Evaluation of Water Quality Changes for Mine Waste Disposal in Pit Lake, Former EL Mine Site Manitoba, Canada

[1]Nikolay Sidenko, [2]Karen Mathers, [3]Caius Priscu, and [4]Steve Sibbick

[1]Stantec Consulting Inc., Winnipeg MB, CANADANikolay.Sidenko@stantec.com
[2]Stantec Consulting Inc., Inc., Winnipeg MB, CANADAKaren Mathers@stantec.com
[3]AMEC Environment and Infrastructure, Burnaby, BC, CANADACaius.Priscu@amec.com
[4]AMEC Environment and Infrastructure, Mississauga, ON, CANADASteve.Sibbick@amec.com

Abstract
The EL Mine site is an abandoned Cu-Ni mine in northwestern Manitoba that is currently undergoing rehabilitation by the Province. The site investigations revealed the presence of acid generation mine waste and a water body locally known as Pit Lake, extending to a depth of approximately 130 m. Pit Lake was formed by the flooding of the former open pit which was connected to the former underground workings through removal of the crown pillar.Investigations indicate Pit Lake to be meromictic with a thermocline and a chemocline at approximately 20 m depth. The chemistry of the discharge from Pit Lake is characterized by pH~5.5, TDS~250 mg/L and elevated concentrations of Al (~0.4 mg/L), Cu (~0.05 mg/L), Ni (~4 mg/L), and Zn (0.05 mg/L). Placement of acid generating mine waste in Pit Lake as a remedial optionwas considered.The evaluations of impacts on the water quality involved experimental mixing of mine waste samples with lake water followed by mass-balance calculations. The calculations indicated that mine waste placement would result in a decrease in water pH to ~3 and an increaseof over an order of magnitude in the concentrationsof some metals, which would require treatment of any discharge.

Key Words:waste rock, geochemistry, predictions, experiment,pit lake, abandoned mine

Introduction

Studies of pit lakes include an understanding of geochemical processes, which control water quality of the discharge and potential use of these lakes including disposal of mine waste(Castendyk and Eary 2009, SENES 1995).

The EL Mine site is located 3.5 km south of the Town of Lynn Lake, Manitoba (Figure 1). The mine operated between 1954 and 1963 using open pit and underground mining techniques. Copper-nickel sulphide ore was associated with gabbro, pyroxenites and peridotites, which dominated the waste rock pile. The pit was surrounded by piles of overburden in order to divert water from the open pit during the mining. Underground mining operations near the end of mine life resulted in the removal of the crown pillar beneath the center of the open pit creating a glory hole extending to a depth of approximately 130 m. The diameter of the pit at ground surface is approximately 200 m.The glory hole and open pit started to flood in 1976 forming a water body locally known as Pit Lake(Figure 1). The EL Mine is classified as an abandoned mine site under the responsibility of the Province of Manitoba. Characterization and rehabilitation of

the mine site started in 2008. Geochemical studies of Pit Lakeand the old mine waste were required to recommend effective options for site rehabilitation. Specific tasks of the study included:

- Characterization of the mine waste.
- Characterization of Pit Lake dimensions, chemistry and inputs.
- Prediction of water chemistry changes for an in-pit waste disposal scenario.

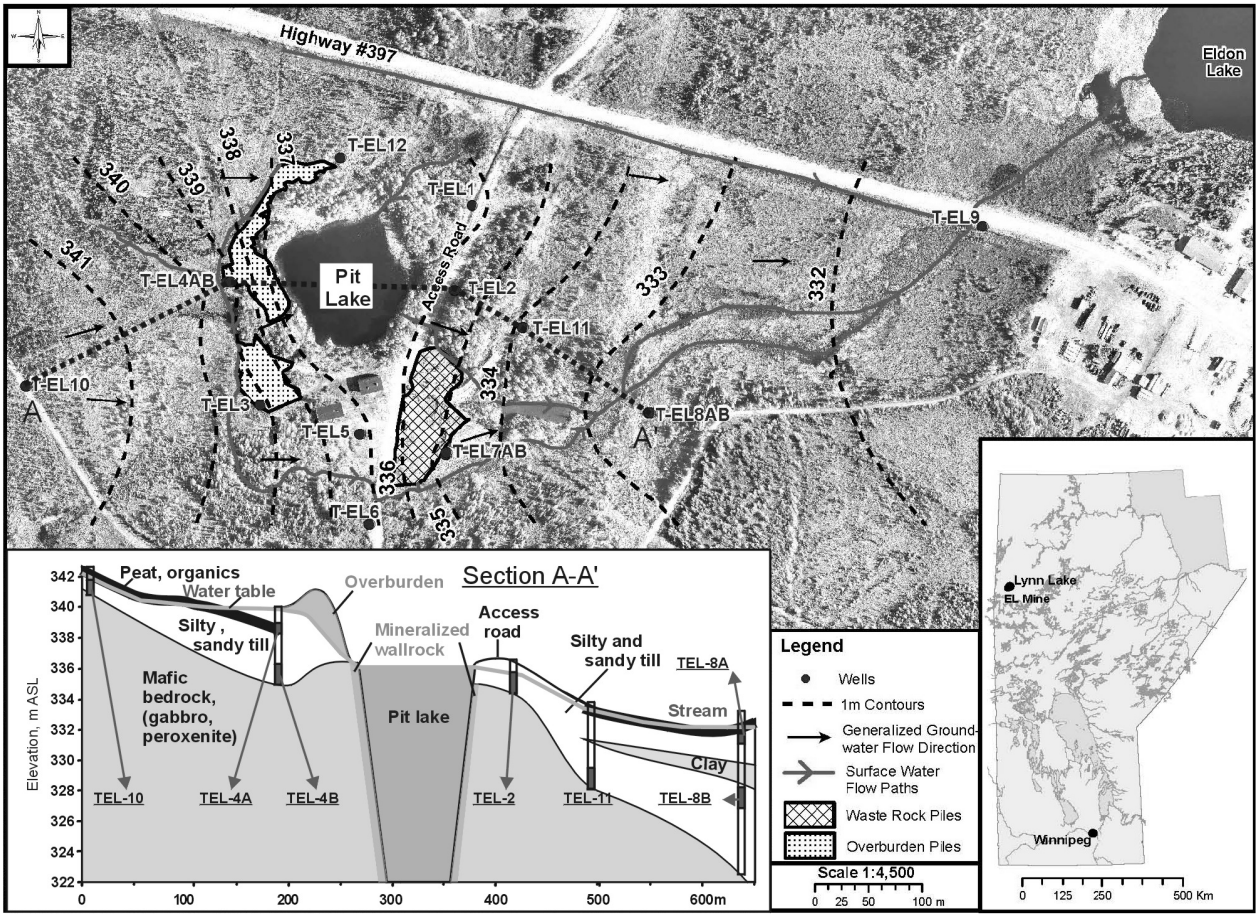

Figure 1. Surface and groundwater flows at former EL Mine, Lynn Lake, Manitoba.

Methods

Eleven samples weighing approximately 5 kgeach were collected from different mine wastes found at the site. Each sample was analyzed for total metals and Acid Base Accounting (ABA) parameters including paste pH, total sulphur, sulphate sulphur, and neutralization potential (modified method from MEND 1991) by CANTEST (now Maxxam Analytics). The mineralogy of thesamples was studied using optical and scanning electron microscopy methods at the University of Manitoba.

The bathymetry of Pit Lake was studied using sonar and the discharge from Pit Lake was measured using a graduated bucket and stopwatch. Sampling of the water column was

performed with a Kemmerer sampler in August and September 2008 in the center of Pit Lake. Temperature, pH, redox potential and conductivity were measured immediately after sampling using meters calibrated against standard solutions. Samples were field filtered through 0.45 μm filters and divided into aliquots for analyses of metals, major ions and isotopes. The aliquot for metals was preserved with nitric acid to pH<2. All samples were kept at temperature near 4°C until delivered and analyzed by ALS EnvironmentalLaboratory in Winnipeg. The Environmental Isotope Laboratory (Waterloo) was also commissioned to perform an analysis of oxygen and hydrogen isotopes in water.

Five samples of mine waste (waste rock and overburden) were mixed with Pit Lake water in 1:3 solid to water volume ratio (5L of solid and 15 L of water). The solutions were tested for pH and sampled 3 days, one month and one year after mixing. The samples were filtered, preserved and analysedby ALS EnvironmentalLaboratoryusing the protocols summarized above.

Saturation indexes were calculated using the WATEQ4f computer program(Ball and Nordstrom 1999). The activities of the Fe redox couple were calculated from measured Eh.

Results and Discussion

Mine waste

During site characterization, two types of mine waste were determined to be present: overburden piles and waste rock from the mining operation.

The estimated volume of the overburden was19,000 m^3.The major minerals in this material were quartz, potassium feldsparand plagioclases. Sulphides occurred in 0.5-1 mm fragments and were surrounded by rims of secondary Fe-oxyhydroxides. Most overburden samples had already depleted their neutralization potential and were acid generating, which was also demonstrated by an average paste pH =3.3 (Table 1). The overburden samples had a negative NNP except forone sample. Concentrations of Ni and Cu in the overburden generally exceeded the Canadian Council of Ministers of the Environment (CCME)Soil Quality Guidelines for Residential and Industrial Land Uses. Based on the ABA and geochemical results, the overburden piles could be an existing source of acidity and metals, particularly Ni and Cu. This was confirmed by analyses of the seeps associated with the piles (Tetr*ES* [now Stantec] 2009).

Table1. Acid-base accounting results for waste materials from the EL Mine site.

Sample ID (waste material)	Paste pH	Total S	Sulphate S	Sulphide S*	MPA**	NP ***	NNP
Units	pH units	Weight %			Kg $CaCO_3$/tonne		
WR-1 (waste rock)	4.2	2.79	0.34	2.45	76.6	4.5	-72
WR-2 (waste rock)	4.5	0.8	0.12	0.68	21.3	2.8	-18.5
WR-3 (overburden)	3	0.49	0.39	0.1	3.1	-2.5	-5.7
WR-4 (overburden)	2.6	0.83	0.44	0.39	12.2	-6.1	-18.2
WR-5 (overburden)	3.1	1.57	0.26	1.31	40.9	-1.3	-42.2
WR-6 (overburden)	4.1	0.19	0.07	0.12	3.8	1	-2.7
WR-7 (overburden)	2.9	0.89	0.34	0.55	17.2	-4	-21.2
WR-8 (waste rock)	6.4	1.08	0.05	1.03	32.2	19.9	-12.2
WR-9 (rock/ore fines)	3.5	6.72	0.36	6.4	199	-6.3	-205.1
WRBJ TOP (waste rock)	3.9	1.11	0.33	0.78	24.4	-2.3	-26.6
WRBJ BOT (overburden)	4.3	0.07	0.03	0.04	1.3	1.5	0.3
Detection Limits:	0.1	0.02	0.01	0.02	0.6	n.a.	n.a.

Notes:

* Based on difference between total sulphur and sulphate-sulphur

** Maximum Potential Acidity based on sulphide S

*** Reference for Mod ABA NP. MEND Acid Rock Drainage Prediction Manual, MEND Project 1.16.1b (pages 6.2-11 to 17), March 1991.

The waste rock volume was estimated to be approximately8,500 m^3. Primary sulphides such as pyrrhotite, chalcopyrite, and pentlandite occurred in 0.5-1 mm ore fragments. The majority of the waste rock grains were represented by basic plagioclase, Ca-Mg amphibole, hornblende, chlorite and quartz. No carbonates were found in the samples, but the mafic composition of the waste rock was more favourable for acid neutralization than the felsic minerals comprising the overburden based on analyses of different rock types byJambor (2003).In most of waste rock samples,the neutralization potential (NP) had not yet been depleted in contrast to the overburden. The positive neutralization potential of the waste rock corresponded well with the observed higher average paste pH (4.8) compared with the overburden. Nevertheless, the net neutralization potential (NNP) was negative in all samples indicating a risk of acid generation in the future. Concentrations of Ni, Cu, Cr and Se in the waste rock exceeded the CCME Soil Quality Guidelines for Residential and Industrial Land Uses.

Boththe waste rock and overburden had the potential to generate acid and release metals in the future. One of the rehabilitation options was underwater disposal of these materials in order to minimize sulphide oxidation causing acid generation and metal leaching. Pit Lake was the first candidate for underwater disposal.

Pit Lake characterization

The bathymetry showed that the shape of Pit Lake resembled a funnel with an upper surface diameter of ~110 m and the diameter of the “neck” of ~50 m. The depth from the surface of the lake to the “funnel neck” was approximately ~20 m (the approximate position of the former crown pillar) and the total depth of the lake was ~130 m, measured to the bottom of the funnel. The estimated volume of water within Pit Lake was 226,000 m^3, which was more than sufficient to retain all of the mine waste from the site.

The lake outflow was controlled by a culvert at elevation 236.4 m above sea level. In 2009, the discharge rate from Pit Lake rangedbetween 0 and 9.6 L/s, with the highest values at the beginning of May, during the snowmelt (Figure 2). At the end of May, the discharge gradually declined and reached summer levels of approximately 1 L/s. The total discharge generated in May, estimated to be 14400 m^3, was almosthalf of the cumulative annualdischarge (~26100 m^3). This indicated that the major water input to Pit Lakewas surface runoff ratherthan seepage of groundwater through the overburden and fractured walls of the pit.

Visual observations and temperature records showed that Pit Lake became completely ice-free by the end of May. This event should be immediately followed by the turnover of the upper portion of the lake according to the temperature and isotopic recordsignature in the discharge (Table 2). During May, heavierwater isotopesdominated in the discharge, while lighter isotopes prevailed after May 31st. The heavierisotopesindicateda signature of snowmelt (Pit In sample, Table2), whereas the relatively lighter water originated from the upper layer of Pit Lake (above 30 m).

The discharge from Pit Lakedid not meet the CCME Water Quality Guidelines established for the Protection of Freshwater Aquatic Life due to its low pH (~5.1) and elevated concentrations of Al, Cu, Fe, Ni, and Zn, which were considered to be parameters of concern. Some of these parameters exhibited substantial seasonal changes. In the beginning of May, discharge from the lake had a pH of 5.6 and elevated concentration of metals except for iron (Figure 2). During May, metal concentrations and sulphate droppedtwo to five times and in the beginning of June, before turnover.After the turnover,concentrations increased up to two timesfor Al, Cu and Zn and four times for Ni and sulphate, reaching summer levels. The concentrations of metals and sulphate generally stayed the same until the freeze-up of the lake.

Iron showed a distinct behaviour in comparison with the other metals (Figure 2). During spring, the iron concentrations were four timeshigher than in the summer (0.8 and 0.2 mg/L, respectively). This pattern wasattributed to the redox state of iron and lake turnover. Under ice cover, iron is likely present in its divalent formas found in other pit lakes(Davis and Ashenberg 1998).

The physical and chemical properties of Pit Lake indicated that the lake was divided into two zones with a boundary at a depth of ~20 m. The upper zone (mixolimnion) was characterized by variable temperature, redox conditions and pH as compared with the lower zone (Figure 3). The lower zone (monimolimnion) had a relatively stable temperature, redox conditions and pH. The concentrations of total dissolved solids (TDS) increased with depth and had an inflection point near the boundary between the zones (~20 m depth). The calculations of water density from the different temperature and TDS concentrations across the water column indicated that the lake does not completely turnover. This was also supported by sharpchanges in isotopic composition between 15 and 30 m (Table 4). Therefore, the lake can be classified as meromictic with a thermocline and a chemocline coinciding at a depth ~20 m, which appears to be controlled by the morphology of the lake.

Table 2. Isotopic composition of water from Pit Lake

Sample ID	Date	$\delta^{18}O$	Result	Repeat	$\delta^{2}H$	Result	Repeat
		H_2O	VSMOW		in H_2O	VSMOW	
Pit out May 5	5-May-09	X	-17.84		X	-142.87	-142.80
Pit out May 9	9-May-09	X	-20.14	-20.43	X	-157.58	-157.25
Pit In	21-May-09	X	-20.03		X	-147.80	-148.09
Pit out May 31	31-May-09	X	-15.32		X	-126.00	-126.08
Pit out June 13	13-Jun-09	X	-14.89	-14.92	X	-124.35	-124.09
Pit out June 27	27-Jun-09	X	-14.33		X	-121.56	-121.53
Pit out Aug 27	27-Jun-09	X	-14.28		X	-117.58	-117.85
PitLake 15 m	18-Sep-08	X	-14.96		X	-123.59	-123.38
PitLake 30 m	18-Sep-08	X	-17.27		X	-132.44	-132.35
Pit Lake 50 m	18-Sep-08	X	-18.06	-18.28	X	-138.16	-138.14
Pit Lake 90 m	18-Sep-08	X	-18.11		X	-138.19	-138.32
Pit Lake 130 m	18-Sep-08	X	-18.06		X	-137.52	-136.86

The concentrations of major ions (Ca, Mg, K, Na sulphate and bicarbonate) were similar to the TDS profile and increased with depth (Figure3). The Fe concentrations sharply increased near the thermocline and remained constant below that level, indicating anoxic conditions at the monimolimnion, deeper than 20 m (Figure3). Thermodynamic calculations showed that the water column was close to ferrihydrite saturation indicating that redox conditions in Pit Lake were likely controlled by the $Fe^{2+}/Fe(OH)_3$ couple (Sidenko *et al.* 2009). Aluminum concentrations were greater in the mixolimnion and negatively associated with pH. Pit Lake was slightly supersaturated with respect to amorphous Al-hydroxide. This fact indicated that concentrations of aluminum appeared to be controlled by the solubility of $Al(OH)_3$, which is pH-dependent.

Divalent transition metals, such as Cu, Zn and Ni, had different concentration trends with depth. The concentrations of Ni were four times lower near the surface of the lake than in the lower zone. By contrast, significantly more Cu and Zn were found in the mixolimnion compared with the monimolimnion. Such distinction in the behaviour of elements that originated from the oxidizing sulphides could be explained by different rates of metal release or attenuation in the two zones of the lake. The lower zone (monimolimnion) likely represented the chemistry of Pit Lake after the flooding of the EL Mine, with some later changes associated with the adsorption of metals onto the Fe and Al-hydroxides and neutralization resulting from dissolution of Ca and Mg pyroxenes, amphiboles and basic plagioclase (Jambor 2003). The concentrations Cu and Zn were orders of magnitude lower that Ni in the monimolimnion and therefore, Cu and Zn behaved as micro- or trace elements in the sorbent-solution system resulting in their better adsorption while Ni behaved as a macrocomponent and required a larger amount of sorbent. In addition, the metal affinity for Fe-hydroxides is known to decrease in the order of Cu>Zn>Ni (Walton-Day 2003). Therefore, Cu and Zn were likely more easily scavenged from the solution than Ni, even if they would have had concentrations similar to Ni. The upper zone (mixolimnion) also received acidic runoff and seepage from the overburden, which likelylowered pH and caused Cu, Zn and Al to be more mobile than in the lower zone. The mixolimnion was probably diluted with respect to Ni since Pit Lake was formed.

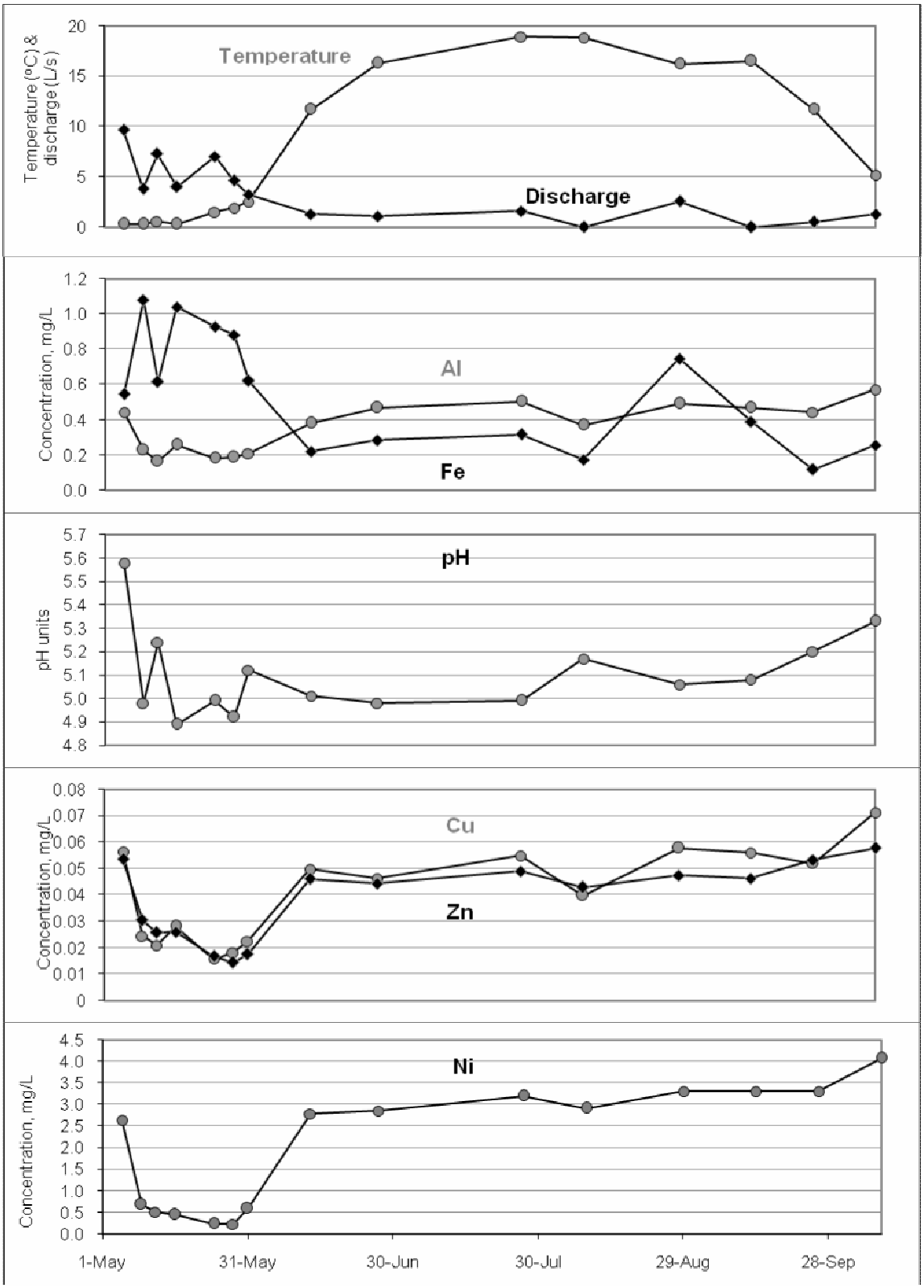

Figure 2. Seasonal variations of temperature, discharge rate and chemistry in the discharge from Pit Lake.

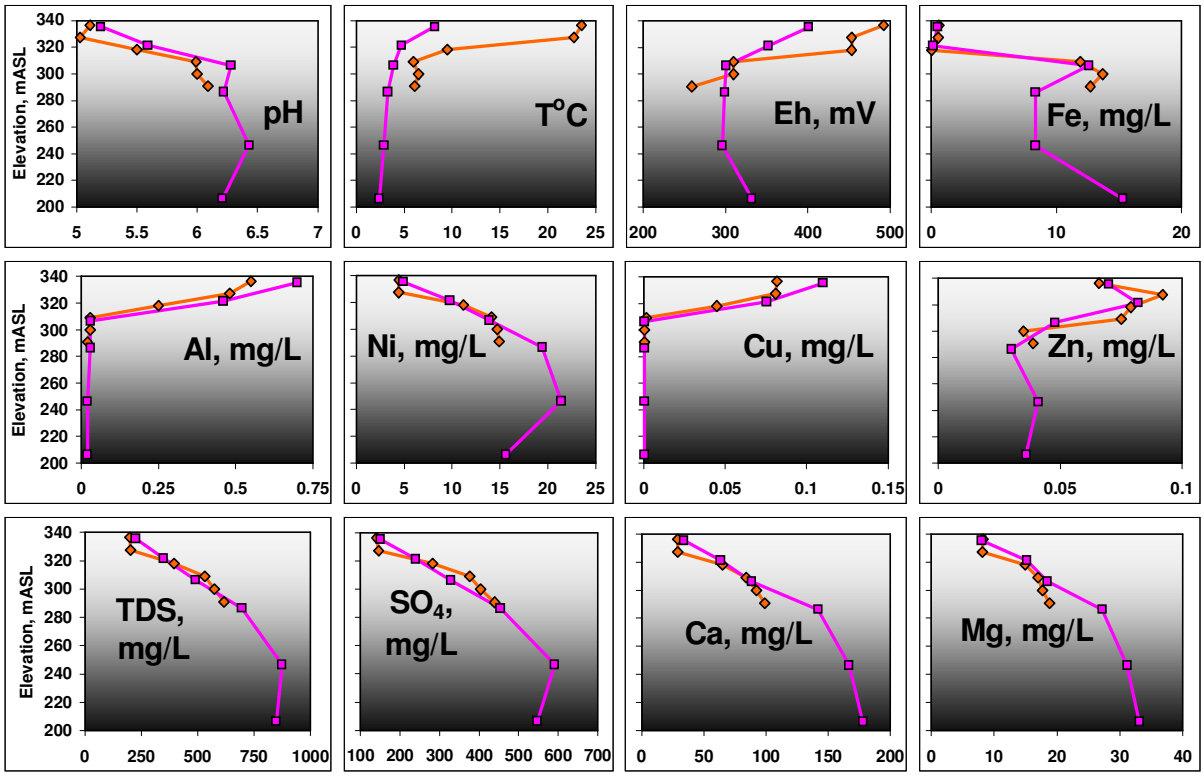

Figure3. Depth profiles of physical and chemical parameters in Pit Lake, August (diamonds) and September (boxes).

Experimental Mixing of Mine Waste and Pit Lake Water

In the mixing experiments, the pH of the solutions decreased from ~5 to ~3 units. The concentrations ofCu and Al increased 5 to10 times compared withthe initial water from Pit Lake; most likely due to the pH drop (Table 3). The concentrations of Ni, Zn and sulfate doubled.

Between three days and one month,the mixing experiments showed an increasein metal concentrations, especially for Fe, Al and Cu (Table 3). Between one month and one year, metal concentrations decreased below or to the initial levels determined in three days after mixing(data not shown). During the one-year period, the pH of the solutions generally increased to the initial (Pit Lake) level or higher.

Prediction of Pit Lake Chemistry Changes

Predictions of the potential changes in the water chemistry of the upper zone were calculated from the results of the mixing experiments, summarized in Table 3. We assumedfast (within one month) deposition of materials into the mixolimnionzone andan instantaneous release of elements and used the following mass-balance equation:

$$C_n = (V_L \times C_L + 3 \times \Sigma_n (V_n \times (C_{Ex\_n} - C_L)) / V_L \qquad \text{(Equation 1)}$$

where,

C_n – element concentration in the lake after deposition of V_n m^3 of waste (Table 4)

V_L – volume of mixolimnion (upper zone) = 120,000 m^3

C_L – concentration of element in Pit Lake water before the experiment, mg/L (Table 4, Column 2)

V_n – total volume of waste material deposited in the lake, m^3 (Table 4, second row)

C_{Ex} – concentration in the solution after the mixing (Table 3, Columns3 and 4)

3 – correction factor for solid:water ratio

Table 3 Summary of mixing experiments.

Parameter	Pit lake	Waste rock	Overburden
Three day experiment			
pH	5.05 ± 0.12	3.4 ± 0.5	2.9 ± 0.3
Al, ppm	0.50 ± 0.09	3.2 ± 0.6	6.7 ± 2.6
Fe, ppm	0.45 ± 0.09	3.2 ± 0.6	6.7 ± 2.6
Cu, ppm	0.07 ± 0.01	1.1 ± 0.4	2.7 ± 1.8
Ni, ppm	4.3 ± 0.28	5.9 ± 0.8	6.9 ± 1.7
Zn, ppm	0.06 ± 0.01	0.08 ± 0.01	0.11 ± 0.01
SO_4, ppm	139 ± 4.73	226 ± 8	352 ± 100
One-month experiment			
pH	5.05 ± 0.12	3.6 ± 0.5	2.9 ± 0.3
Al, ppm	0.45 ± 0.22	0.3 ± 0.3	57.1 ± 71.4
Fe, ppm	0.50 ± 0.09	8.0 ± 3.3	11.3 ± 8.1
Cu, ppm	0.07 ± 0.01	2.5 ± 1.1	10.9 ± 11.3
Ni, ppm	4.29 ± 0.28	9.1 ± 3.6	9.3 ± 5.2
Zn, ppm	0.06 ± 0.01	0.23 ± 0.27	0.20 ± 0.10
SO_4, ppm	139 ± 4.73	185 ± 154	759 ± 645

The concentrations of protons were obtained from pH measurements using the convention:

$$[H^+] = 10^{-pH} \quad \text{(Equation 2)}$$

Then concentrations of protons in Pit Lake (C_L) and in the solution after the experiments (C_{Ex}) were used in equation(1) to obtain the concentration of protons (Cn) after instantaneous deposition of volume V_n. The resultant concentration of protons was then converted back to pH using equation (2) and reported in Table 4.

The error was calculated using the following equation:

$$E_n = \delta_{Ex} / C_{Ex} \times C_n$$

(Equation 3)

where,

E_n – error of the calculation associated with calculated concentration of element C_n, mg/L (Table 2)

δ_{Ex} – standard deviation associated with measured concentration of element in the solution after the experiment $C_{Ex.}$

For cumulative deposition of overburden and waste rock, the errorpropagation was done using the following equation:

$$E = (\Sigma_n (E_n)^2)^{0.5}$$

(Equation 4)

The results of the calculations indicated if waste rock was deposited above the chemocline, the pH would drop to levels as low as 3.6, and the concentrations of Cu and Fe would increase 8 and 4 times,

respectively, above their startingconcentrationsin the discharge (Table 3). The concentrations ofNi, Zn and sulphate, however,were predicted to not increase more than 2 times.

Overburden deposition would result in a drop of pH to ~2.9 above the chemocline. If one-month concentrations were used as the input, Cu, Al and Fe would increase 70, 60, and 10 times, respectively, in comparison with the initial concentrations. Zn and Ni wouldapproximatelydoubleabove initial discharge concentrations. Similar changes were expected in the scenario of combined deposition of overburden and waste rock (Table 4) although deposition of waste rock seemed to have less impact on water quality than deposition of the overburden likely due to finer grain size and presence of soluble metal sulfates in the overburden.

Table 4. Predicted changes in Pit Lake water chemistry as a function of type and volume of deposited materials.

Material	Pit Lake	Waste Rock	Overburden	All Mine Waste
Waste Volume	0	9100 m^3	19000 m^3	28100 m^3
Three day experiment input - Short term changes (days)				
pH	5.05 ± 0.12	3.4 ± 0.5	2.9 ± 0.3	3.0 ± 0.5
Al, ppm	0.50 ± 0.09	1.1 ± 0.2	3.5 ± 1.3	4.1 ± 1.3
Fe, ppm	0.45 ± 0.22	0.1 ± 0.1	2.4 ± 2.8	2.3 ± 2.8
Cu, ppm	0.07 ± 0.01	0.3 ± 0.1	1.3 ± 0.9	1.6 ± 0.9
Ni, ppm	4.3 ± 0.28	4.7 ± 0.6	5.5 ± 1.4	5.9 ± 1.5
Zn, ppm	0.06 ± 0.01	0.06 ± 0.01	0.08 ± 0.01	0.1 ± 0.02
SO_4, ppm	139 ± 4.73	159 ± 6	240 ± 68	260 ± 69
One-month experimentinput - Long term changes (>month)				
pH	5.05 ± 0.12	3.6 ± 0.5	2.9 ± 0.3	3.1 ± 0.6
Fe, ppm	0.45 ± 0.22	0.3 ± 0.3	27 ± 34	27 ± 34
Al, ppm	0.50 ± 0.09	2.2 ± 0.9	5.6 ± 4.0	7.3 ± 4.1
Cu, ppm	0.07 ± 0.01	0.6 ± 0.3	5.2 ± 5.4	5.8 ± 5.4
Ni, ppm	4.3 ± 0.28	5.4 ± 2.2	6.7 ± 3.7	7.8 ± 4.3
Zn, ppm	0.06 ± 0.01	0.1 ± 0.11	0.12 ± 0.06	0.2 ± 0.1
SO_4, ppm	140 ± 4.73	165 ± 101	434 ± 369	459 ± 382

Implications for Mine Waste Management

At EL Mine, assessment of on surface waste rock and overburden piles were found to have the potential to generate acid and release metals in the future. One of the rehabilitation options considered was the disposal of these materials in nearby Pit Lake to minimize sulphide oxidation causing acid generation and metal leaching. Simple experimental mixing of mine waste with Pit Lake water coupled with the extrapolation of this data to the site conditions showed that, in-pit disposal of mine waste would result in the deterioration of the pit water quality. Further the overflow discharge of pit water to the receiving environment would have required activewater treatment to allow their release.Although the placement of the mine waste could have been carried out over a long timeframe (years) to reduce loadings and water quality impacts, from a logistical and cost standpoint the successful implementation of this option would require disposal of the wastes in a single campaign, likely during a single year. In addition, placement of over 27,000 m^3 of solids in the pit might have precludedany efforts to reopen the old mine by restricting future access to remaining underground resources. For these reasons, the in-pit disposal of mine waste and overburden made this option less attractive in comparison with other alternatives during the selection process.

The presence of an engineeredmine waste containment facility located approximately 5 km north of the site provided an opportunity for off-site disposal. The facility was built by the Province of Manitoba to contain the highly reactive sulphide wastes (tailings and concentrate spills) from an abandoned mine site. . Ultimately, the waste rock and overburden from the EL Mine site were disposed of at this facility.

Conclusions

Geochemical investigation of Pit Lake identified that the deposition of EL Mine mine wastes would result in significant impacts to the water quality of the lake. Mitigation of these impacts (using active water treatment, even on a temporary basis) made the in-pit disposal option less attractive compared to waste relocation to a nearby engineered containment facility. Subsequently, the closure plan for the site was modified and the mine wastes were successfully relocated off site.

Despite the remediation results at EL Mine site, in-pit and underwater mine waste disposal remains a viable and preferred option for limiting ARD/ML at many sites. It emphasized, however that individual site characteristics and conditions are unique. The application of well considered geochemical investigations to assess the site specific characteristics are a critical aspect of the decision making process for mine closure.

References

Ball, J.W. and Nordstrom, D.K. (1991)*User's manual for WATEQ4f, with revised thermodynamic data base and test cases for calculating speciation of major, trace, and redox elements in natural waters.* U.S. Geol. Surv. Open-File Rep. 91-183, XXXp.

Castendyk D. N. and Eary L.E. 2009(Eds.). *Mine Pit Lakes: Characteristics, Predictive Modeling, and Sustainability.*Society for Mining, Metallurgy & Exploration, Littleton, Colorado.

CCME (1999) *Canadian Soil Quality Guidelines for the Protection of Environmental and Human Health*.

David, A. and Ashenberg, D. (1988) The aqueous geochemistry of Berkeley Pit, Butte, Montana, USA. Applied Geochemistry, Vol. 4, pp. 23-36.

Jambor, J.L. (2003) Mine waste mineralogy and mineralogical perspectives of acid-base accounting. In: Jambor, J.L., Blowes, D.W., Ritchie, A.M.I. (Eds.)*Environmental aspects of mine waste.* Mineralogical Association of Canada Short Course Ser., 31, 117-147.

MEND (1991) Acid Rock Drainage Prediction Manual, MEND Project Report 1.16.1b.

SENES Consultants Ltd.(1995) Review of in-pit disposal practices for the prevention of acid drainage – case studies. MEND Report 2.36.1.

Sidenko N.V., Harron D., Mathers K.H. and McKernan, J. M. Aqueous geochemistry of pit lake at EL mine site, Manitoba, Canada: Implications for site remediation. In proceedings of International Applied Geochemistry Symposium (IAGS), Fredericton, NB, Canada, May 1-4th, 2009.

TetrES Consultants Inc. (now Stantec Consulting Ltd.)(2009) Environmental Site Assessment for EL Mine Site, Lynn Lake, Manitoba. Report to Manitoba Mines Branch, Winnipeg.

Walton-Day, K. (2003) Passive and active treatment of mine drainage. In: Jambor, J.L., Blowes, D.W., Ritchie, A.M.I. (Eds.), *Environmental aspects of mine waste.*Mineralogical Association of Canada Short Course Series, 31, 117-147.