calcite, ankerite-dolomite, sericite, andalusite, clays, marcasite, and pyrite, with trace amounts of realgar, stibnite, and orpiment dispersed in the rock matrices and associated with barren quartz veins.

The wallrock in the SCP area have a supergene stratigraphy based on the scale of leaching and extent of mineral-water interactions. The upper 10 m of all lithologies is completely oxidised. This is most noticeable in the sulfide-bearing lithologies and breccias as intense Fe staining and formation of gossan textures. From 10-30 m, a transitional zone exists in which the extent of mineral-water reactions is less noticeable, going from a macroscopic to microscopic scale of impact. Below this, sulfides are largely unoxidized (this corresponds to the reduced portion of the pit lake). Within the transitional zone, secondary products of sulfide oxidation may exist and any fluctuations in water level imbalance the equilibrium, leading to dissolution of these salts.

Within the hypogene sulfide and transition zones, sulfide oxidation causes increased sulfate levels in the pit lake and, depending on the sulfides involved, increased metals and/or metalloid levels, and lowered pH. The water from the underground dewatering created a highly turbid plume in the lake, leading to precipitation of thicker sediment on wallrock and the base of the pit in the southeastern side of the pit.

Limnology

Pit lakes in temperate climatic zones can develop vertical density stratification that may be seasonal or permanent. The density of water is a function of both its temperature and its salinity or total dissolved solids (TDS) content. Freshwater is densest at a temperature of about 4°C, and water density increases with increasing TDS.

Thermally induced seasonal density stratification in mid-latitude lakes of uniform dilute chemistry (low TDS) is due to increases in ambient temperature in the spring and summer. This heating causes the density of the surface layer to decrease. The lake then has a surface layer (epilimnion) of uniform lower density and higher temperature and an underlying layer (hypolimnion) of higher density and lower temperature. A zone called the thermocline or metalimnion, in which the temperature decreases rapidly with depth, separates these layers. Above the thermocline, the surface water is mixed by wind or surface inflow and is typically in equilibrium with atmospheric oxygen. The epilimnion is typically less than about 6 m deep, because wind-induced mixing in mid-latitude pit lakes seldom reaches deeper. Below the thermocline, oxygen may gradually become depleted by oxidation of dead algae and lake fauna that fall into the hypolimnion from the surface.

In March 1997, Getchell began an in-situ monitoring program in the SCP to measure and monitor fundamental water-quality parameters and their variation with depth and time. The goal of the program was to characterize the stratification and mixing behavior in the lake. Details of the program design and engineering are presented in the Getchell Gold Summer Camp Pit Lake In-Situ Monitoring Report (Schafer and Associates 1999), hereafter referred to as the Schafer Report. Two types of monitoring probes were connected in a vertical array to measure a number of water-quality parameters at discrete depths from the bottom of the lake. All but one were anchored to the bottom because the surface elevation of the lake varied. Figure 2 shows a schematic diagram of the array.

Ten Campbell Scientific 247 probes were connected at 2.4-m increments beginning 3.5 m above the bottom and continuing to the lake surface. These probes were designed to measure electrical conductivity (EC), and temperature. Temperature correction allowed conversion of EC to specific conductance (SC), which is a measure of the TDS content of the water. Three Hydrolab Reporter™ multiprobes were also deployed. One was positioned at 1 m above bottom elevation (abe), the second was positioned at mid-depth (13 m abe), and the third, the

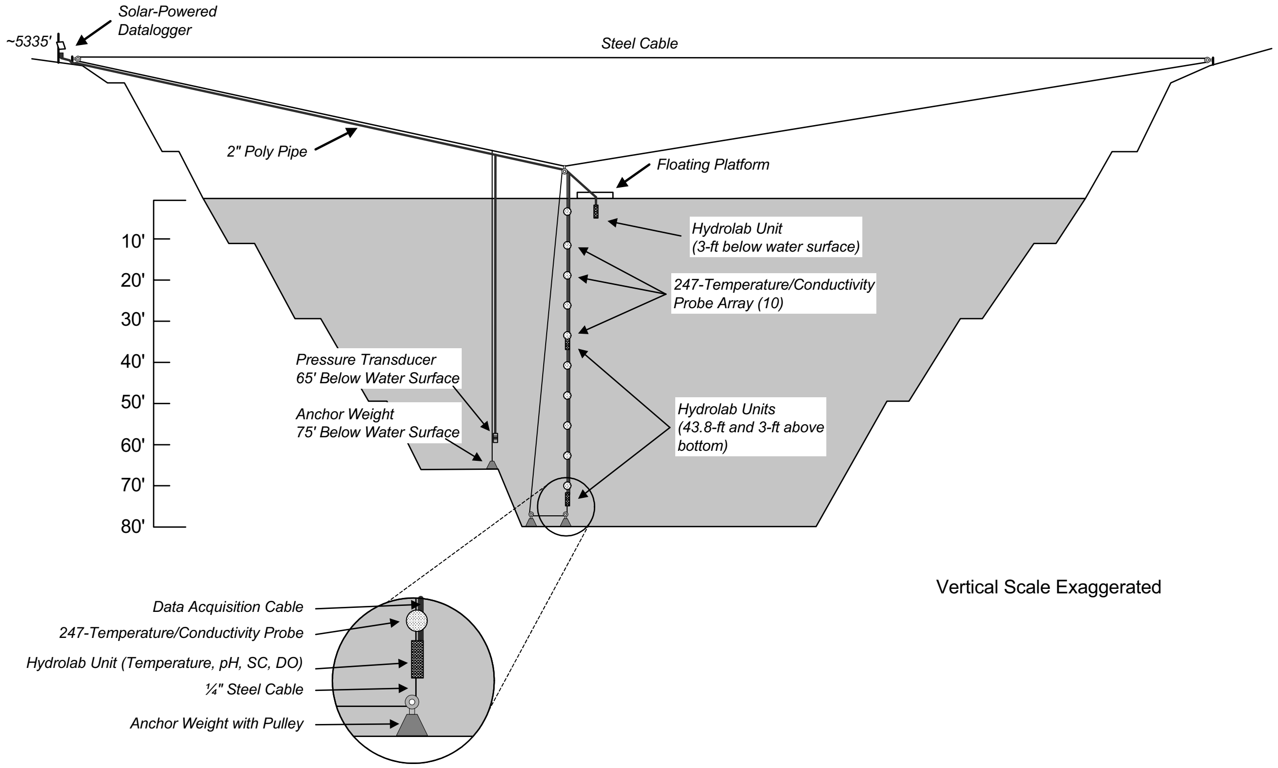


Figure 2. Summer Camp pit lake monitoring array (scale in 3 m bars)

near-surface probe, was tethered to a floating platform and set to measure at a constant 1 m below the lake surface. Each Hydrolab multiprobe unit was equipped with individual probes to measure pH, temperature, EC, and dissolved oxygen (DO).

One Keller Scientific pressure transducer was anchored at 3 m abe (about 20 m below the lake surface) to measure changes in lake elevation with time. The pressure transducer and all probes were connected to an on-site solar-powered data logger for data storage and retrieval. Initially, all data were collected hourly and averaged daily. Over time, the data logger battery voltage began to fluctuate, so data collection was reduced to twice daily.

Quarterly maintenance was performed on all instruments. During maintenance, probes were calibrated with standard solutions, comparisons were made between the Hydrolab and adjacent 247 probes for temperature and SC, and the probe data were compared with data obtained from periodic collection of water-quality samples from multiple depths. The pressure transducer results appeared erratic, so beginning in 1998, monthly depth measurements were made manually for comparison.

Detailed monitoring of depth variations within the SCP occurred on 6/13/97, 8/12/97, 2/25/98, 3/3/98 and 6/9/98. Samples were taken from different depths on each occasion using a peristaltic pump: 0, 3, 6, 12 and 24 m on 6/13/97; every 6 m down to 24 m on 8/12/97; every 3 m down to 24 m on 2/25/98; 0, 3, 12 and 24 m on 3/3/98; and every 3 m down to 21 m on 6/9/98. This data is summarized in Table 1 (SRK 1997, 1998, 2001). Samples were analysed by Sierra Environmental Monitoring of Sparks, Nevada.

Results

Limnology

Temperature, SC, density, DO, and pH measurements from the probe array are provided in Figures 3-8. The temperature results for the Hydrolab probes (Figure 3) show the formation and decay of a summer thermocline in both 1997 and 1998. Although air temperature dropped below the freezing point of water for prolonged periods in December 1997, and March 1997 and 1998, the lake surface never froze. Water pumped from the underground operations has a temperature of about 18-22°C throughout the year. It is possible that the heat of this water, which flows in at the lake surface, keeps the surface water temperature of the lake above freezing.

The SC is a direct measure of the TDS of a water, which can be obtained by multiplying the SC by 0.6

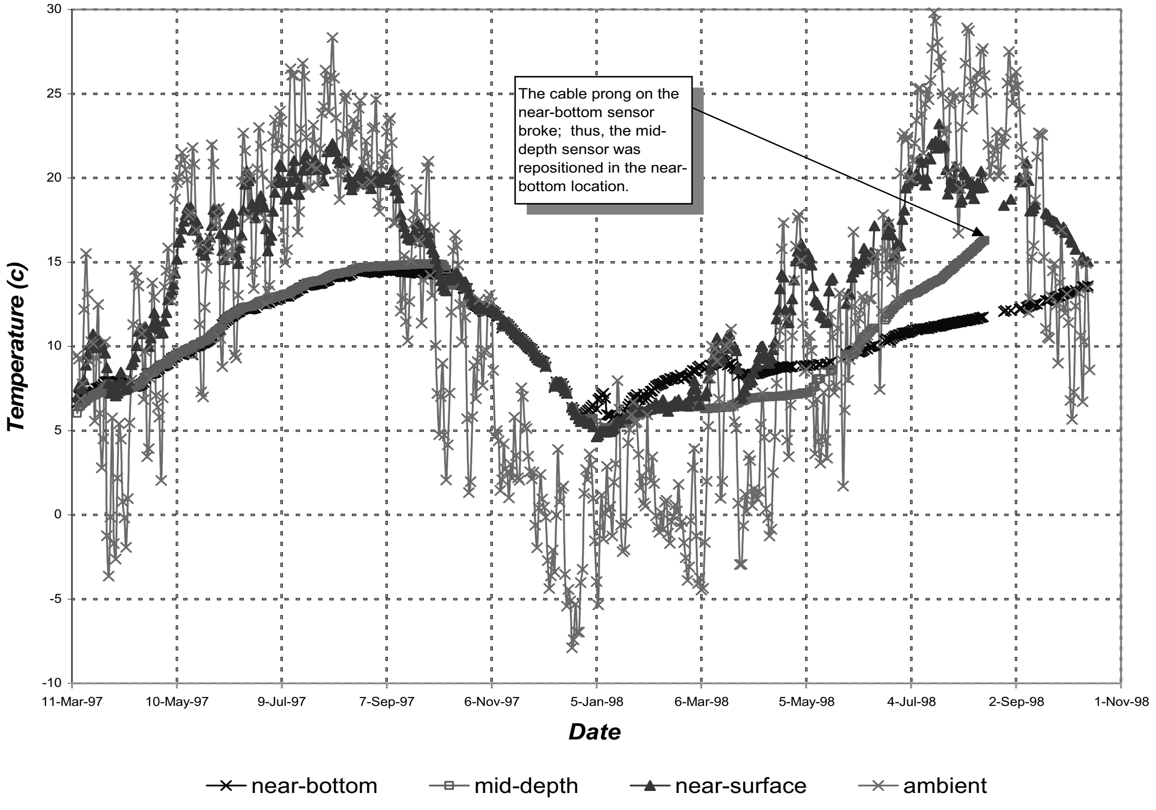


Figure 3. Hydrolab probe temperature measurements

Table 1. Summer Camp Pit Water Chemistry

Sampling Event	Depth m	Total Alk mg/L $CaCO_3$	pH su	SO_4 mg/L	TDS mg/L	As mg/L	Ca mg/L	Mg mg/L	Fe mg/L	Mn mg/L	Zn mg/L	Al mg/L
June 13, 1997												
	0	63	8.57	570	986	3.7	210	22	0.24	0.18	0.01	--
	3	60	8.6	580	1023	3.5	210	22	0.27	0.12	0.02	--
	6	105	7.55	830	1366	0.59	290	28	0.72	0.7	0.27	--
	12	102	7.53	810	1364	0.57	290	28	0.83	0.69	0.33	--
	24	104	7.6	810	1368	0.53	290	28	0.25	0.7	0.3	--
August 12, 1997												
	0	70	8.67	420	878	7	170	21	0.21	0.034	<0.02	--
	3	105	7.64	700	1301	0.76	270	29	0.05	0.52	0.02	--
	6	103	7.45	760	1287	0.75	270	28	0.05	0.51	0.02	--
	12	104	7.72	710	1294	0.79	280	31	0.05	0.5	0.03	--
	24	0	3.3	2900	5134	18	370	85	840	2.3	38	--
February 25, 1998												
	0	74	8.01	370	714	1.1	140	16	0.37	0.06	0.01	0.21
	3	75	8.01	370	710	1.1	140	17	0.65	0.065	0.02	0.44
	6	74	7.78	380	722	0.99	140	16	0.58	0.069	0.02	0.34
	9	78	7.94	380	726	0.89	140	17	0.52	0.069	0.02	0.25
	12	82	7.74	390	763	0.84	150	17	0.38	0.068	0.03	0.13
	15	75	7.51	400	761	0.83	140	17	0.36	0.067	0.03	0.11
	18	68	7.47	390	736	0.69	150	17	0.63	0.073	0.04	0.12
	21	72	7.34	390	784	0.58	150	17	0.83	0.079	0.06	0.1
	24	0	3.67	2200	3487	7.9	400	46	410	1.1	16	22
March 3, 1998												
	0	78	8.06	370	--	1	140	18	0.49	0.062	<0.03	0.35
	3	77	7.81	380	--	0.92	150	18	0.37	0.06	0.03	0.16
	12	72	7.74	390	--	0.82	160	16	0.32	0.06	0.06	0.14
	24	75	7.76	400	--	5.83	150	18	390	1.3	15	16
June 9, 1998												
	0	154	8.54	22	245	0.021	30	7.5	12	0.21	0.03	--
	3	87	7.69	410	806	0.49	170	18	1.2	0.19	0.14	0.43
	6	88	7.63	430	804	0.44	170	18	0.001	0.19	0.14	0.4
	9	84	8.59	370	732	1.8	160	18	0.55	0.077	0.03	0.33
	12	86	7.61	390	808	0.44	170	19	1.1	0.19	0.15	0.31
	18	85	7.5	420	808	0.43	160	19	1.1	0.19	0.15	0.22
	21	124	8.09	480	922	16	190	22	160	2.7	4	55

(Hem 1985). The SC data from the Hydrolab probes (Figure 4) indicate that the near-surface and mid-depth SC values remained nearly identical throughout the monitoring period in 1998. The near-bottom SC fluctuated beginning in late December 1997 and then increased to about 6000 µmhos/cm, a value almost six times as high as the near-surface and mid-depth SC value of about 1000 µmhos/cm. (From mid-March to late May, 1998, the probe malfunctioned, so the data for this period are invalid.)

Thus, in the summer of 1997, both a thermocline and a chemocline existed at the same depth (3 m below the lake surface). This chemocline disappeared in late October 1997, when the surface water temperature dropped below that of the underlying water. In late December, a new, stronger chemocline appeared between 1 and 3.5 m abe.

Density is the parameter that controls stability and overturn in a water column. Density is a complex function of both temperature and TDS. As discussed above, freshwater is densest at a temperature of about 4°C. Above this temperature, the density increases with decreasing temperature. Below this temperature, the density decreases with decreasing temperature until it reaches its freezing point. At a given temperature, water density increases with increasing TDS. For example, pure, distilled water has a density of 1.000 g/mL at 4°C; seawater, with a TDS of 35,000 mg/L, has a density of 1.024 g/mL at 4°C. Because density variations are small, the density excess, or"sigma," which is a measure of the density relative to pure water at 4°C, is typically used to discuss density differences. Sigma is defined as:

Sigma = (density in g/cm^3 - 1) x 1000

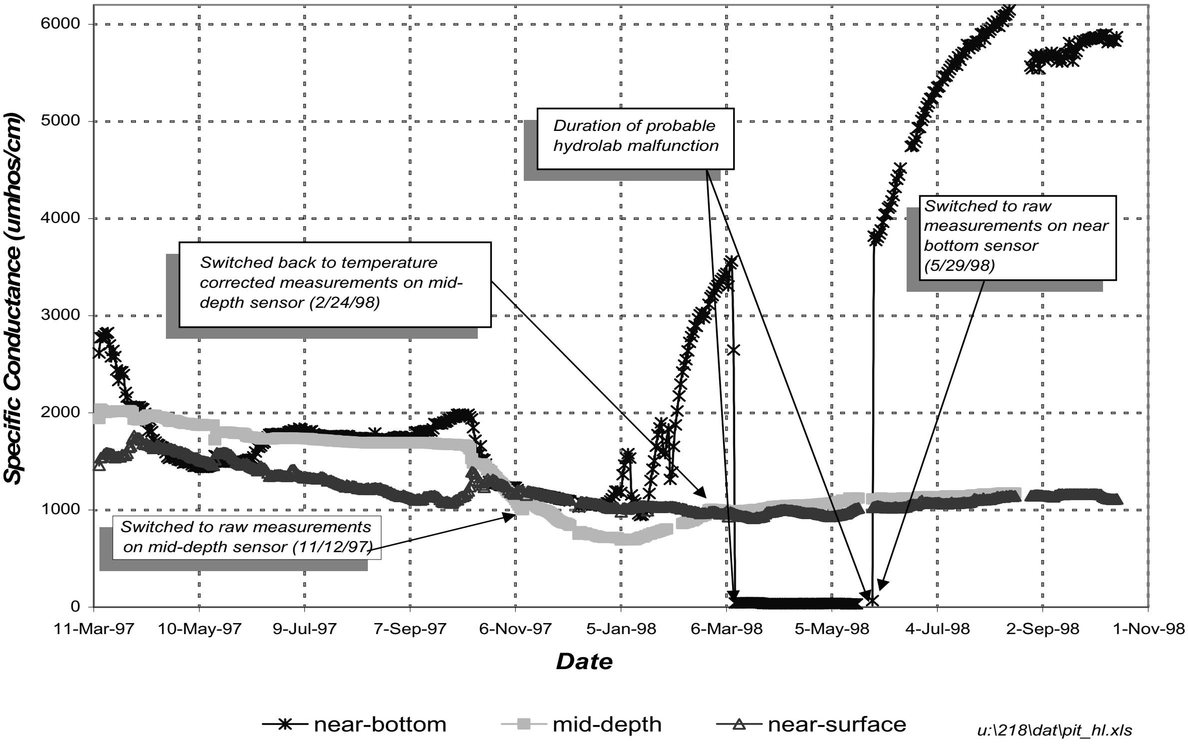


Figure 4. Hydrolab probe specific conductance measurements

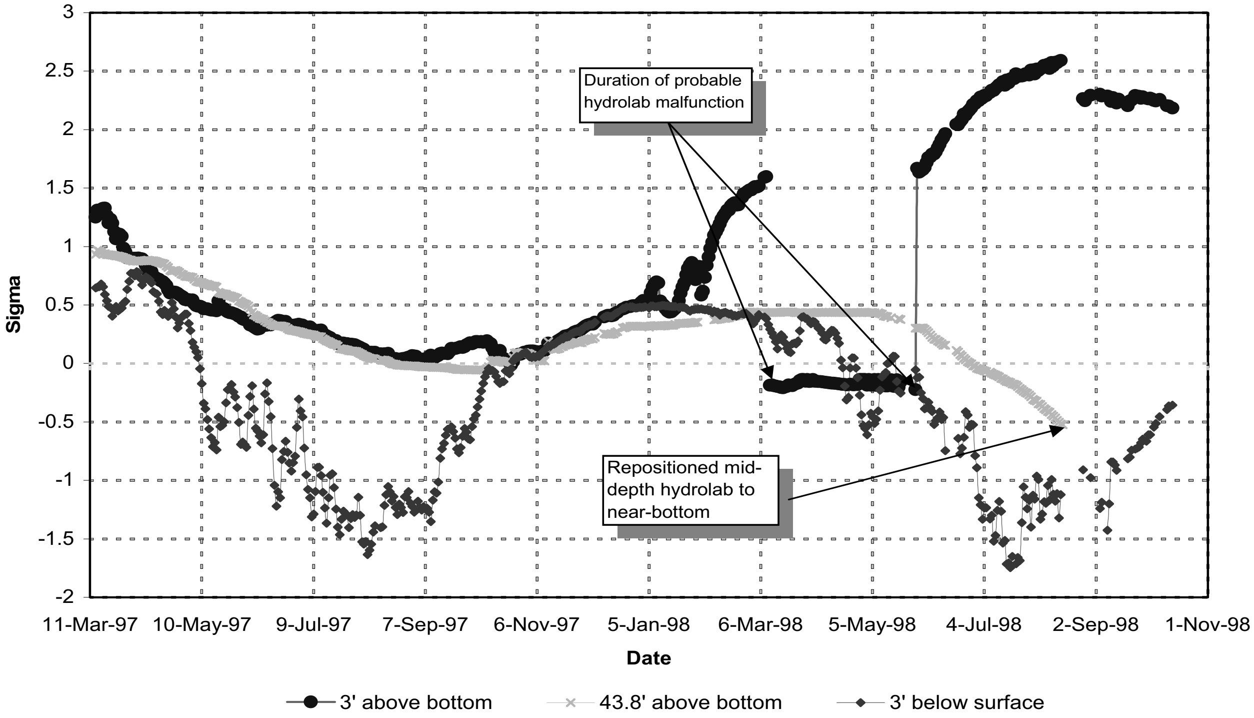
Sigma values were calculated using an empirical formula derived by Millero (1980) for dilution of seawater and includes functions for both temperature and TDS. The sigma values are approximate because the ratio of the various ions in the pit lake water is different from that in seawater. Therefore, the calculations cannot be used to investigate small density differences (which are also problematic due to the differing SC calibrations for the individual probes), but allow identification of pycnoclines (zones of rapid changes in density, analogous to thermoclines for temperature).

Figures 5 and 6 show the temporal variation in density at each Hydrolab and 247 probe, respectively. When monitoring began on March 14 1997, the lake had a stable vertical density gradient, with density increasing with depth. The gradient decreased with time and culminated in an overturn/mixing event, which occurred to within 1 m of the lake bottom in late-March/early-April 1997. This was followed by rapid formation of a near-surface pycnocline. The formation and decay of the summer thermocline in both 1997 and 1998 are clearly shown in both figures. In late October 1997, another overturn event mixed the waters to within 1 m abe. Thus, it appears that the temperature drop in late October was large enough to compensate for the difference in TDS/SC between the formation and decay of the summer thermocline in both 1997 and 1998 are clearly shown in both figures.

In late October 1997, another overturn event mixed the waters to within 1 m abe, indicating that the temperature drop in late October was large enough to compensate for the difference in TDS/SC between the near-surface and underlying waters. Mixing apparently continued to within 3.5 m abe throughout the winter of 1997-98, whereas the near-bottom water became significantly more dense beginning in late December 1997 and continuing until the end of the monitoring period in October 1998.

These results indicate that the density of the mid-depth and near-bottom water changed regimes between 1997 and 1998. In spring and summer 1997, mid-depth water was similar in density and TDS to the near-bottom water and both were significantly higher in density and TDS than the near-surface water. In spring and summer 1998, the density and TDS of the near-bottom water increased significantly while that of the mid-depth water decreased and became more similar to that of the near-surface water.

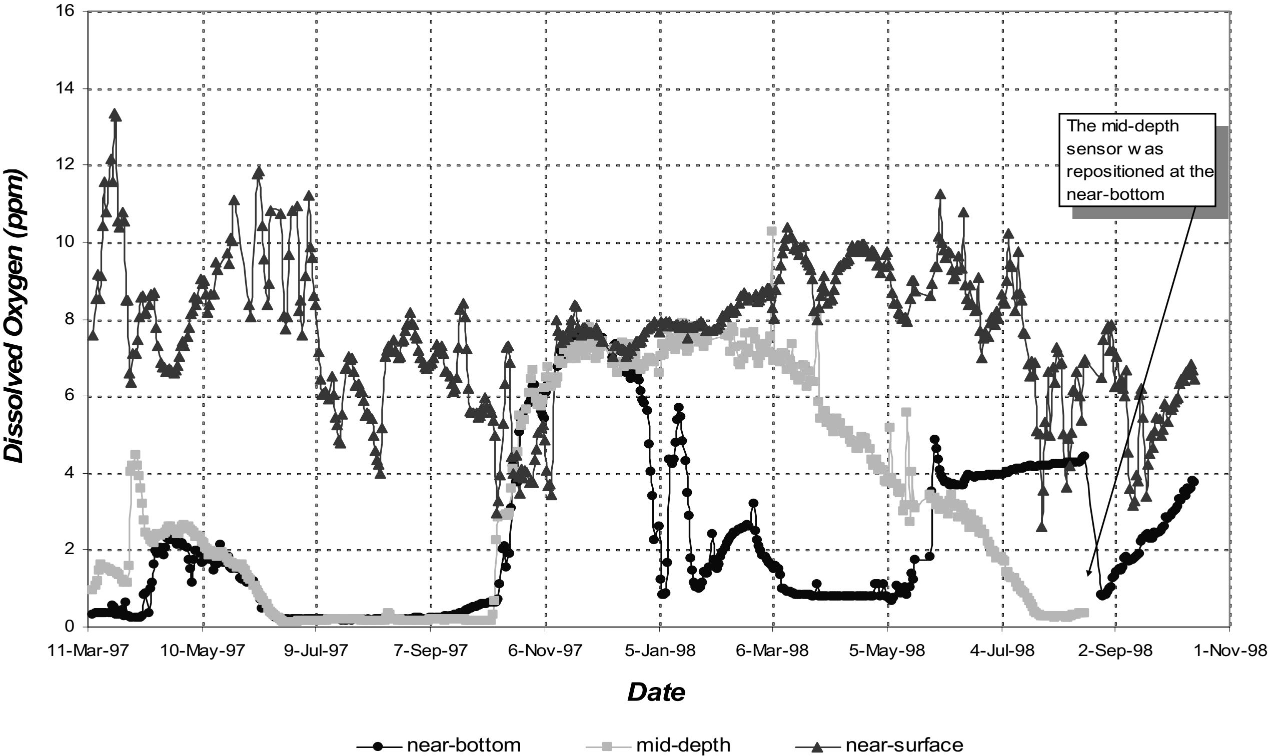
Most DO is derived from the atmosphere, but some may be contributed by photosynthesis within the lake. Figure 7 shows the DO content of the near-surface, mid-depth, and near-bottom water, as measured by the Hydrolab probes. The near-surface probe shows high DO throughout the year, but especially in the spring, when increased solar radiation allows rapid growth of algae in the near-surface waters. Near-



Duration of probable hydrolab malfunction

Repositioned mid-depth hydrolab to near-bottom

Figure 5. Hydrolab probe density measurements



The mid-depth sensor w as repositioned at the near-bottom

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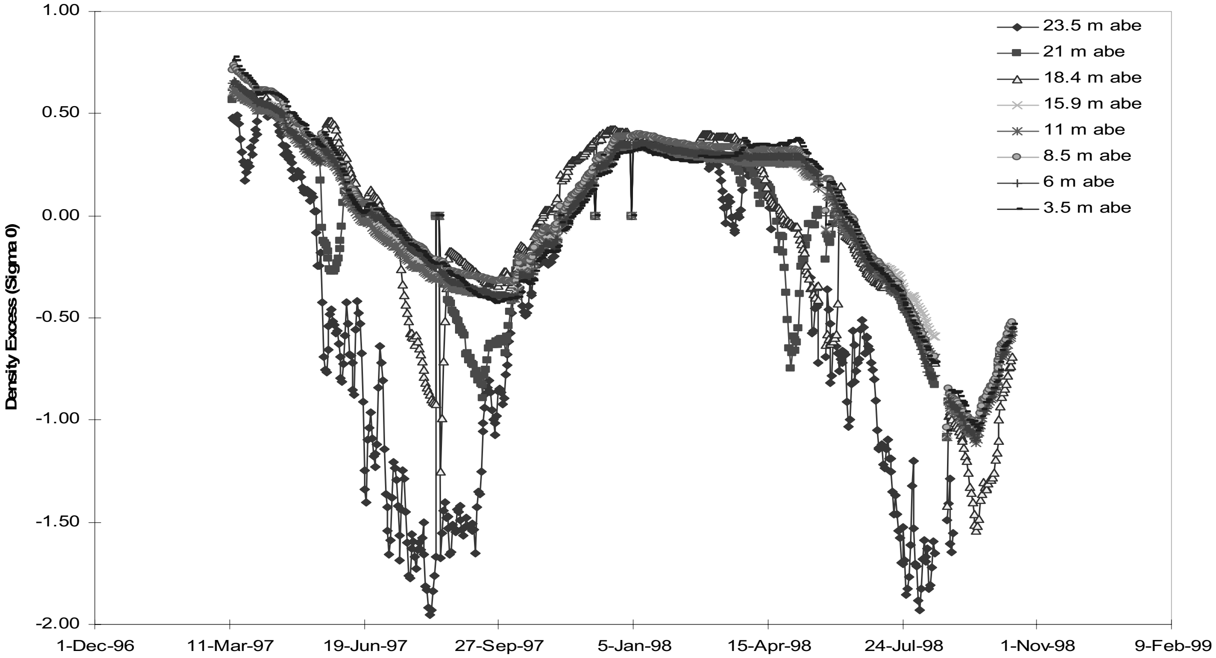
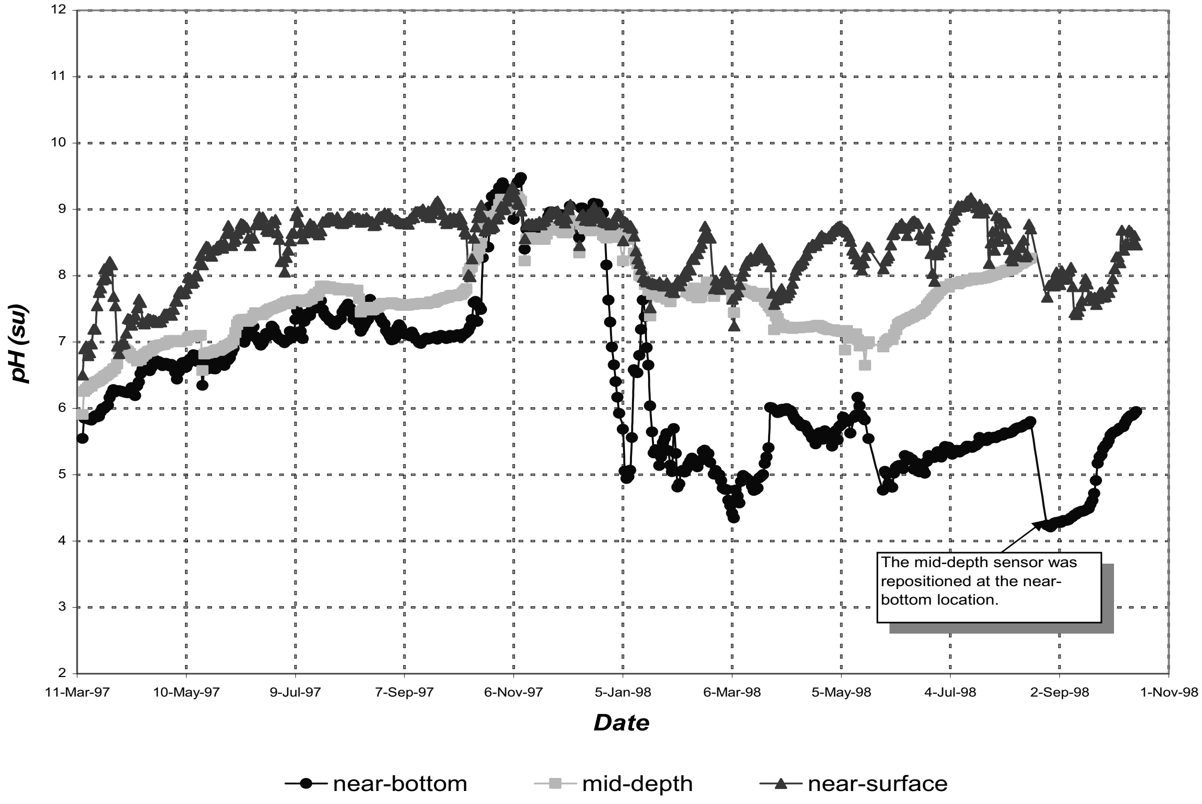
Figure 6. 247density measurements

surface DO concentrations dropped in mid-July in both 1997 and 1998, probably due to algal die-off and/or growth of aquatic fauna. The overturn events in both spring and fall 1997 provided increased oxygen to the mid-depth and near-bottom waters. The high near-bottom DO values throughout November and most of December 1997 provide evidence for continued mixing to at least 1 m abe during that time. Consistent with SC and density data, DO data show different patterns for the mid-depth water in 1997 and 1998. In 1997, DO in mid-depth water rapidly fell to the same low levels as in the near-bottom water, while in 1998, DO slowly decreased throughout the spring and summer, until it reached less than 1 mg/L in mid-July.



a.b.e. = above bottom elevation

Figure 7. Hydrolab probe dissolved oxygen measurements



The mid-depth sensor was repositioned at the near-bottom location.

Figure 8. Hydrolab probe pH measurements

The pH measured using the Hydrolab probes at near- in Figure 8. Initial pH values in mid-March 1997 are all at or below pH 7, with the lowest (5.5) at near-bottom, intermediate (5.9) at mid-depth, and 7.0 at the near-surface. After the mixing event in late March, the pH values at all 3 depths increased until mid-July, when they stabilized at 7.0-7.5 for the near-bottom, 7.5-7.8 for the mid-depth water, and 8.7-9 for the near-surface water.

After the late-October 1997 mixing event, pH ranged from 8.5 to 9 throughout the water column to within 1 m ABE. The pH values at the mid-depth and near-surface probe tended to track each other at about 7.7-8 through late March 1998. After that, the mid-depth pH dropped slowly to about 7 and then rose to over 8 by late August, while the near-surface pH rose to between 8 and 9. In late-December 1997, the pH in the near-bottom water underwent rapid fluctuations before tending to stabilize at about pH 5 in February. The pH of the near-bottom water then varied between 4 and 6 during the rest of the monitoring period.

Geochemistry

In addition to monitoring the limnological characteristics of the SCP, we also evaluated how pit lake chemistry varied with time and depth. This was done through an ongoing monitoring program, with the earliest data collected in 1989 (Bowell 2002). Initially, the only parameters measured were pH, TDS, and As. However, with time, the suite of parameters analyzed was expanded, allowing greater insight into the lake hydrochemistry. Water samples collected using an isoperistaltic pump enabled representative samples to be sampled from distinct depths in the lake. This has facilitated an understanding of the pit lake system, seasonal controls, depth related variations, and ultimately, design of a conceptual model, illustrated in Figure 9. In this model, the lake is subdivided into epilimnion and hypolimnion zones based on chemical variations with increasing depth (SRK 1998, 2001). Descending through the lake, water chemistry changes from a buffered alkaline solution at the surface with low dissolved metals to an acidic solution at depth with dissolved metals typically an order of magnitude higher than the surface water. As discussed above, in 1998, the intermediate water had an anaerobic metalimnion in summer, with TDS similar to the epilimnion, and became oxygenated in late fall through the winter, when it mixed with the epilimnion.

The variations of selected parameters (SO_4, pH, Fe, and As) with depth are summarized in Figures 10 – surface, mid-depth, and near-bottom are shown 13 and also shown for more parameters in Table 1. Based on the trends shown in these figures, metals and sulfate generally increased with depth whereas pH decreased. At 23 m, the water was reducing with negative redox potentials. The pH and redox trends measured during these sampling events generally agree with the trends in the in-situ measurements of pH and dissolved oxygen discussed in the previous section, although the exact values of pH are somewhat different. The contrasting chemistry is best shown in a comparison of samples taken from 3 and 23 m, and the differences are most distinct on 8/12/97 and 2/25/98. During these monitoring periods, the pH was 4 units lower at 23 m than the circumneutral values obtained on other sampling occasions.

Concomitantly, TDS was 5,000 mg/L on 8/12/97 compared to approximately 900 on 6/9/98, and SO_4 was 2,900 mg/L, compared to 480 mg/L. This data is summarized in Table 2. The water samples were collected at fixed distances from the surface and the water level fluctuated over time; thus, the samples were collected at varying distances from the lake bottom. A stable hypolimnion with a fixed vertical thickness could give rise to variations in the chemistry of the 23 m water samples if the samples sometimes penetrated the hypolimnion and sometimes were collected from just above it.

Thus, lower TDS samples, such as occurred on 3/3/98 and 6/9/98, do not necessarily imply lack of, or changes in, a dense hypolimnion. The Fe concentrations observed on 3/3/98 suggest the presence of a chemically distinct hypolimnion on this date. However, the laboratory pH of 7.76 would suggest Fe levels should be lower than observed. The field pH agrees better with the observed Fe concentration. Comparison of the TDS at 21 m on 3/3/98 with the TDS calculated from specific conductance measurements for the Hydrolab probe at 1 m abe (581 and 2039 mg/L, respectively) indicates that a denser bottom layer did occur on that date below 21 m.

Table 2. Summary of hydrochemistry at 24 m for the period 1997/98; All values are in mg/L unless stated

	6/13/97[1]	8/12/97	2/25/98	3/3/98[1]	6/9/98[1,2]
pH_{Lab}	7.60	3.30	3.67	7.76	8.09
pH_{Field}				4.6	
TDS	1368	5134	3487	581[3]	922
Fe	0.25	840	410	390	160
SO_4	810	2900	2200	400	480
As	0.53	17.5	7.9	5.8	16

[1] Metal concentrations are reported as dissolved concentrations; [2] sampled from 70ft; [3] TDS calculated as 0.59 × conductivity (µMHO/cm).

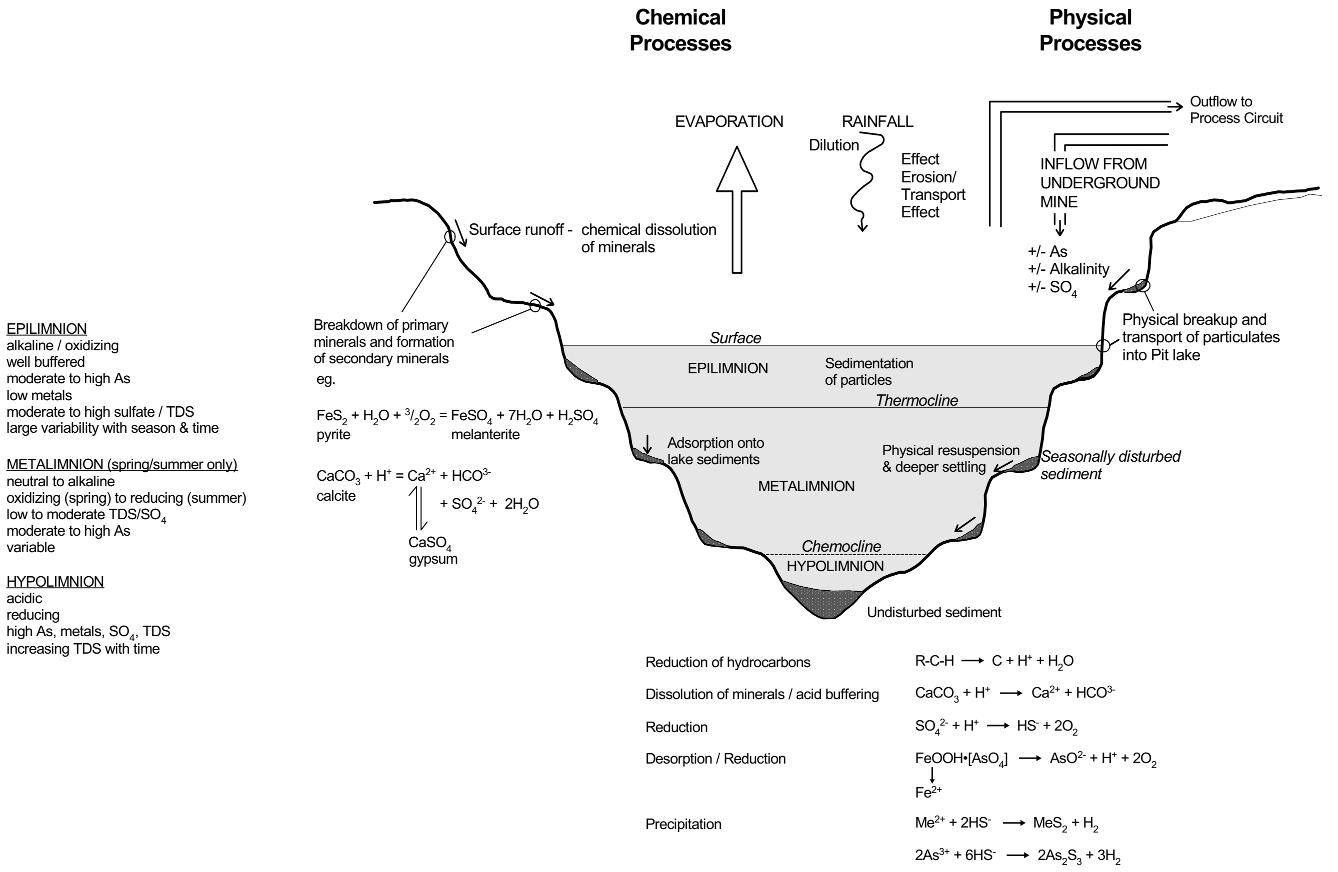


Figure 9. Conceptual model

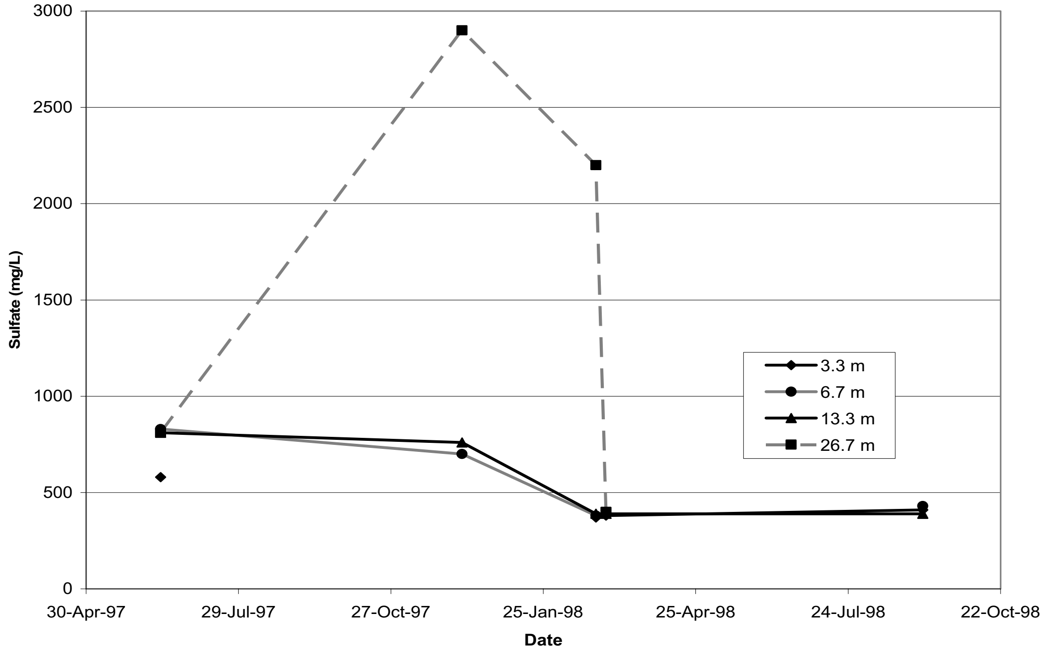


Figure 10. Variation in sulfate concentrations with depth in the Summer Camp Pit

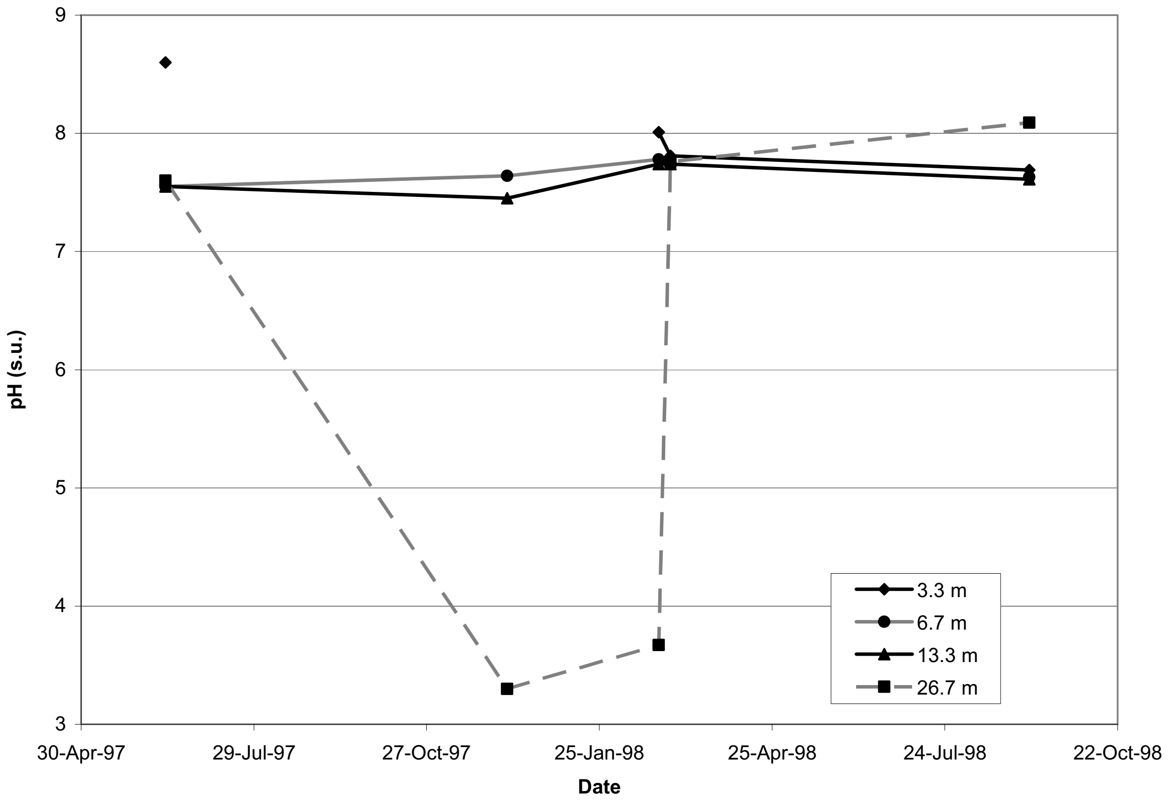


Figure 11. Variation in pH with depth in the Summer Camp Pit

The elevated TDS level observed in the hypolimnion was approximately 2000 mg/l, and was associated with elevated concentrations of SO_4, Fe, Ca, and Zn. Cd and Ni were also elevated at 24 m (on 8/12/97 and 2/25/98), at concentrations of approximately 0.5 and 2.5 mg/L respectively. These concentrations were an order of magnitude higher than the concentrations of Cd and Ni observed in the overlying water column and on other sampling occasions. Although most trace metals were found to have their highest concentrations on 8/12/97 and 2/25/98, a number, including Ag, Cr, Hg, and Mo, were also detected on other sampling occasions, although never in excess of 0.5 mg/L. Also, the detection of these trace metals was not restricted to the samples recovered from 24 m, apart from Ag and Hg, which were only detected on 6/9/98, at 24 m. Anomalous to the trace metal trend described above, Ba concentration decreased between 18 and 24 m on 8/12/97. This would indicate barite ($BaSO_4$) precipitation may have occurred within the basal areas of the lake.

In comparison to the trends described above, Na and K behave more conservatively on all sampling occasions, showing little variation with depth. This is most likely due to their high solubility. Consequently, such elements may potentially accumulate within the SCP until saturation of a phase containing these elements is reached.

Discussion of Limnology and Hydrogeochemistry

Limnology

Sampling in June 1996 (Gannon et al. 1996), while the lake was still filling, indicated that a 3-layer thermal/chemical stratification already existed at that time (Figure 9). The layers included an approximately 7.6-m thick higher temperature, relatively low TDS (850 mg/L) epilimnion; an approximately 6-m thick moderate TDS (980-1800 mg/L) metalimnion; and an approximately 3-to-5-m thick, high TDS (3740 mg/L) hypolimnion. (The sulfate and TDS analytical data in the Gannon report are incorrect. However, independent analyses contracted by SRK indicate that the three-layer pattern is correct.)

At the beginning of in-situ monitoring (Schafer 1999) in early March 1997, the lake appeared to have a vertical TDS/density gradient of about 730 mg/L from the near-surface (940 mg/L) to the near-bottom probe (1670 mg/L). By April, the water column (at least to within 1 m abe) overturned, homogenising the TDS at about 1100 mg/L. The overturn event may have been related to the collapse of a portion of the high wall and a significant input of flood waters and mud in 1997. TDS values in March and early April show potential instabilities. It is possible that the sliding of the rock mass into the pit caused an internal wave or seiche that stirred up the water column.

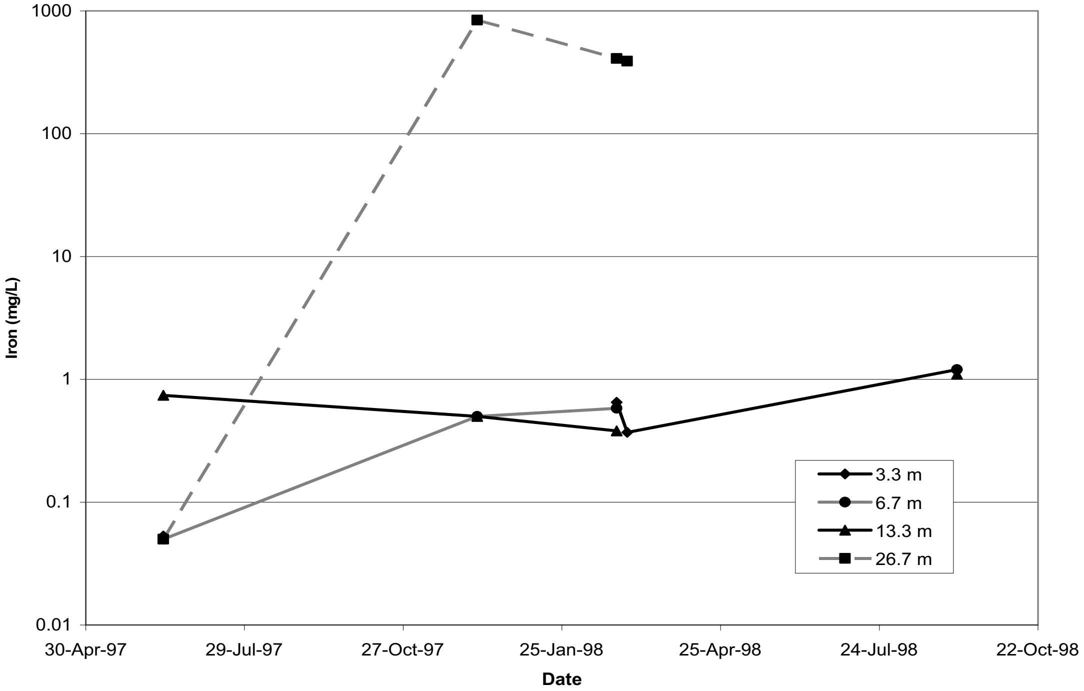


Figure 12. Variation in iron concentrations with depth in the Summer Camp pit lake

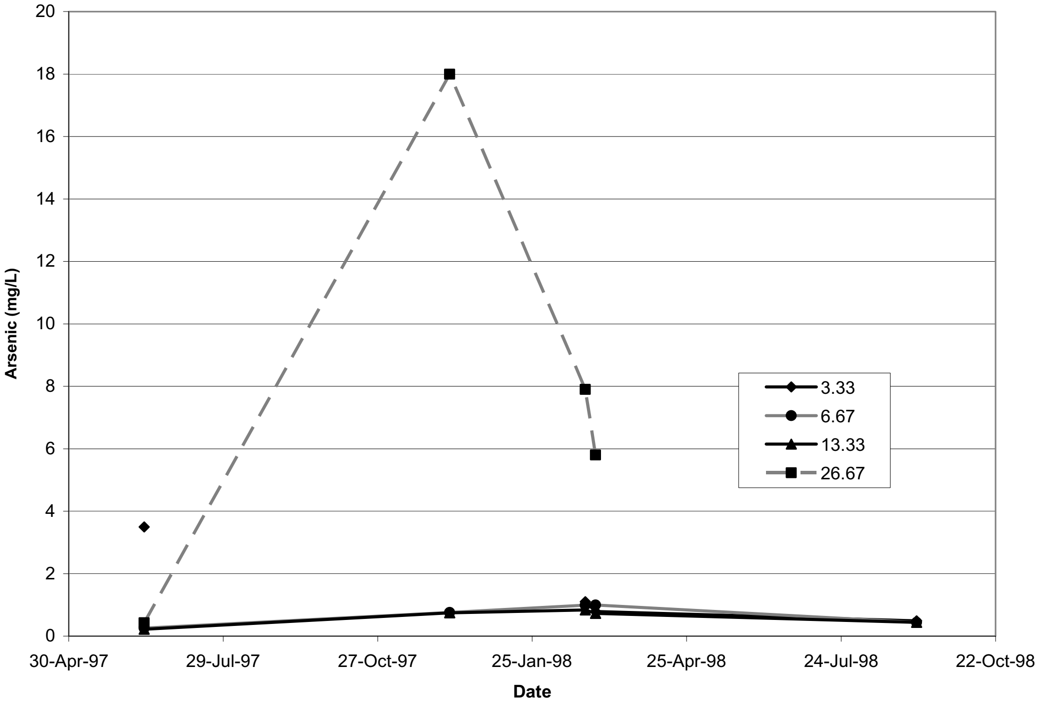


Figure 13. Variation in arsenic concentrations with depth in the Summer Camp pit lake

The in-situ monitoring program established that an epilimnion developed in the uppermost 1 to 6 m of the SCP lake during the summer months of both 1997 and 1998 due, at least in part, to thermal stratification. A chemo/hypolimnion similar to, but thinner than that observed by Gannon et al. in 1996 became evident in water sampling at about 24 m from the surface in August 1997. This layer was not evident in the near-bottom Hydrolab probe and suggests that the layer was less than 1 m abe. In summer 1997, mid-depth water was similar in density to the near-bottom water at 1 m abe. These results suggest that a 3-layer chemical stratification may also have existed at that time. The lake would possibly have had a thin (less than 3-m thick) relatively low TDS (800-900 mg/L) epilimnion; a thick (about 21-m thick) moderate TDS (1100-1300 mg/L) metalimnion; and a very thin (less than 1 m abe) very high TDS (5134 mg/L) hypolimnion that was not observed in the near-bottom Hydrolab probe.

Overturn to at least 1 m from the bottom occurred late in 1997 when the surface temperature cooled enough to be denser than the deeper water. It is unknown whether the very deep, hypolimnion overturned. However, based on the significant density contrast between it and the overlying water, it is likely that it did not. During the winter of 1997-98, the chemo/hypolimnion grew to at least 1 m abe. It also appeared to strengthen with time. The strengthening of the hypolimnion resulted in the mid-depth water changing regimes between 1997 and 1998 (Figure 14). As discussed above, in the summer of 1997, the TDS of mid-depth water was 300-400 mg/L higher than near-surface water. In the summer of 1997, the mid-depth water became similar to near-surface water (with a TDS 0-50 mg/L higher than the near-surface water), suggesting that something occurred between the two summers to change the internal structure of the pit lake.

Beginning in late December 1997, the near-bottom Hydrolab probe began measuring rapid fluctuations in several parameters. These fluctuations appeared to have triggered the rapid growth of a dense bottom layer and the decrease in density of the mid-depth water. Hydrolab probes indicate that an exothermic oxidation event with pH decrease and mixing began on about 12/26/97, and continued in successively less intense cycles, or pulses, until the dissolution products of the reaction finally limited the mixing by making the deeper water more dense (Figure 15). The oxygen concentration at depth was high enough to initiate oxidation of pyrite, causing an exothermic reaction that continued until the oxygen was used up. The generated heat caused a thermal convection cell that brought in more oxygen and restarted the process in a cyclical pattern that finally subsided in early February. It is possible that the portion of highwall that slid into the lake bottom exposed fresh pyrite at this depth. Oxygen from the fall overturn oxidized this pyrite and set off a chain of events.

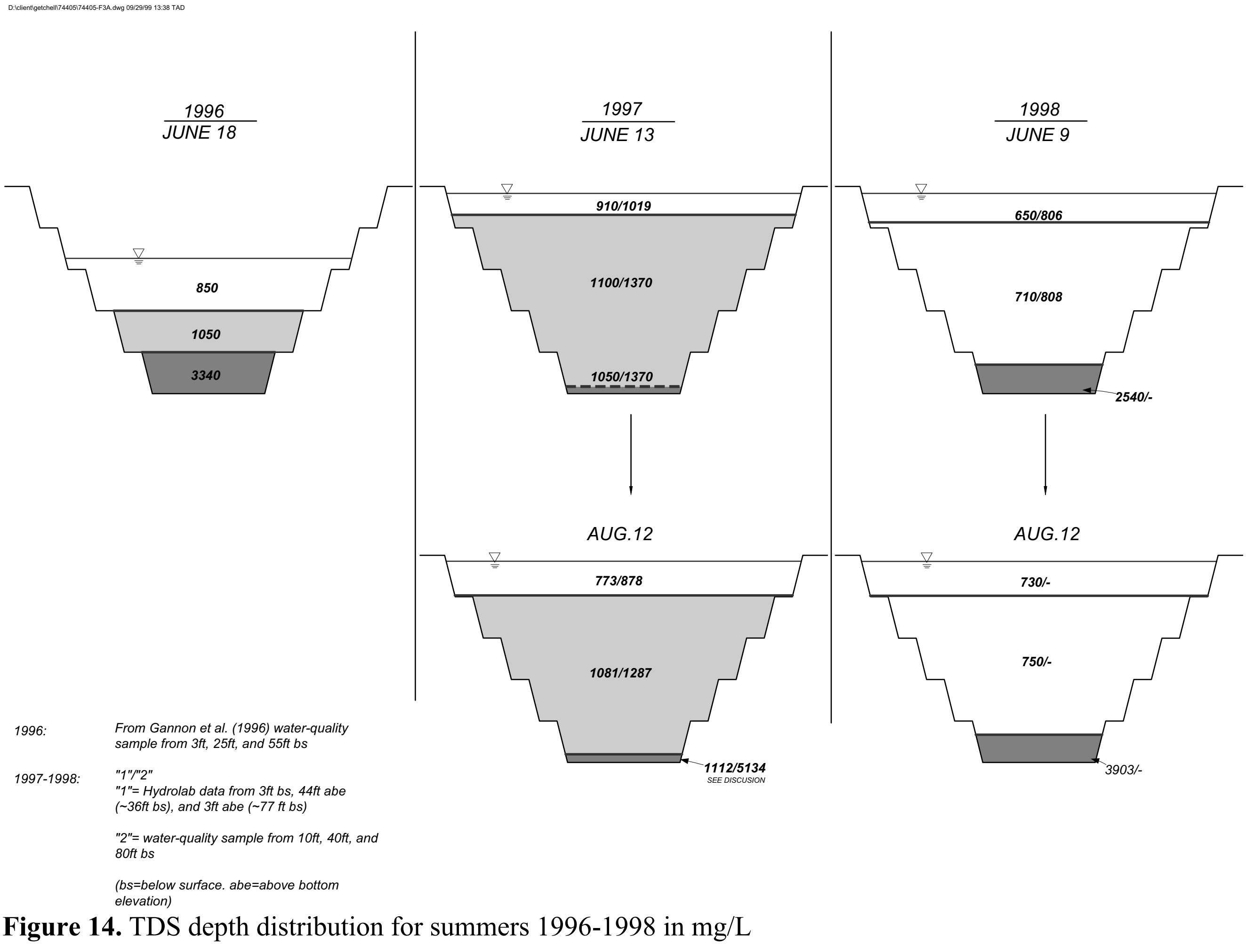


Figure 14. TDS depth distribution for summers 1996-1998 in mg/L

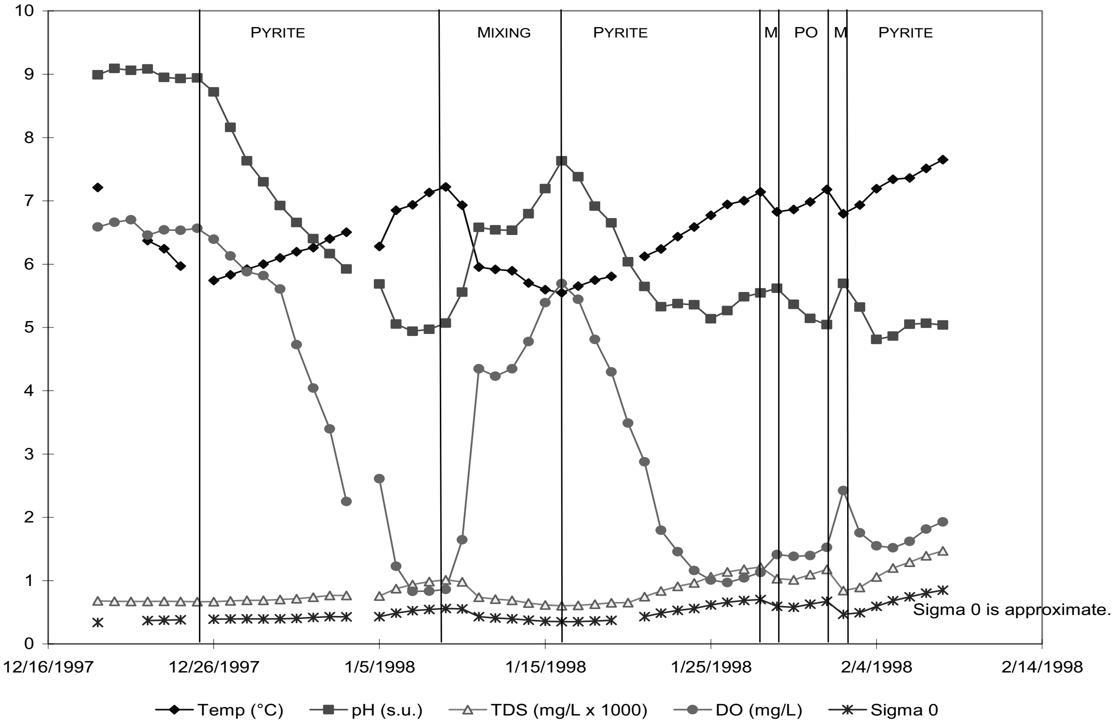


Figure 15. Pyrite oxidation and mixing cycles 1 m above the pit lake bottom, based on Hydrolab probe measurements

It is likely that the bottom layer continued to increase in density by reduction and dissolution of ferric hydroxide precipitates that fell from the surface water to the lake bottom. Loss of ferric hydroxide from the mid-depth to the hypolimnion would cause a permanent decrease in mid-depth TDS if the hydroxides had previously been re-dissolved within this middle layer during prior summer cycles of anoxia. Due to the large density difference between the bottom layer and the overlying water, it is likely that the next fall overturn event did not affect the bottom layer, which would remain anoxic. It is possible that prior to this event, only local depressions on the pit bottom had been permanently anoxic high-density waters. This event appeared to have brought significantly more water into the hypolimnion and increased the thickness of the layer to cover the entire pit bottom.

Hydrolab probes indicate that the lake was moderately alkaline at near-surface and mid-depth (pH 7-9) throughout the monitoring period. At near-bottom depths, pH ranged from neutral throughout most of 1997 to moderately acid (pH 4-6) throughout 1998. Analyses of water samples (Table 1) indicate that near-bottom (24-m depth) waters were neutral (pH 7.6) in June 1997 and acidic (pH 3.3 and 3.7) in August 1997 and February 1998, respectively. Acid bottom waters in water-quality samples, discussed above, provide additional evidence to indicate that pyrite had been oxidized and had formed a thin (about 1 m thick), stable, long-term (permanent?) chemo-hypolimnion.

Seasonal control

As described above, chemical stratification of the SCP lake is most distinct on 8/12/97 and 2/25/98. These two sampling routines span a period of 6 months. In-situ monitoring showed that turnover occurred between these two sampling dates, mixing and oxygenating water to at least 1 m abe. It appears that the overturn event oxidized fresh pyrite on the pit floor, possibly from a collapsed high wall, and caused growth and strengthening of a chemically denser, low pH bottom layer.

As discussed previously, iron precipitates from the surface waters eventually settle to the lake bottom. This is demonstrated by the distinct increase in Fe concentrations with depth and the oxidizing conditions within the surface waters. However, the Eh decreases with depth, ultimately becoming reducing at 24 m within the hypolimnion. This in turn affects the stability of the settling iron hydroxide, resulting in their dissolution within the hypolimnion. This causes a release of Fe and other trace metals scavenged by the iron hydroxides during formation in the surface waters and during descent. This process, combined with the oxidation of pyrite, ultimately caused a change in regimes of the intermediate water in the lake between 1997 and 1998. In 1997, the intermediate water had a TDS of ~1200 mg/L, compared with a surface-water TDS of ~900 mg/L; in 1998, both intermediate and surface water had a TDS of ~800 mg/L. (Table 1). It is possible that before the winter of 1997-98, the chemical hypolimnion did not cover the entire pit lake bottom, but only filled local depressions, allowing the majority of iron precipitates to redissolve into the intermediate water. The pyrite oxidation event in the winter of 1997-98 appeared to cause a major vertical thickening of the bottom layer and permanent removal of the iron hydroxide from the intermediate layer. This lowered the TDS of the summer metalimnion.

Supplementing the effects of seasonal turnover are those more closely related to the geology of the wall rocks. During the summer, pit lake levels subside, possibly exposing unoxidized or partially oxidized sulfides on wallrock and pit benches. Consequently, aerobic oxidation of the acid generating material, particularly pyrite within the carbonaceous hornfels and oxidized breccia, would be facilitated.

Due to the arid summer conditions prevalent in Nevada, the sulfide oxidation products accumulate as secondary salts, consisting primarily of gypsum and iron sulfate minerals such as copiapite, melanterite, and jarosite on wall rocks and pit benches. During wetter periods, the highly soluble secondary salts formed are re-dissolved. These may accumulate in the basal areas of the lake, particularly if they are sufficiently saline to have higher density. This causes an increase in the levels in trace metals and possibly a decrease in pH within the hypolimnion.

This process may be occurring in the oxidizing surficial environment within the SCP. Overall, the net result is an increase in proton acidity (a decrease in pH) and sulfate and a release of trace metals from within the jarosite.

As discussed in Bowell and Parshley (submitted), the majority of leached SO_4, acidity, and trace metals mobilized from the acid-generating lithologies occur within the first four pore rinses of a leaching experiment. Therefore, the flushing of secondary products would occur rapidly and completely in response to elevated run-off. Consequently, in addition to seasonal lake stratification, the distinct zonation noted on 6/13/97, 8/12/97 (and 3/3/98) may contain a contribution from secondary salt flushing.

Under the more acid conditions within the hypolimnion, the solubility of trace metals from both acid-generating and acid-consuming phases may be enhanced, further increasing the TDS of the hypolimnion water.

Increased solubility of otherwise immobile trace metals will also occur through complexation with ligands such as Cl and F. This was apparent on 8/12/97 and 2/25/98, where at 24 m, dissolved fluoride was 4.7 and 4.9 mg/L, respectively, compared to <1mg/L at all other depths. This process of increasing solubility through complexation will be particularly effective for a range of metals including Ag, Al, Ba, and Pb within the hypolimnion. Possible complexes for Al and Ag include AlF^{2+}, AlF_2^{+}, and AlF^{4-} and AgCl, $AgCl^{2-}$, and $AgCl_3^{2-}$. The net effect is the accumulation of solutes in the lake's basal zone.

On 8/12/97 and 2/25/98, it appears that ferric oxidation of pyrite may have occurred within the hypolimnion. The existence of ferric iron within the hypolimnion was confirmed on 3/3/98 when the concentration of ferrous iron (Fe^{2+}) does not account for total iron. Ferric oxidation of pyrite would contribute to the accumulation of solutes, particularly Fe and SO_4, within the hypolimnion. This would also release impurities contained within the pyrite. However, oxidation of the ore material would be expected to generate a selenium anomaly, which was not observed, so the extent of the above reaction and its importance in controlling lake chemistry cannot be confidently confirmed. The appearance of a Se anomaly however, may be limited by the acid pH, which would limit Se solubility.

During drier periods, the pit lake level subsides, with the influx of acidic, metal bearing leachate decreasing due to reduced run-off and flushing. Coupled with the effects of mixing, the pH of the lake water at depth returns to circumneutral values, as observed in the spring and summer of 1997 (Figure 8). However, this is not simply due to a decrease in the extent of pyrite oxidation/runoff. The recovery in pH may also be a combination of oxidation of non-acid generating sulfides, buffering by groundwater, bacterial activity, and host rock acid consumption.

The latter buffering mechanism, such as the consumption of protons by limestone, will have occurred during lake stratification. However, the amount of buffering capacity offered by such lithologies would be subordinate to the amount of acidity, resulting in net acidic conditions. Therefore, based solely on geological controls, the pH of the pit lake is governed by the relative dominance of acid-generating (pyrite oxidation/flushing of secondary salts) versus acid-consuming processes. Both of these processes are ultimately controlled by seasonal fluctuations, in addition to mining operations that affect lake hydrology (e.g., pumping).

Goethite and jarosite are highly supersaturated, as expected, in the oxidizing epilimnion conditions that exist at the surface of the lake (SRK 2001). Jarosite shows a slight decrease in supersaturation with increasing pH and a general decrease with time.

The behavior of goethite and jarosite agrees well with field and analytical observations, and both minerals are considered major controls on surface water chemistry. The degree of supersaturation of these minerals reflects the stability of these phases. Consequently, low Fe concentrations (<1mg/L) are found in the surface waters. This leads to the conclusion that Fe speciation within the oxidizing portion of the SCP lake is dominated by sulfate salts and iron oxyhydroxides, as confirmed by speciation modeling available within the MINTEQA2 package (Allison et al. 1991). MINTEQA2 predictions indicate the stability of amorphous ferric hydroxide in the sediments (SRK 2001). Selective extraction confirmed the presence of amorphous iron phases in pit bottom sediments (SRK 2001). It is presumed that this phase forms as a consequence of hydration of dissolved iron and settles in the lake.

The settling of this phase has a significant control over the seasonal variation in SCP lake chemistry. Due to the concentration of amorphous ferric hydroxide and physiochemical conditions in SCP, the presence of this phase also influences the behavior of some trace elements, noticeably As species and phosphate (e.g., compare Figures 14 and 15). With sedimentation and over time, this phase will crystallize to goethite, releasing weakly sorbed trace elements (Waychunas et al. 1993). This may, in part, explain the high dissolved trace element concentrations in the hypolimnion.

Conclusions

The limnological studies of the SCP lake indicate that under the controls that existed at the time of the study, the lake had stratified into three distinct layers. Furthermore a pronounced fall-winter mixing event occurred along with a lower impact event in spring. However, the hypolimnion appears to recover quickly, remaining acidic and metal-sulfate rich.

The metalimnion shows a constant chemistry with respect to its depth but changes significantly with time. During stratification, the metalimnion appears to be chemically similar to the hypolimnion. Due to temperature-density differences, mixing eventually occurs and causes the metalimnion and the epilimnion to become a single layer. This leads to a settling of colloidal hydrous ferric oxide-clay particles into the hypolimnion. Adsorption of trace metals onto the colloidal particles causes a depletion of trace metals from the metalimnion and epilimnion and an increase in trace metal content of the hypolimnion. Following mixing, solutes gradually accumulate again within the metalimnion until the next turnover event.

Epilimnion chemistry is relatively stable throughout the year and is more oxidizing and dilute than lower zones while the pit lake is stratified. A strong control on this is the inflow of dewatering solutions from the underground mining operations.

In 2001, the introduction of underground water was terminated to SCP. The lake has steadily evaporated and over time chemistry in the lake has approached hypolimnion chemistry as stratification was lost. Consequently the pit lake is being managed by periodic lime addition but in the long term will be drained and backfilled.

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