The implications of redox conditions for the perpetual management of mine pit lakes

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Abstract

The perpetual management of mine pit lakes to promote acceptable water quality and ecological values is dependent on multiple physical, chemical and biological factors operating on differing daily to decadal time-frames. The critical factor in long term management of mine pit lakes is to establish an acceptable and stable redox regime where contaminants of concern are naturally mitigated. Various contaminants that may be mobile and bioavailable under oxic conditions can be removed from the system under anoxic conditions and vice versa.

The complex interaction of physical, biological and chemical conditions for any given pit lake (heterogeneous both spatially and temporally) require that individual sites are independently assessed. Case studies from literature and author investigations are used to summarise conditions which have proven to either ameliorate or promote mobilisation of various metals. Results from author limnological surveys of five natural lakes and two mine pit lakes, as well as in-situ experiments using nutrient, organic carbon and ARD lime treatment sludge additions, are used to illustrate the influence of nutrient status and biochemical processes on metal mobilisation. These lakes range from 5 m to 600 m deep, oxic to anoxic and from oligotrophic to highly eutrophic. The implications of active water treatment in the short term and pit lake engineering for the long term are assessed.

Keywords: mine pit lakes, voids, biogeochemistry, remediation, management.

Introduction

Management of water resources is perhaps the most difficult aspect of both stakeholder engagement and environmental stewardship for the vast majority of proposed, operational or decommissioned mines. In most cases the largely short-term issues of noise, dust, air emissions and physical land disturbance impact a relatively small spatial area and/or can be mitigated by available technologies. It is the impact to water quality and quantity that has the greatest potential long term management implications. While on purely economic grounds the access and impact to water resources would favour mining by several orders of magnitude, water is an emotional subject. For instance irrigation, one of the highest value agricultural land uses on a per unit area basis, produces on average 45 times less income than an average mine lease per hectare (Australian Bureau of Statistics 2012). An average 20-30 year mine life being equivalent to around 1000 years of high value agriculture on the same land area. The fact that mining is still generally regarded with such enmity in the environmental debate is largely due to concerns over water quality and quantity.

Open pit mining on any large scale is more likely than not to require excavation below the ambient water table and subsequent dewatering during operations. Upon mine closure or pit decommissioning the void will typically fill with groundwater to form a mine pit lake, reaching a level slightly below the pre-mine water table (due to evaporation and topographic effects), creating a groundwater sink in the area. Pit lake waters commonly have quality issues due to exposure to elevated mineralisation in the pit walls/spoil and drainage from waste rock dumps/overburden/tailings storage areas. There are several engineering options available to mine operators to alter the hydrologic regime of the pit lake including backfilling, surface water diversion (either into or away from the void), addit sealing, spillway creation and/or various pumping/dewatering approaches. In addition there are options to alter the water quality through remediating inflows and/or in-situ treatments. The critical consideration for long-term or perpetual planning is to find a combination of measures that allows the pit lake to self-mitigate the potential water quality issues specific to its physical and geochemical setting.

The aim of this paper is to illustrate to mine closure planners that the broad physical, chemical and biological conditions typically present within a pit lake over the longer term can either promote or hinder remediation for any given element of concern.

Methods and Study Sites

The example datasets used in this paper have come from a range of studies for which methodology has been written up previously and for which further information can be provided from the authors if required. Most of these studies were conducted by the authors though have included many collaborators. The intent of this paper is not to present the findings of the example studies in any detail but to use the data to support the general concepts of mine pit lake water quality management.

In addition to references to literature, we have included data from the following studies:

- Biogeochemistry and remediation trials of the Equity Silver Mine (B.C., Canada) pit lakes (Whittle, 2004);
- Lake Buluan (Philippines) limnological study (Hydrobiology 2010);
- Malili Lakes (Lakes Matano, Towuti and Mahalona, Indonesia) limnological study (Hydrobiology 2011); and
- Lake Kutubu (Papua New Guinea) limnological study (Hydrobiology 2010).

The Equity Silver Mine (Whittle 2004) pit lake study involved a two year sampling program for two pit lakes. The Main Zone pit lake was 120 m deep and maintained in an oxic state throughout the water column year-round by engineered deposition of acid rock drainage (ARD) lime treatment plant sludge as a density current. The Waterline pit lake was 45 m deep and permanently anoxic below ~8 m depth, with no inputs other than groundwater, a small creek and incident rainfall. Both lakes were subject to winter freeze-over. The other five lakes studied (Lakes Buluan, Matano, Towuti, Mahalona and Kutubu; Table 1) were all natural with varying degrees of mining and other anthropogenic impacts. Results from "limnocorral" experiments in the Main Zone and Waterline pit lakes are referenced. These experiments involved the in-situ treatment of the water column with various combinations of nutrients and labile carbon (ethanol) to induce biological processes including eutrophication and bacterial sulfate reduction.

Additional limnological descriptions for the referenced natural lake systems can be found Osborne & Totome (1992; Lake Kutubu) and Crowe et al (2008; Lake Matano).

Table 1 *Physico-chemical description of example lake systems.*

Name	Location	Depth (m)	Area (km^2)	Description
Main Zone pit lake	B.C., Canada	120	0.25	Oxic year-round. ARD treatment sludge deposition. Fe, Cu, Ba and Zn elevated at surface.
Water Line pit lake	B.C., Canada	45	0.03	Anoxic below ~8 m. Elevated As, Cd, Co, Cu, Fe, Mn, Ni and Zn.
Lake Buluan	Philippines	6	56	Deil oxygen variation. Eutrophic.
Lake Kutubu	PNG	70	54	Anoxic below ~15 m. Near pristine.
Lake Matano	Indonesia	590	164	Anoxic below ~70 m. Elevated Cr and Ni.
Lake Towuti	Indonesia	200	560	Anoxic below ~40 m. Elevated Cr and Zn.
Lake Mahalona	Indonesia	70	23	Anoxic near bottom. Periodic overturn. Elevated Cr, Ni and Zn.

Results

While there are many approaches to the intensive treatment of mine waters with lime treatment plants, reverse osmosis and more recently bioreactors being the most common, it is assumed for the purposes of this paper that these methods are prohibitively costly for perpetual lake water quality management. Ideally interventions need to be either a once-off engineering project upon mine closure, periodic low cost ameliorations or a combination of both. There are essentially three mechanisms for in-situ removal of dissolved metals from mine pit lake waters (1) adsorption to solids and settling out (flocculation), (2) changing chemical conditions so that they form non-bioavailable solids (mineralisation/complexation) and (3) dilution. The redox conditions required for the first two of these mechanisms differ depending on the element of concern.

Figure 1 provides a simplified schematic of the "chain" of redox reactions common in natural waters ranging from well oxygenated to anoxic and sulfidic/methanic. Primarily biologically mediated, respiration of organic matter in lake waters can change the redox conditions within the lake depending on the mass of organic matter (OM) available and the various concentrations of oxidants such as dissolved oxygen, manganese/iron oxy-hydroxides, nitrate and others. In near-surface waters the primary oxidant will almost always be dissolved oxygen unless there is a very large pool of available OM. In many pit lakes a physical reduction in surface water mixing, due to factors such as the wind breaks provided by high pit walls, high surface area to depth ratios and/or physico-chemical stratification induced by inflows of varying density, can reduce the replenishment of dissolved oxygen. This can subsequently reduce the depth to anoxic waters. Pit lakes also commonly have mineralised surface/groundwater inputs containing substitute oxidants such as iron/manganese oxy-hydroxides and sulfate. The combination of these features can lead to anoxic bottom waters with high levels of metals and other toxicants.

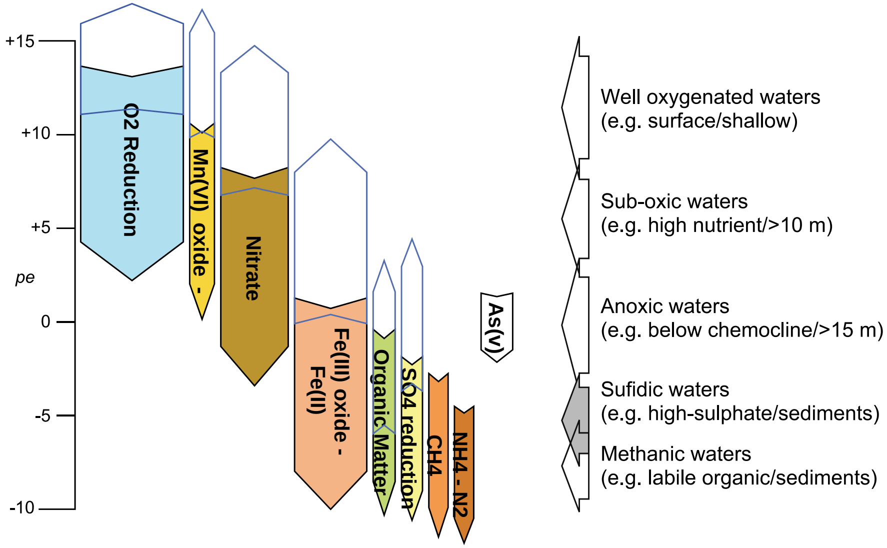
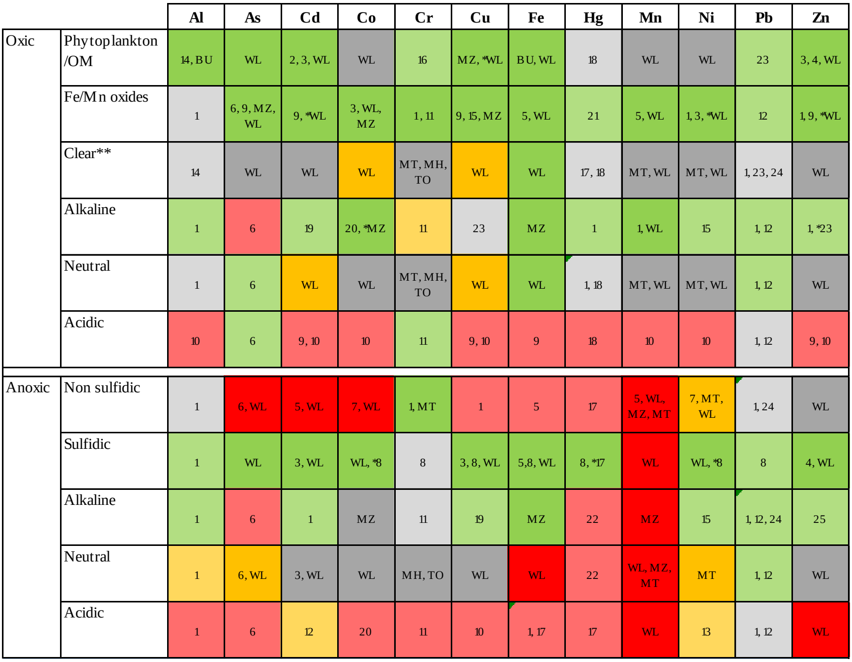


***Figure 1** Simplified reduction sequence for electron acceptors in typical lake systems (Note: chervon width proportional to energy (ΔG°) released from the reductive reaction (at pH 7). Blue outlines show approximate pe range where reverse reactions are favoured. Adapted from Libes 1992.*

Although each pit lake will have its own unique set of physical and biochemical conditions, there are general considerations for final void closure. Pit lakes that are likely to be shallow may have sediment re-suspension problems as well as difficulty in maintaining anoxic conditions at the sediment-water interface. Deep pit lakes may form semi-permanent anoxic bottom water with potential for partial/full mixing during strong wind or cold weather events. Depending on the toxicants of concern, there are certain redox “danger zones” with respect to managing and mitigating the presence of these toxicants in bioavailable (predominantly dissolved) form at problem concentrations.

Table 2 provides a generalised matrix of the potential toxicant source or mitigating conditions for a range of dissolved form metals in relation to ecological health values. These categorisations have been derived from both the example lake system studies by the authors and literature. It should be noted that the specific conditions at each lake can alter its response to a given acid-base or redox regime including various combinations (e.g. a lake with sulfidic sediments may have an acidic water column). Aspects such as water residence time, concentrations of major and minor ions, seasonal variations, kinetic limitations and biological processes can influence contaminant concentrations in the water column. In addition oxic processes can often occur in the surface layer of pit lakes and interact with anoxic bottom water/sediment processes to create complex cycling. The information in Table 2 should be treated as relevant to the specific sites studied and as a guide to patterns of metal mobilisation in lakes. Broad generalisations about toxicant responses are difficult due to the complex interactions mentioned above.

Table 2 *Matrix of potential for dissolved metal release or solid phase sequestration based on lake physico-chemical conditions.*



		Al	As	Cd	Co	Cr	Cu	Fe	Hg	Mn	Ni	Pb	Zn
Oxic	Phytoplankton /OM	14, BU	WL	2, 3, WL	WL	16	MZ, *WL	BU, WL	18	WL	WL	23	3, 4, WL
	Fe/Mn oxides	1	6, 9, MZ, WL	9, *WL	3, WL, MZ	1, 11	9, 15, MZ	5, WL	21	5, WL	1, 3, *WL	12	1, 9, *WL
	Clear**	14	WL	WL	WL	MT, MH, TO	WL	WL	17, 18	MT, WL	MT, WL	1, 23, 24	WL
	Alkaline	1	6	19	20, *MZ	11	23	MZ	1	1, WL	15	1, 12	1, *23
	Neutral	1	6	WL	WL	MT, MH, TO	WL	WL	1, 18	MT, WL	MT, WL	1, 12	WL
	Acidic	10	6	9, 10	10	11	9, 10	9	18	10	10	1, 12	9, 10
Anoxic	Non sulfidic	1	6, WL	5, WL	7, WL	1, MT	1	5	17	5, WL, MZ, MT	7, MT, WL	1, 24	WL
	Sulfidic	1	WL	3, WL	WL, *8	8	3, 8, WL	5,8, WL	8, *17	WL	WL, *8	8	4, WL
	Alkaline	1	6	1	MZ	11	19	MZ	22	MZ	15	1, 12, 24	25
	Neutral	1	6, WL	3, WL	WL	MH, TO	WL	WL	22	WL, MZ, MT	MT	1, 12	WL
	Acidic	1	6	12	20	11	10	1, 17	17	WL	13	1, 12	WL

🟥	Dissolved	🟨	Pot. Dissolved	⬛	Non-mitigating	🟩	Pot. Mitigating
🟥	Dissolved	🟨	Pot. Dissolved	⬜	Non-mitigating	🟩	Pot. Mitigating

* reference contradicts or shows little/no effect

Darker shades from author studies, lighter shades from literature.

MZ	Main Zone pit lake (MZ)	5	Szarek and Zurek (2006)	16	Kumar et al (2006)
WL	Water Line pit lake (WL)	6	Smedley and Kinniburgh (2002)	17	Shipp and Zierenberg (2008)
BU	Lake Buluan (BU)	7	Viollier et al (1995)	18	Luengen and Flegal (2009)
KU	Lake Kutubu (KU)	8	Morse and Luther (1999)	19	Libes (1992)
MT	Lake Matano (MT)	9	Romero et al (2007)	20	Nagpal (2003)
TO	Lake Towuti (TO)	10	Khorasanipour et al (2011)	21	Qu´emerais et al (1998)
MH	Lake Mahalona (MH)	11	Ajouyed et al (2010)	22	Jacobs et al (1995)
1	Langmiur, D (1997)	12	Dong et al (2010)	23	Nelson et al (1998)
2	Cassis et al (2011)	13	Xu et al (2007)	24	Turner (1987)
3	Balistrieri et al (1992)	14	Orians and Bruland (1985)	25	Webb (2001)
4	Hamilton-Taylor et al (1996)	15	Kanti et al (2002)		

An example of contrasting responses can be seen for dissolved copper in the MZ and WL pit lakes respectively where algal blooms induced by nutrient additions had a remediating effect in MZ waters though no effect in WL waters. This was postulated to be due to differing forms of ligands (complexing oraganic compounds) in each lake (Martin et al 2003). Additionaly, aluminium is often remediated under neutral pH conditions though low to moderate acid drainage inputs (common in pit lakes) can overcome the kinetic limitations to aluminium precipitation and cause lingering elevated dissolved aluminium concentrations to be an issue. This is less true where lime dosing is used to raise pH as localised alkaline conditions are often generated at the point of liming despite the overall lake being neutral to slightly acidic.

As a general rule lake waters which are anoxic/sub-oxic though which are not sulphate reducing (sulfidic) will tend to mobilise metals to the dissolved phase and contain elevated concentrations of these dissolved metals in the bottom waters. Management in this case may be targeted towards inducing oxygenation, sulfate reduction or increasing alkalinity. Similarly lakes with slight to moderate acidity (pH <6) will tend to increasingly mobilise metals with decreasing pH. Bacterial sulphate reduction has the effect of increasing alkalinity while sequestering a variety of metals into a solid sulfide mineral phase that tends to precipitate into the sediments and be relatively stable if sediment re-suspension can be avoided. Addition of nutrients to the surface waters can induce phytoplankton blooms which scavenge some dissolved metals from the water column, increase alkalinity and provide an OM sedimentation effect to drive sulfate reduction in the bottom waters/sediments.

Short term engineering such as oxidation covers on ARD producing materials, reactive barriers (e.g. crushed limestone channels), diversions of surface drainage to/from the pit lake, wind breaks and large scale water quality ameliorations (e.g. liming/sediment covers) can be used to set-up the initial conditions required for minimal or self-mitigation for perpetuity. The challenge is then balancing the in-lake amelioration processes with the competing inputs from the mining impacted catchment.

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