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December 1, 2011

Mr. Bruce Donald
Teck Metals
Bag 2000
Kimberley, BC V1A 3E1

Dear Mr. Donald:

RE: Assessment of Total and Dissolved Metals Concentrations in the Water Column of Garrow Lake

Garrow Lake is a meromictic lake, that is, it contains horizontal layers of water that are permanently isolated from one another and never mix. This vertical stratification is primarily due to the very large differences in salinity and temperature between the cold (~0^{o}C), slightly brackish (2 – 7 ppt salinity) mixolimnion (i.e., equivalent to the epilimnion) from surface to about 9 m depth and the warm (8^{o}C), anoxic, hyper saline (70 – 80 ppt) monimolimnion (i.e., equivalent to the hypolimnion) at depths greater than 12 m. Separating these two layers is the pycnocline, a 2-3 m thick layer of water where there is a very sharp increase in salinity and temperature. Density of the water also increases greatly over this depth range and it is this density barrier that maintains the isolation of the mixolimnion and the monimolimnion.

Total metals concentrations in the upper layer or the mixolimnion of Garrow Lake are relatively uniform in concentration, to just above the pycnocline at about 9 m depth. Between 9 and 11 m, within the depth range of the pycnocline total metals concentrations, including zinc, nearly double before diminishing to very low concentrations in the deep monimolimnion. Since cessation of tailings deposition to the monimolimnion, high concentrations of sulfides in the anoxic environment of the monimolimnion have scavenged metals from the water column, causing them to precipitate and settle out of solution to be sequestered on the lake bottom. In particular, iron and manganese and hydrogen sulfides act as reducing agents in the water column and are primarily responsible for reductions in metals. In surface waters, iron and manganese concentrations are 5 µ/L and 12 µg/L respectively, but increase to 160 µg/L and 120 µg/L within the pycnocline and up to 500 µg/L for iron in the monimolimnion, almost entirely in the dissolved phase. Zinc reduction by sulfides in the monimolimnion has effectively removed most of the zinc from the deeper water column. Over the last 10 years all metals concentrations have diminished considerably and continue to decline.

The elevated concentrations of metals at the pycnocline layer just above the transition zone to the monimolimnion, has been a bit of a curiosity. In our annual assessment of Garrow Lake chemistry, Azimuth (2005) had speculated that bacteria or another biogenic source may be responsible for this accumulation of metals above the density layer where there is a natural accumulation of particulates in meromictic lakes. An accumulation of a phototrophic bacterial biomass often occurs at the oxic-anoxic boundary of sulphide-containing meromictic lakes, provided that sufficient light is available (Pfennig, 1989; Garcia-Gil et al., 1999), which it is in Garrow Lake.

In 2009, Lorax reviewed of the Garrow Lake water quality report by Azimuth (2005) (December 3, 2009 Draft Technical Memo from A. Martin (LORAX) to H. Hartmaier (AMEC)) and questioned whether bacteria were responsible for this metals accumulation. To help answer the question, Lorax recommended that dissolved metals concentrations be measured at discrete depths, which was done in 2011. They argue that in order for the accumulation of zinc to be bacterial in nature it would likely be in the particulate phase as most bacteria would be retained on a 0.45 µm filter and removed from the water sample. Thus, dissolved zinc concentrations should be correspondingly low if the metals were in fact associated with bacteria.

To address this curiosity, we measured total and dissolved metals at several discrete depths above (3 m, 7 m), within (9 m, 10 m, 11 m) and below the pycnocline (15 m) in September 2011. We also measured chlorophyll α concentration (as a measure of phytoplankton abundance) and heterotrophic bacterial count (colony forming units, or CFU/mL) from the same sample depths. Results for total and dissolved zinc, chlorophyll α and bacterial counts are as follows:

Depth (m)	Total Zn (µg/L)	Diss Zn (µg/L)	% Dissolved	Chlorophyll α	Bacteria (CFU/mL)
3 m	**186**	**102**	**54**	**0.7**	**3**
7 m	**180**	**107**	**59**	**0.7**	**2**
9 m	**221**	**114**	**52**	**<0.5**	**1**
10 m	**376**	**221**	**58**	**<0.5**	**<1**
11m	**153**	**43**	**28**	**<0.5**	**<1**
15 m	**9**	**<2**	**<20**	**-**	**<1**

Average total and dissolved zinc concentrations nearly doubled between the mixolimnion and maximum concentrations within the pycnocline at 10 m, with no change in the proportion of zinc in the dissolved phase, averaging 55%. Chlorophyll α concentration was low and indicative of an oligotrophic system, with no peak above the pycnocline. Similarly, the number of bacterial colony forming units (CFU/mL) was also low in surface waters with no increase above the pycnocline, suggesting that relative abundance of bacterial colonies was no greater with increasing proximity to the pycnocline. However, given that holding times for bacterial survival were exceeded by the time water samples arrived at the laboratory, it cannot be said with certainty what the true influence of bacteria has on metals accumulation at the pycnocline.

Given that the relative percentage of dissolved zinc (and most other metals) did not diminish towards the pycnocline suggests that there are also non-biogenic drivers for the accumulation / expression of metals at 10 – 11, that is likely due to changes in redox conditions. Moving through the pycnocline there is a rapid, 10-fold increase in salt concentration, sulfides and a near complete loss of oxygen. This rapid change in redox conditions causes an accumulation/precipitation of fine colloidal and dissolved particles of metal salts in the highly saline pycnocline. A special feature often observed in lakes with anoxic hypolimnia and high concentrations of dissolved iron and/or manganese is the occurrence of a zone of elevated metals caused by continual oxidation of Fe^{+2} and Mn^{+2} brought up from the anoxic zone (e.g., Yagi 1986; Balistrieri et al. 1992). Moving through the pycnocline (below 11 m) into the monimolimnion, metals have been scavenged from the water column by sulfides and iron and manganese hydroxides. By 15 m depth zinc concentration is very low and dissolved concentration is non-detectable.

Summary

Zinc concentration has been the major focus of water quality monitoring in Garrow Lake as a major component of tailings materials. Tailings discharge to the monimolimnion of Garrow Lake prevented metals from diffusing upwards through the pycnocline and into the mixolimnion. The high density of the pycnocline presented a physical barrier, while the abundance of sulfides scavenged metals from the water column, acting as a chemical barrier. The historic spill of tailings into surface waters in 1984/85 has continued to influence zinc concentrations within the mixolimnion of Garrow Lake. Although surface water concentrations have diminished slowly over time, the pattern and relative magnitude of concentrations have not changed much and are still elevated above pre-mining times. Elevated zinc concentration at the pycnocline is partly due to a natural accumulation of particulate and dissolved material of biogenic origin that is typical of meromictic lakes, and from metals precipitated under the redox conditions associated with high salt, sulfides and iron and manganese and low oxygen in the transition zone towards the monimolimnion. This was also the conclusion of the Lorax review of the chemistry data.

Sincerely,
Azimuth Consulting Group Inc.

Randy Baker, M.Sc., R.P.Bio. Principal

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