Appendix 2.6E
Pit Lake Treatment

TECHNICAL MEMORANDUM

To: Ryan Todd (New Gold) **Date:** February 24, 2013

Cc: Keith Ferguson

From: Alan Martin **Project #:** A302-3

Subject: Blackwater Gold Project – Considerations for Pit Lake Bioremediation

1. Introduction

Due to the oxidation of exposed sulfide minerals on pit walls and the flushing of soluble metals during pit filling, mine-site pit lakes can be characterized by poor water quality. Given the implications for environmental protection, regulatory compliance and potential long-term liability of pit lakes, considerable attention has been given to their management, characterization and remediation (Castro and Moore, 2000). In particular, the *in situ* bioremediation of pit lakes has been shown to provide a potentially cost-effective means for the treatment of mine-impacted waters (Martin *et al.*, 2006).

This memorandum discusses considerations for *in situ* bioremediation for the final pit lake that will be present at closure at New Gold's Blackwater Project. At closure, based on the PEA configuration, the pit lake will have a surface area of ~170 ha, a maximum depth of ~360 m, and a total volume of approximately 270×10^6 m^3. In addition to natural runoff from the pit walls and surrounding catchment, the pit may also be used to manage tailings pond water in the initial closure stages. Given the potential for elevated levels of parameters such as Cd and Zn in the pit lake, New Gold wishes to assess the potential merits and risks associated with passive bioremediation methods.

In the sections to follow, information is provided with respect to the following aspects of pit lake bioremediation:

- Principles of operation;
- Case studies;
- Application to Blackwater Project; and
- Cost.

2. Principles of Pit Lake Bioremediation

In the following sections, background principles are provided with respect to the various forms of pit lake bioremediation, the beneficial mechanisms, and the factors controlling lake primary production (*i.e.*, algal growth).

2.1 Forms of *In Situ* Pit Lake Bioremediation and Beneficial Mechanisms

The *in situ* bioremediation of mine site pit lakes typically involves the addition of nutrients and/or organic matter to create conditions conducive to contaminant removal. The addition of organic matter, in the form of liquid or solid amendments, provides a direct source of organic carbon to the water column. In contrast, the addition of nutreints (nitrogen and phosphorus) adds organic carbon indirectly to the system through the promotion of enhanced algal and bacterial growth. Organic ammendments may include sewage sludge, green wastes, molasses and other forms of organic matter (*e.g.*, ethanol and other alcohols, pyruvate, sugars, fats, proteins), while nutrient sources include liquid fertilizers, pellet-based fertilizers and phosphate rock.

For both direct and indirect forms of organic enrichment, the increase in organic matter content in the water column serves several functions critical to successful bioremediation. First, a key result of organic enrichment is an increase in particle concentration in the water column. Settling particles, especially organic aggregates, play a dominant role in the binding and transfer of heavy metals to lake sediments, thereby regulating the concentrations of dissolved species in surface waters (Sigg, 1985; Jackson and Bistricki, 1995). In this regard, metal attenuation can be viewed as a two stage process: 1) phase transfer from dissolved to particulate via algal assimilation and/or adsorption to cellular surfaces; and 2) particle settling, which may include the sinking of organic aggregates or zooplankton faecal pellets.

A secondary benefit associated with increased oxidation demand is the potential to enhance suboxia in lake bottom waters. For metal sulfide precipitation to occur, for example, suboxic conditions must be achieved to allow sulfate reduction and precipitation of secondary sulfide minerals (*e.g.*, ZnS, CdS). In this regard, the depletion of oxygen and onset to sulfate reduction in pit lakes can be accelerated through the addition of nutrients and/or organic amendments (Polling *et al.*, 2003; Paulson *et al.*, 2002). A secondary beneficial reaction associated with sulfate reduction is the generation of alkalinity (HCO_3^- at neutral pH), which can serve to neutralize acidity.

Suboxic conditions are more likely to develop in the bottom waters of stratified lakes due to the reduced influence of atmospheric interaction with pit bottom waters. Pit lakes differ from natural lakes in that they are often deep, steep sided, and sheltered from wind by pit walls. These features contribute to an increased tendency for seasonal and/or permanent stratification (meromixis). Preliminary lake modelling for the Blackwater Pit suggests that there is the potential for temperature and salinity stratification of the water column. Bioremediation can enhance pit lake stratification via the export of organic matter from the surface layer, and re-mineralization at depth, thereby adding a source of salinity to pit bottom waters.

2.2 Relationship Between Nutrient Addition and Algal Growth

The basis of *in situ* bioremediation through lake fertilization relates to the predictable response of freshwater systems to nutrient addition, and the corresponding changes to lake trophic status. The trophic status of a lake reflects the rate of *in situ* primary production (phytoplankton growth), and in a strict sense, can be expressed as grams of carbon generated per unit area per unit time (*e.g.*, gC/m^2/d). In practice, however, proxy parameters are measured to ascertain trophic status including chlorophyll *a* (proxy for algal biomass), nutrient loadings, lake nutrient concentrations and phytoplankton standing crop and composition. The term "oligotrophy" is used to describe lakes which are poorly productive, and are typically characterized by low nutrient inputs. Conversely, "eutrophy" is applied to lakes that are highly productive. General categories for oligotrophic, mesotrophic and eutrophic lakes have been established based on nitrogen, phosphorus and chlorophyll concentrations (Table 1).

Table 1:
Classification of Lakes into Trophic State Based on Summer Surface Averages (Yeasted and Morel, 1978).

	Oligotrophic	Mesotrophic	Eutrophic
Total Phosphorus (µg/L)	<10	10-20	>20
Total Nitrogen (µg/L)	<350	350-650	>650
Chlorophyll a (µg/L)	<4	4-10	>10

In general, the term "eutrophication" is used to describe a multi-faceted alteration to the physical, chemical and biological environment associated with excessive nutrient loadings to an aquatic system (Schindler, 1990). Specifically, eutrophic systems are typically characterized by:

- Increase in primary production (g/C/m^2);
- Increase in phytoplankton standing crop;
- Decrease in water transparency;
- Alteration to benthic and planktonic algal species composition;
- Decrease in species diversity;
- Shortening of food chains; and
- Increased water and sediment oxygen demand.

Eutrophication is a common phenomenon in freshwater and coastal environments proximal to human activities. Although eutrophication may occur naturally via alteration to natural water cycles (*e.g.*, climate change), the condition largely results from anthropogenic-induced nutrient loadings associated with sewage production, industry, deforestation, agriculture and livestock. For pit lake bioremediation, eutrophication is a desired state.

The factors governing the nature of primary production in lakes have been exhaustively examined via whole-lake manipulation experiments (*e.g.*, Schindler, 1978). Primary producers in freshwaters and in the world oceans require nitrogen (N), phosphorus (P) and carbon (C) for growth. In freshwater environments, P is typically the limiting nutrient, and therefore often governs the rate of *in situ* primary production. The dominant role of P in controlling phytoplankton standing crop is illustrated in Figure 1, which shows a near-linear relationship between summer average chlorophyll (proxy for algal biomass) and the P concentration measured at spring overturn in various Canadian lakes (Dillon and Rigler, 1974). This relationship between P loading and algal growth forms the basis, and predictability, for pit lake bioremediation via nutrient addition. Based on this relationship, numerous models have been formulated for freshwater systems in order to provide more accurate predictions of lake response to both increases and decreases in nutrient loadings (*e.g.*, Dillon and Rigler, 1975; Imboden, 1974; Vollenweider, 1969).

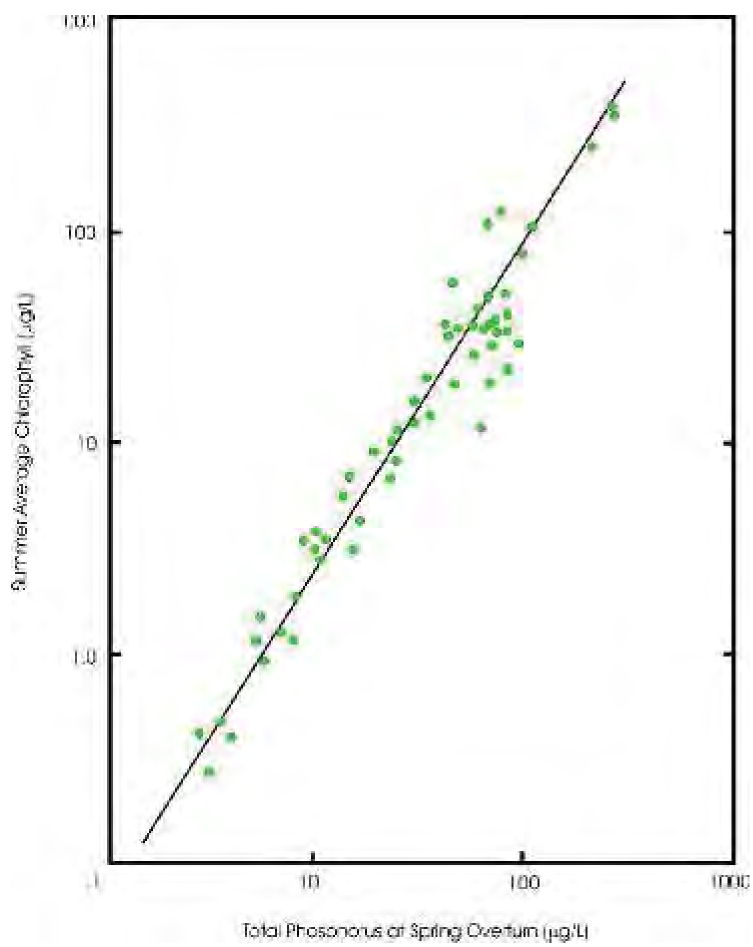

Figure 1: Relationship between summer average chlorophyll *a* and total P at spring overturn for various Canadian lakes

The nitrogen to phosphorus ratio in lakes often reflects lake trophic status. For example, the total N (TN) to total P (TP) ratio in lake surface waters is typically high in oligotrophic lakes and very low in eutrophic lakes. Natural, unperturbed watersheds typically export P-deficient drainages, resulting in relatively high TN:TP ratios in lakes and streams ranging from ~30 to 250. Conversely, the low TN:TP ratios of eutrophic lakes reflect the P-replete nature of sewage (TN:TP = 3 to 10), pasture-land runoff (TN:TP = 4 to 20) and urban runoff (TN:TP = 5 to 10) (Downing and McCauley, 1992). In general, at N to P supply ratios of <15:1, nitrogen limitation applies to most phytoplankton assemblages. Conversely, N to P supply ratios of >15:1 generally imply P-limitation (Downing and McCauley, 1992; Hendzel *et al.*, 1994; Levine and Schindler, 1999). Under N-limiting conditions, nitrogen-fixing cyanobacteria (*i.e.*, blue-green algae) can dominate the composition of primary producers (Hendzel *et al.*, 1994). Given the low P concentrations in background surface waters in the region of the Blackwater Project, and the likelihood of elevated N loadings associated with the leaching of residual blasting residues from pit walls and residual waste rock, P-limitation is predicted to apply to the end pit lake at closure. Therefore, the highly predictable relationship shown in Figure 1 will likely apply to the Blackwater pit lake.

2.3 Primary Productivity in Pit Lakes

As a general rule, pit lakes tend to be highly oligotrophic, exhibiting low rates of *in situ* algal productivity. This low productivity relates to the way nutrients are delivered to and re-cycled within pit lake environments. First, the catchment areas of pit lakes are typically very small in comparison to natural lakes, due to the fact that pit lakes are often situated in the headwaters of their catchments, and due to water management measures (*e.g.*, diversion of natural flows around the pit). Since terrestrial run-off presents the primary source of nutrients to lakes, the small catchment areas of such environments limit nutrient inputs and associated algal production.

The oligotrophic nature of pit lakes also reflects lake geometry. Pit lakes are typically steep-sided and deep. Accordingly, in contrast to most natural lakes, the surface areas of pit lakes are often small relative to their depth. The deep nature of pit lakes restricts nutrient recycling into surface waters, while the high volume to surface area ratio limits the potential influence of sediment-water exchanges. The recycling of nutrients into surface waters can be further hindered by stratification, which can strongly restrict nutrient recycling into the surface layer. The paucity or absence of littoral zones in pit lake settings also limits the importance of macrophyte and benthic algal production and associated nutrient regeneration in the near-shore environment. Collectively, these physical features contribute to the oligotrophic nature of pit lake environments. Given the relatively-small catchment of the Blackwater pit, the high ratio of depth to lake surface area, and the potential for stratified conditions, oligotrophic conditions are predicted for this system in the absence of phosphorus addition.

3. Case Studies

3.1 Grum Lake, Faro Mine, Yukon

In support of closure planning for the Faro Mine in Yukon Territory, Canada, Lorax conducted whole-lake fertilization of the Grum pit lake to lower Zn levels in surface waters. The growing season (summer months) at the northern latitude of the mine is short, and therefore a fertilizer blend was designed to induce hyper-eutrophic conditions in the lake in order to maximize phytoplankton growth. Grum Lake was a non-discharging lake, and therefore the export of nutrients and algae to downstream receiving environments was not a concern. The fertilizer used was a custom agricultural liquid fertilizer with a blend of urea ammonium nitrate and ammonium phosphate. Liquid fertilizers are advantageous as they are made immediately available to algae. Further, there is the potential for powdered or pelletized fertilizers to sink out of the photic zone before they are become dissolved and assimilated. This concern does not apply to liquid fertilizers. The fertilizer mixture produced an N:P ratio of 10.4:1 by weight or a molar ratio of approximately 23, thereby providing N in excess of the 16:1 N:P ratio at which phytoplankton typically acquire nutrients (*i.e.*, P limitation was maintained). Fertilizer was applied at a rate of 1170 mg N/m^2/wk and 110 mg P/m^2/wk.

Chlorophyll concentration was monitored throughout the water column as an indicator of phytoplankton biomass. Phytoplankton were present at depth at the start of fertilization, with relatively low biomass in the surface waters (Figure 2). This profile of phytoplankton biomass is typical of a lake in which nutrients have been depleted from the upper photic zone. Within 2-3 weeks of fertilization, a large increase in phytoplankton biomass was recorded in the upper 3 m of the water column (Figure 2). The highest concentration of phytoplankton was present at 3 m. At that depth, Zn levels progressively decreased throughout the summer (Figure 3). Initial dissolved Zn (~10 mg/L) decreased to 4 mg/L by week 5 of fertilizer additions, and to 1 mg/L on week 9. The lowering of Zn levels was accompanied by an increase in phytoplankton biomass. Total Zn levels in the upper 3 m also decreased as phytoplankton cells with their absorbed Zn loads sank out of the surface layer (Figure 3). At 5 m, where phytoplankton biomass was relatively low, and growth of phytoplankton was likely limited by low light levels, Zn levels remained at relatively unchanged throughout the summer (~10 mg/L). Overall, the stimulation of primary production effectively lowered Zn concentration to desired objectives in surface waters.

3.2 DJX Pit Lake, Cluff Lake Uranium Mine, Saskatchewan

A study of the effectiveness of phytoplankton growth as a mean of remediating pit lake water with elevated metal levels was conducted using mesocosms in the DJX pit at the Cluff Lake Uranium Mine in Saskatchewan, Canada (Dessouki *et al.*, 2005). Co, Mo, Ni, U and Zn were present in the lake at levels above their respective Saskatchewan surface water quality objectives. The lake hosted elevated nitrogen levels, and therefore only phosphorous addition was required to promote phytoplankton growth. The concentration of P added was varied between mesocosms, but phytoplankton growth was stimulated by all levels of P addition. Concentrations of As, Co, Cu, Mn, Ni, and Zn significantly decreased in the lake surface layer, where phytoplankton growth was highest. The rate of metal removal was highest in mesocosms with higher P loads added. Selenium and molybdenum did not significantly decrease, owing to their low affinity for biogenic particles. Data for sediment traps showed that the addition of P caused an increase in the mass of particles sinking out of the surface layer, and that the sinking particles contained elevated levels of the metals which were being removed from the dissolved fraction in surface waters. The study concluded that phytoremediation may be an effective and inexpensive method to improve pit lake water quality.

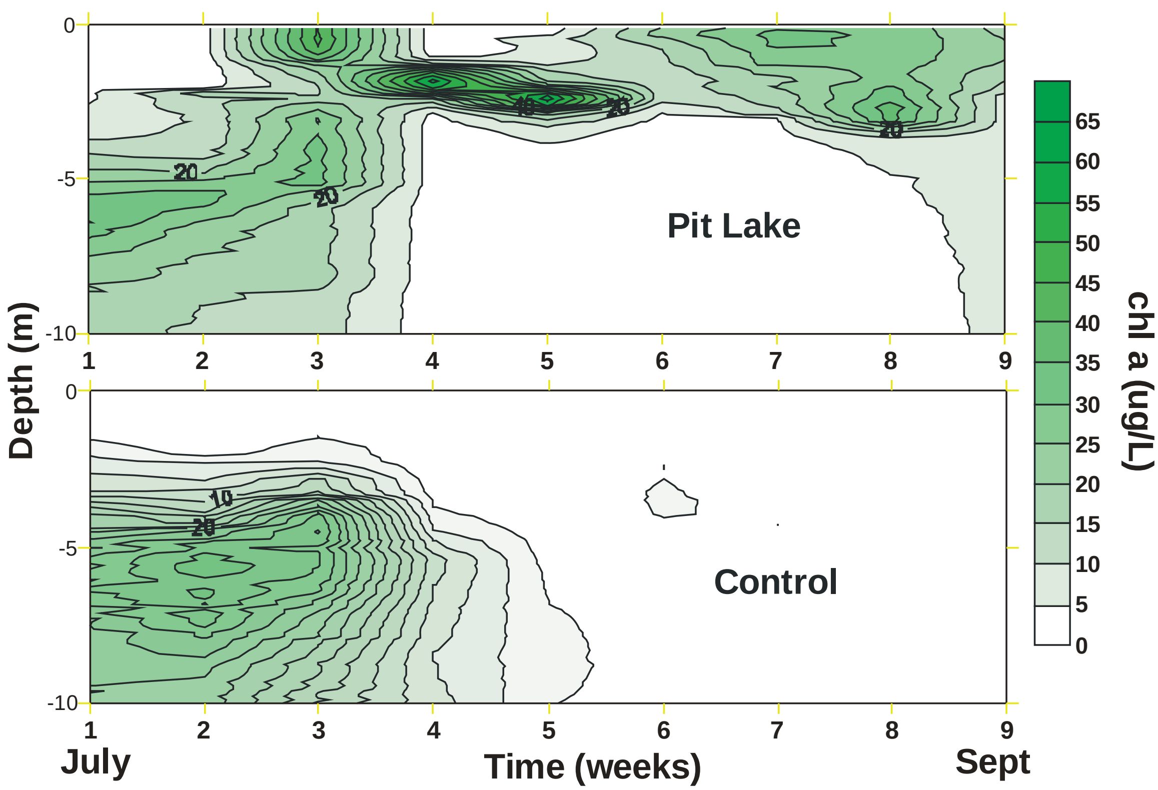

Figure 3. Depth-time distribution of chlorophyll a in the upper 10 m of the Grum Pit Lake water column (Faro Mine, Yukon), showing the response of lake fertilization on algal growth in comparison to a control.

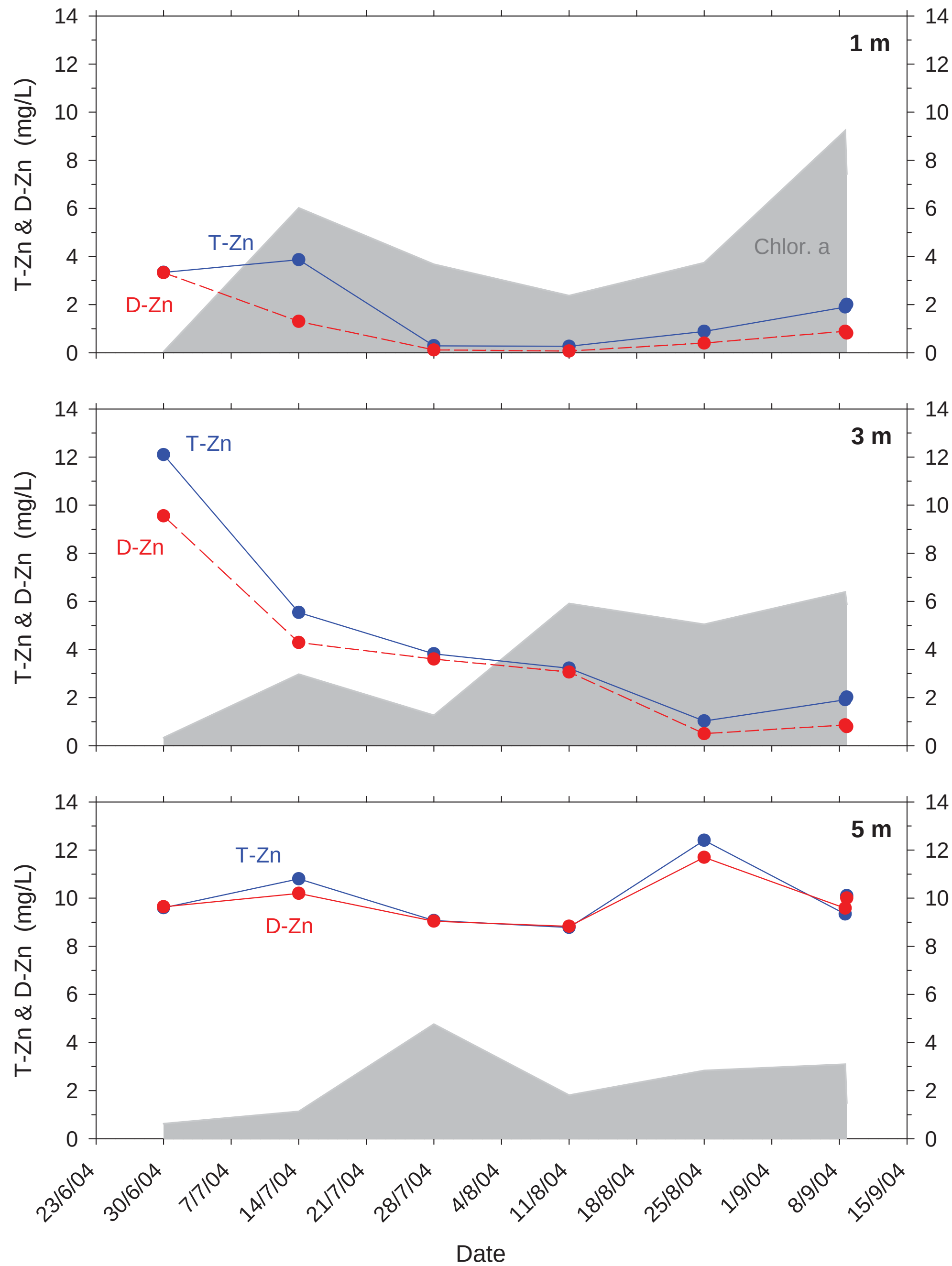

Figure 4. Time series profiles of total and dissolved zinc at water depths of 1 m, 3 m and 5 m in the Grum Pit Lake (Faro Mine, Yukon), showing the response of zinc concentrations in response to enhanced algal growth. Shaded grey areas show relative concentration of chlorophyll *a* (proxy for algal biomass).

4. Application of Bioremediation to Blackwater Pit

4.1 Response to Fertilization

As outlined above, given the low P concentrations in background surface waters in the region of the Blackwater Project, and the predicted elevated levels of nitrate-N in the pit resulting from the leaching of residual blasting residues, it can be expected that algal productivity in the lake will be limited by the availability of P. In the absence of algal toxicity, therefore, lake primary production should respond effectively, and predictably, to fertilization. There is the potential that algal productivity may be limited by elevated levels of mine-related parameters that invoke algal toxicity (e.g., Cd, Cu, Zn, ammonia). Toxicity test work with mine-site drainages (or suitable lab-based proxies) and local species assemblages can be conducted to assess the potential for algal toxicity.

4.2 Parameters of Concern

In terms of the primary parameters of concern, both Zn and Cd are amenable to bioremediation via lake fertilization, although treatment for Zn is more favourable. Both Cd and Zn show strong associations with organic matter in natural systems. In the world oceans, for example, dissolved Cd and phosphate show strong positive correlations with depth, demonstrating nutrient-like behaviour (Bruland, 1980) whereby Cd is sequestered by phytoplankton in the surface layer and released at depth commensurate with the breakdown of organic matter. Zn shows stronger associations with organic matter in comparison to Cd. In lacustrine systems, Zn shows a naturally high abundances in suspended sediments and organic aggregates (Nriagu *et al*., 1982). Further, dissolved Zn can show positive correlations with nutrients such as phosphate and silicate demonstrating nutrient-like behaviour (Bruland *et al.*, 1994; Reynolds and Hamilton-Taylor, 1992). Zinc also shows a strong affinity for Fe oxide phases, which can serve as sorption sites as coatings on algal cells in mine-impacted systems (Jackson and Bistricki, T., 1995). In comparison, Cd shows relatively much weaker interactions with Fe oxides. Overall, there is a much higher degree of confidence in the ability to treat Zn in comparison to Cd via in-pit bioremediation.

4.3 Duration and Frequency of Application

The duration of nutrient amendments will depend on several site-specific factors, including the response of native algal communities, the degree of metal removal, and the water quality targets for lake surface waters. At a minimum, however, it can be assumed that amendments would be applied on a weekly basis for a minimum of two months during the growing season (May through September). Due to the high rate of nutrient assimilation by phytoplankton, nutrients added in one year would not be available in the year following, and therefore bioremediation in this form should be viewed as an annual occurrence as long some form of treatment is required. Depending on pit lake chemical evolution at the Blackwater site, it is possible that such treatment may be required for only one or two seasons. For example, block modelling shows that only limited PAG exposures will be present above the water table of the flooded pit. This may imply that loadings from the pit walls will be significantly reduced following flooding, and that active bioremediation may only be required for a finite period.

4.4 Fertilization Dosage and Cost

The addition of organic matter, in the form of liquid or solid amendments, provides a direct source of organic carbon to the water column. In contrast, the addition of nutreints (nitrogen and phosphorus) adds organic carbon indirectly to the system through the promotion of enhanced algal and bacterial growth. The latter is far more cost effective, since the addition of 1 mole of phosphorus results in the generation of 106 moles of carbon through photosynthesis. Accordingly, the costs provided here are for the addition of nutrients (*i.e.*, fertilizer) only.

Fertilizer cost and transportation costs will be site specific. Based on experience from the Grum Pit Lake, the cost for liquid fertilizer for the Blackwater is estimated to range from $0.01/m^2/month to $0.02/m^2/month. A lake surface area of 1.7×10^6 m^2 (170 ha), and a two month application period, translate to an annual fertilizer cost of $34,000 to $68,000. Other costs include transportation and storage of fertilizer, a system to deliver fertilizer to the lake, and water quality monitoring. Costs for these components are not provided. The fertilizer delivery system may be as simple as pumping fertilizer from a tank into a surface flow or seep entering the pit lake.

5. Summary of Advantages and Risks

Overall, the main advantage of *in situ* pit lake treatment is the semi-passive feature and the ability to remediate large volumes of water at relatively low cost. The risks include:

- The potential generation of anoxic waters that may require secondary treatment (*e.g.*, aeration and settlement) prior to discharge to receiving water courses. This risk has most relevance to the discharge of lake bottom waters from a stratified pit scenario. Given that water management plans for the Blackwater site are to maintain a surface discharge from the pit, this risk is not considered to be relevant;
- Potential for downstream eutrophication: for pit lake systems that are required to discharge on a seasonal basis, there is the risk of promoting eutrophication in downstream systems associated with the export of nutrients and algae from the pit. Such risks can be managed with effective water management (*i.e.*, pit drawdown prior to fertilization). Water management plans for the Project entail the discharge of water from the pit to a TSF-wetland complex for final polishing prior to discharge. This will provide an effective means to reduce nutrient loadings to receiving systems;

- Degradation of aquatic habitat: if viable aquatic habitat features are a closure objective for the pit lake, there is the risk of limiting the value of habitat as a result of lake eutrophication. This has most relevance to fish habitat, and less relevance to water birds and wildlife; and
- Algal toxicity: as outlined previously there is the potential for water quality conditions (e.g., elevated Cd, Cu, NH_3) to limit the growth of algae in response to fertilizer addition. Such risks can be assessed through toxicity testwork using native algal species.

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