Reclamation Performance: Reviewing the Effectiveness of an Adit Plug at the Tom Property, Yukon

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Abstract
The Tom lead-zinc-silver deposit located in eastern Yukon was explored and developed from the 1950s to the early 1990s. The site, including underground workings, was closed in 1994. The Tom Property is owned by Hudson Bay Mining and Smelting Co., Limited (HBMS), who is responsible for care and maintenance, and reclamation of the site. Over the past decade, HBMS developed and implemented a reclamation program to address site environmental issues, especially acid rock drainage and metal leaching. HBMS installed an adit plug as a long term passive treatment solution to improve the adit discharge quality by reducing the oxidation of sulphide minerals, resulting in decreased acidity, zinc and other metal concentrations. This type of passive treatment is required for a remote northern site that has seasonal access and no local power source. This paper presents early results demonstrating that the adit plug has been reasonably effective in stabilizing and improving discharge quality. Water quality predictions are compared with the post-adit flushing phase results. The results will be incorporated into long term reclamation and closure planning for the site.

Key Words: hydraulic plug, water quality prediction, acid rock drainage, passive remediation

Introduction
The Tom Property, owned by Hudson Bay Mining and Smelting Co., Limited (HBMS), is located in the remote Macmillan Pass area, near the Yukon-Northwest Territories border (Figure 1). The property was discovered in 1951. The estimated mineral resource for the Tom deposit is 4.98 million indicated tonnes of 6.6 % zinc, 4.4 % lead and 47.8 g/t silver, and 13.55 million inferred tonnes of 6.7% zinc, 3.1% lead and 31.8 g/t silver, NI 43–101 compliant (HudBay, 2009).

Between 1970 and 1982, 3,523 m of underground development was done via an adit located at 1,440 masl (Abermin Corporation, 1986). Approximately 52,000 m^3 of waste rock and ore from the underground development was stockpiled on the slopes adjacent to the adit. When the underground workings were extended, significant inflows of water eventually forced a shut down in 1982. Exploration activities ended at the Tom property in the early 1990's due to the economics of the project, and between 1992 and 1994 the adits were covered with granular fill and drainage pipes were installed to permit the water from the underground workings to drain out to surface. In 1994 HBMS received notification from the federal government that property had been reclaimed to satisfactory conditions.

In the spring of 1999, a routine inspection by government inspectors found that the adit backfill had been breached by water from the adit. It was hypothesized that the drainage pipes through the backfill in the adit had frozen and the hydraulic head that had developed behind the frozen face eventually overcame the resistance of the backfill and washed it out. The adit discharge had degraded since decommissioning and did not meet regulatory standards; it was acidic and contained elevated concentrations of metals.

In order to address the site's environmental issues, HBMS developed and implemented a surface and underground reclamation program between 2000 and 2010. As part of comprehensive reclamation measures, HBMS installed an adit plug as a long term passive treatment solution to improve the adit discharge quality by reducing the oxidation of sulphide minerals, resulting in decreased acidity, zinc and other metal concentrations. This type of passive treatment is required for a remote northern site that has seasonal access and no local power source. This paper presents early results of the adit plug's performance. Water quality predictions are compared with the post-adit results for the flushing phase. Implications for ongoing closure and reclamation planning are discussed.

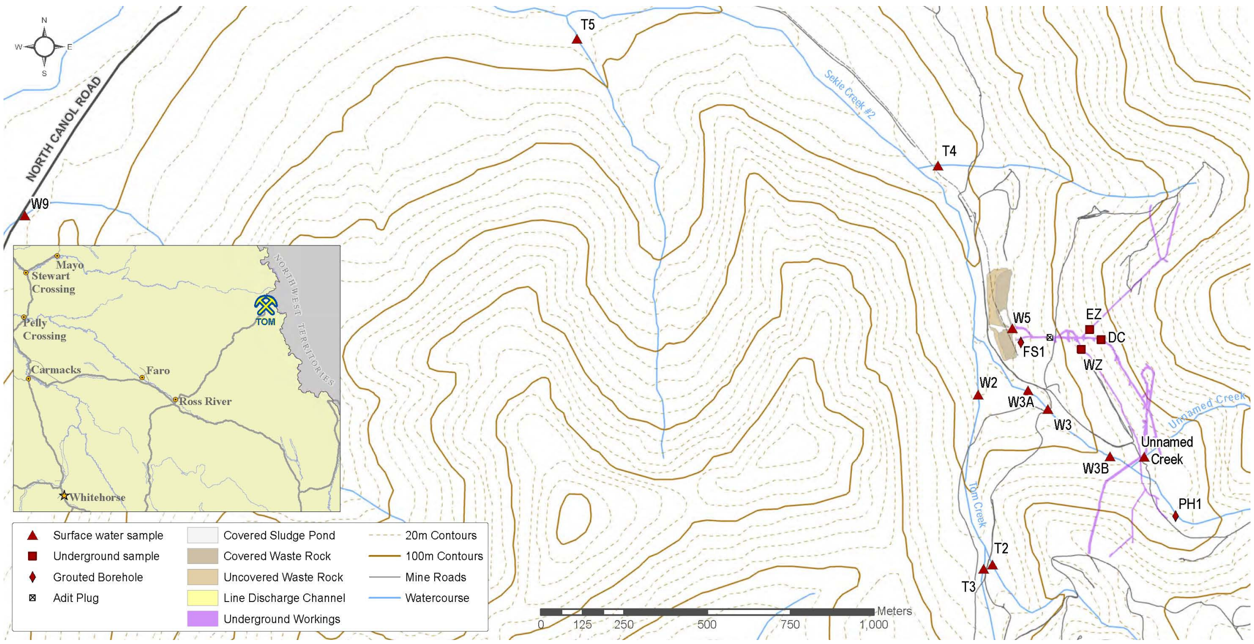

Figure 1 Water quality monitoring locations at the Tom Property

Site Conditions

The Tom deposit is a Sedex type lead-zinc-silver deposit that is hosted within the Lower Earn Group (Devonian). The Group contains the Itsi Member (sandstone, siltstone and Shale), Tom Sequence (shale and chert), and Macmillan Pass Member (chert pebble conglomerate) (Abbot, 1983). HBMS has conducted static geochemical testing on approximately 22 samples identifying that all the units are acid generating and metal leaching. The sedimentary rocks contain sulphide minerals including: pyrite, sphalerite and galena.

Naturally elevated metals in the area's surface waters have been well documented in studies completed during the past 20 years. HBMS has conducted over ten years of studies for the purposes of characterizing anthropogenic and natural metal loading observed in the Upper South Macmillan River watershed, including Sekie Creek #2 (Figure 1). Background water quality is influenced by natural acid rock drainage (ARD) and metal leaching with the loadings contributing the majority of zinc to the receiving environment, Sekie Creek #2 and the South Macmillan River. Investigations and studies show the Tom adit's contribution to metal loading at downstream locations with known fisheries presence is insignificant. In spite of this, discussions with various regulators and agencies suggested that the status quo of the adit discharge was not acceptable; therefore a reclamation plan was developed.

Tom Property Reclamation Plan

From 2000-2009, HBMS undertook baseline data collection, reclamation planning, and procured the necessary regulatory project approvals to implement the reclamation plan. Figures 1, 2 and 3 show the main reclamation program features. The reclamation plan was implemented in 2009 and completed in 2010 including:

- Installing the Tom adit plug;
- Constructing a bypass raise including shotcreting the downstream raise;
- Constructing a temporary sludge containment pond;
- Installing covers for the waste rock pile and the sludge pond;
- Installing a lined discharge channel; and
- Grouting two artesian boreholes.

Construction of the adit plug was completed in 18 weeks. The adit plug construction was completed on August 28, 2010. Between August 28 and September 13, 2010 (16 days), water flooded the underground workings (~18,000 m^3) with discharge resuming from the adit on September 13, 2010 when the water level reached 24 m above the adit floor. The hydrostatic pressure (water level) behind the plug is continuously monitored by a vibrating wire piezometer connected to a data logger (Figure 4). The adit discharge is now isolated from the waste rock dump and flows through a high density polyethylene (HDPE) lined channel.

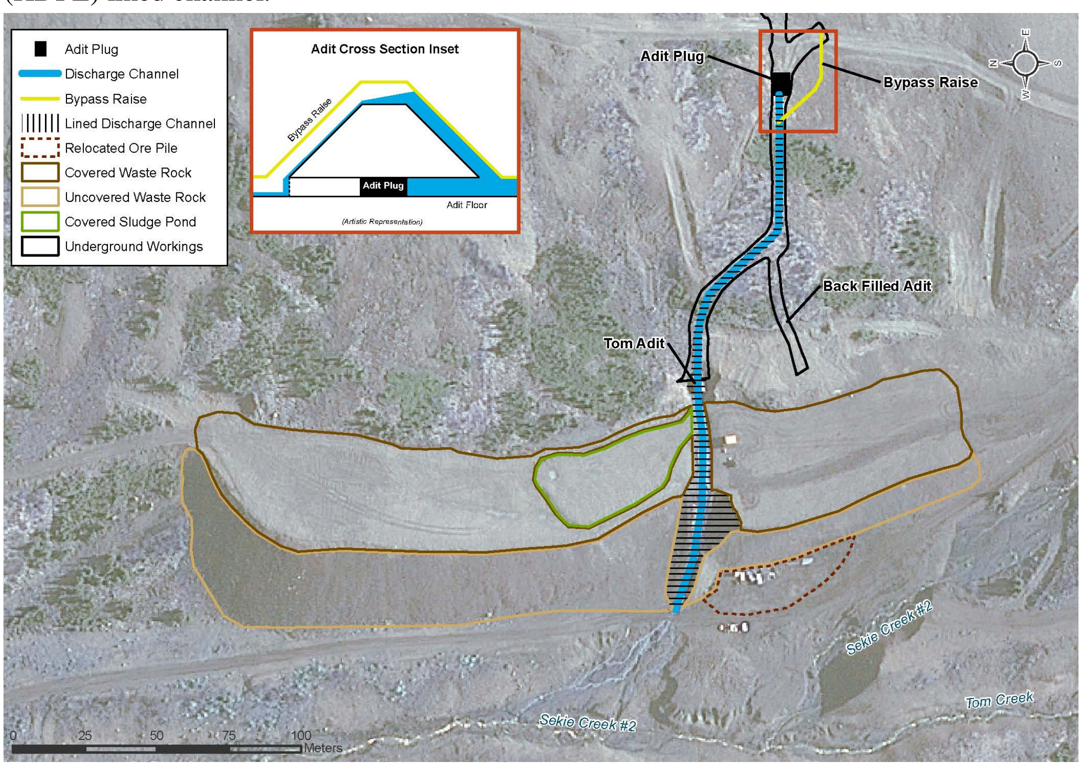

Figure 2 Tom Property reclamation plan features layout

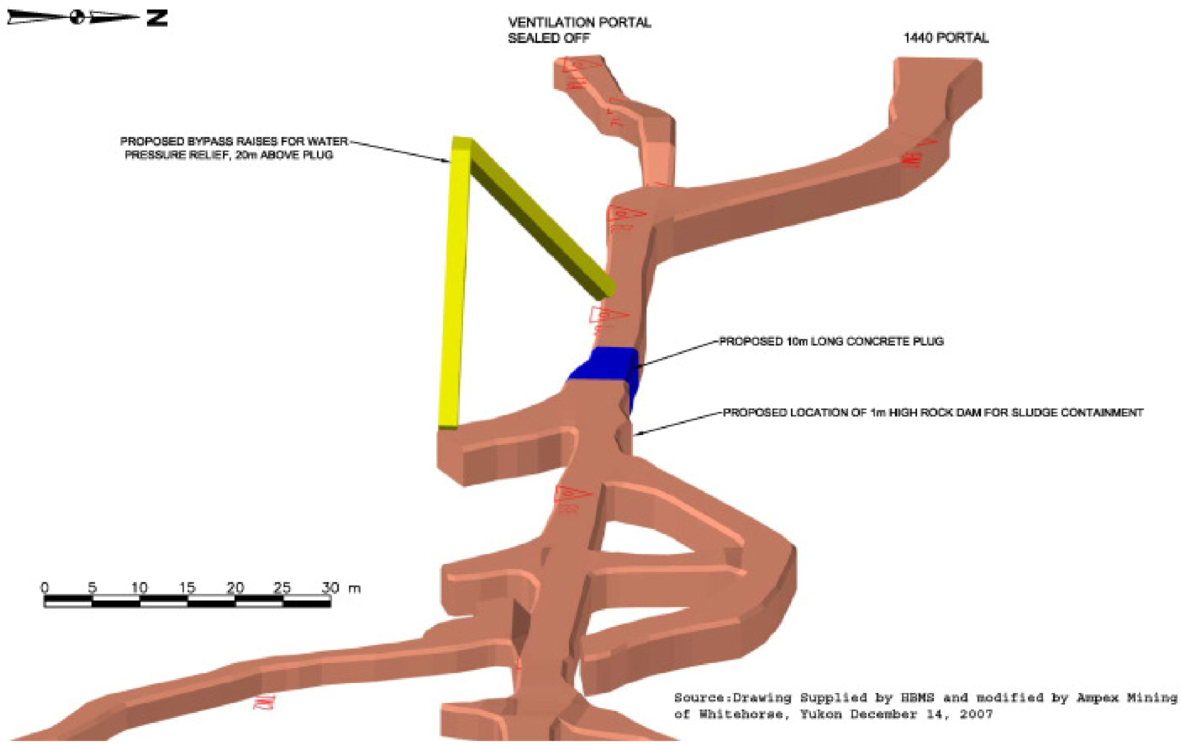

Figure 3 Tom underground workings oblique view of adit plug and bypass raise

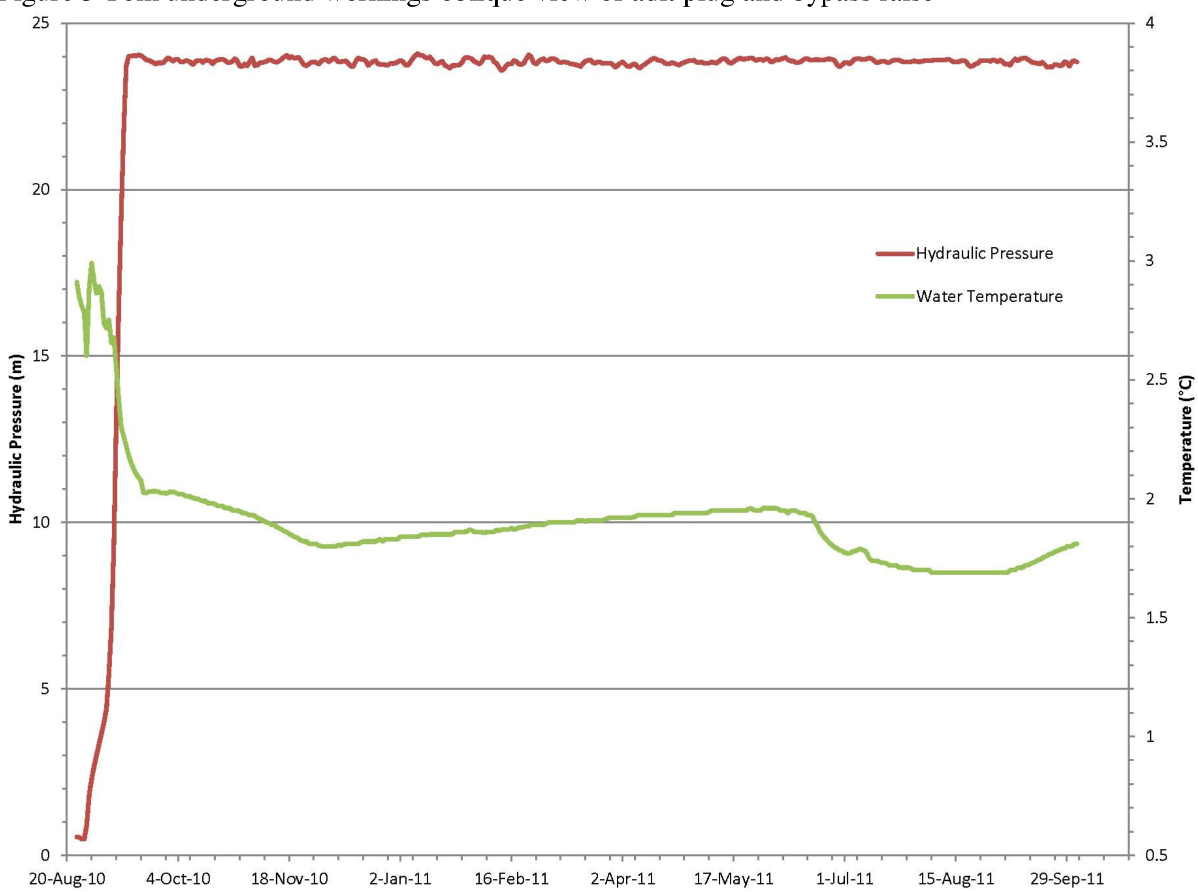

Figure 4 Hydrostatic pressure and water temperature behind the Tom adit plug

Post Adit Plug Water Quality Predictions

As part of the environmental assessment and regulatory applications, post adit plug water quality was predicted for three different post adit plug phases: flushing, short term and long term (Table 2). Due to a number of environmental variables the different phases were not initially defined with fixed time periods, but will be determined through monitoring of the adit discharge. The flushing phase was anticipated to last approximately one year, the short term phase was anticipated to last 1-5 years and the long term phase is expected to start thereafter. These three phases were developed to replicate the expected adit discharge transition from oxygen rich to oxygen depleted conditions and their associated metal concentrations. The water quality predictions for the three different phases were conducted using three different data sets (static geochemical testing, historical adit water quality, and background water quality).

The flushing phase was predicted using the maximum concentration from shake flask tests using adit wall rock and adit water sampled in July 2007. Table 1 summarizes the result of seven rocks samples collected in 2007 from the adit wall and submitted for static geochemical testing. These samples are characterized by total sulphur ranging from 1.08 to 4.63%, acid potential (AP) ranging from 25.3 to 112.8 t $CaCO_3$/1000 t and bulk neutralization potential (NP) ranging from -3.3 to 4.6 t $CaCO_3$/1000 t with neutralization potential ratios (NPR) of less than one indicating acid generating potential. Shake flask tests were conducted on the same seven rock samples using adit water rather than de-ionized water to predict the water quality during the flushing phase. Table 2 presents the maximum concentrations observed from the shake flask tests that were incorporated into the flushing phase water quality predictions.

Table 1 ABA testing results of Tom adit rock wall samples

Sample Name	Paste pH	Total Sulphur	Sulphide Sulphur	Sulphate Sulphur	Carbon Dioxide	AP	bulk-NP	NPR
	pH units	(Weight %)	(Weight %)	(Weight %)	(Weight %)	(t $CaCO_3$/ 1000t)	(t $CaCO_3$/ 1000t)	(NP/AP)
RS1	3.74	1.66	1.31	0.11	0.01	40.9	1.3	0.032
RS2	4.28	1.91	1.49	0.09	0.01	46.6	0.5	0.011
RS3	4.59	1.08	0.81	0.04	0.01	25.3	1.0	0.040
RS4	4.03	3.54	2.98	0.09	0.01	93.1	0.8	0.009
RS5	5.21	1.79	1.58	0.10	0.03	49.4	4.6	0.093
RS6	3.40	1.31	0.96	0.09	0.01	30.0	-0.8	-0.027
RS7	2.80	4.63	3.61	0.29	0.01	112.8	-3.3	-0.029

The short term adit water quality was predicted using the 75th percentile from the adit discharge pre-plug covering a 10 year data set consisting of 40 sampling events. The long term phase was predicted using the 95th percentile of the 11 background stations (W2, W3, W3A, W3B, W3C, W9, T2, T3, T4, T5 and Unnamed Creek) that are upstream of the Tom adit and workings or in adjacent unimpacted watersheds (Figure 1). The flooded decline samples (DC) provided an example of the potential water quality that can be achieved once the underground workings are flooded for a number of years (pH~6 and zinc~15 mg/L, Table 3).

Table 2 Summary of predicted Tom adit water quality post adit plug

Parameter	Unit	Flushing[a]	Short Term[b]	Long Term[c]
Physical Parameters				
Field pH	pH	3.1	3.4	3.8
Specific Conductance (field)	µS/cm	5124	1825	2130
Acidity	mg/L $CaCO_3$	2800	893	1413
Sulphate	mg/L	3200	1100	1300
Metals				
Total Aluminum	mg/L	117	64.6	149
Total Cadmium	mg/L	0.488	0.0818	1.70
Total Chromium	mg/L	0.135	0.0394	0.235
Total Copper	mg/L	2.12	0.0995	1.6
Total Iron	mg/L	858	218	209
Total Lead	mg/L	0.0663	0.117	0.047
Total Nickel	mg/L	2.78	1.56	2.7
Total Selenium	mg/L	0.023	0.0025	0.046
Total Silver	mg/L	0.00164	0.00013	0.0004
Total Thallium	mg/L	0.0333	0.0021	0.0036
Total Zinc	mg/L	31.4	25.9	23.8
Dissolved Arsenic	mg/L	0.429	0.0291	0.0389

a) Flushing phase concentrations were predicted from the maximum concentrations obtained from shake flask extractions using adit wall rock and adit discharge water from July 2007.
b) Short-Term Threshold concentration from upper 75th Percentile adit discharge concentration from April 4, 2000 to August 25, 2010
c) Long-Term Threshold concentration from the upper 95th percentile background concentrations from 2000 to 2011

Additionally, several underground investigations were undertaken to better understand the mass balance of the adit discharge from the east zone, west zone and flooded decline. Unfortunately, due to up to 1 m of iron hydroxide sludge the original water sources of the East and West zones were not observed due to the limited access. The flooded decline was flowing at approximately 3 L/s with the East zone and West zone both flowing at 4 L/s. The east (EZ) and west zone (WZ) were characterized by pH 3 water with elevated metals including zinc greater than 30 mg/L (Figure 1). Whereas, the decline water quality had a pH of 6.5 and zinc concentration of 15 mg/L. A summary of the decline water quality (DC) is presented in Table 3 and Figure 5.

Results

Results from the first year of post plug adit discharge monitoring for the project are presented and subsequently discussed. The initial post adit plug discharge water quality shows both improvements and degradation in comparison to the pre-plug period of April 4, 2000 to August 25, 2010. The minimum sample set for the reference period is 24 samples depending on the parameter. The Tom adit discharge water quality (W5) summary statistics from eleven sampling events from September 13, 2010 to October 3, 2011 are presented in Table 3.

Figure 5 shows box plots for six water quality parameters (field pH, sulphate, total iron, total lead, total zinc, and dissolved arsenic) monitored between 2000 to 2011 for background stations, the flooded decline prior to the construction of the adit plug and the adit plug pre and post adit plug construction. The background stations data is a compilation of 11 stations (W2, W3, W3A, W3B, W3C, W9, T2, T3, T4, T5 and Unnamed Creek) that are upstream of the Tom adit and workings in the Sekie Creek #2 watershed or located in the adjacent watershed.

Table 1 Summary statistics for Tom adit (W5), flooded decline (DC) and background stations

	Field pH pH unit	Specific Conductance µs/cm	Sulphate mg/L	Total Iron mg/L	Total Lead mg/L	Total Nickel mg/L	Total Zinc mg/L	Dissolved Arsenic mg/L
W5 – Tom Adit Discharge Pre-Plug, April 4, 2000 to August 25, 2010								
number of observations	24	26	37	40	40	40	40	39
Minimum	2.80	1215	155	80.0	0.085	0.698	10.5	0.0114
Median	3.33	1586	1000	190	0.108	1.37	24.3	0.0246
Maximum	3.90	2004	1530	269	0.128	2.31	30.1	0.0360
3rd Quartile	3.40	1825	1100	218	0.117	1.56	25.9	0.0291
95th Percentile	3.73	1920	1412	248	0.126	2.05	28.7	0.0331
W5 – Tom Adit Discharge Post-Plug, September 13, 2010 to October 3, 2011								
number of observations	11	11	11	11	11	11	11	11
Minimum	4.00	1325	730	109	0.0637	0.848	16.7	0.00090
Median	4.41	1622	1000	222	0.192	1.57	22.2	0.0674
Maximum	4.89	1782	1300	260	0.212	1.92	29.0	0.0908
3rd Quartile	4.48	1661	1185	241	0.206	1.72	25.3	0.0772
95th Percentile	4.85	1744	1250	258	0.211	1.82	28.6	0.0905
DC - Flooded Tom Decline Discharge Pre-Plug, July, 2008 to June, 2010								
number of observations	7	7	7	7	7	7	7	7
Minimum	6.15	1036	585	107	0.0003	0.535	12.6	0.0056
Median	6.25	1211	640	132	0.00045	0.63	14.5	0.0127
Maximum	6.57	1270	662	140	0.00079	0.71	17.7	0.0171
3rd Quartile	6.41	1230	645	137	0.00066	0.67	15.8	0.0144
95th Percentile	6.54	1259	658	139	0.00076	0.71	17.3	0.0167
Background Stations, 2000 to 2011								
Number of observations	131	136	161	165	163	165	165	165
Minimum	2.00	8	11	0.015	0.00005	0.0105	0.0104	0.00008
Median	3.03	961	404	47.8	0.0050	0.82	4.69	0.0025
Maximum	4.50	2791	2000	320	0.0805	5.20	47.4	0.0702
3rd Quartile	3.20	1468	835	99.4	0.0259	1.51	8.52	0.0101
95 Percentile	3.82	2130	1300	209	0.0474	2.66	23.8	0.0389

pH
The post-plug adit discharge pH has increased from the median pre-plug pH of 3.3 to a pH ranging from 4.0 to 4.9. The first post plug adit discharge pH of 4.9 is believed to be attributed to the alkalization of the adit water from the shotcreted downstream bypass raise. Visual observations of the bypass raise indicated that the majority of the shotcrete has been now covered by iron precipitation and the more alkaline pH currently observed is a by-product of the flooded underground workings and the reduction in oxidation of the acid generating adit wall rock (Woloshyn et al., 2011).

Copper
This first sample collected post adit plug on September 13th had an elevated total copper concentration of 1.86 mg/L in comparison to the dissolved copper concentration of 0.951 mg/L and total copper concentrations have subsequently significantly decreased ever since (0.0446 to 0.232 mg/L). The sample collected on September 13th was collected within the first 30 minutes of the adit resuming flow and contained elevated total suspended solids from the flushing of the underground wall rock. The copper concentrations post-adit plug observed have been within the predicted flushing phase threshold (2.12 mg/L). The post-plug copper concentrations have been slightly above the short-term threshold during the 2011 open water season.

Lead
The post plug lead concentrations have ranged from 0.064 to 0.227 mg/L for the 12 monitoring events post adit plug installation. The lead concentrations are above the predicted flushing phase threshold of 0.0663 mg/L for every event with the exception of the first event. The lead concentrations observed to date are all below the effluent quality standard of 0.4 mg/L for the Tom adit that are scheduled to come into effect on October 1, 2012. The lead concentrations was showing an increasing trend, but the last two samples show a potential decreasing trend after reaching the maximum concentration on July 12, 2011. Additional monitoring will confirm if this was seasonal variance, a change in trend or if the increasing trend may resume in spring of 2012.

Zinc
Total zinc concentrations post adit plug have ranged from 16.7 to 29.6 mg/L and have all been below the predicted flushing phase threshold of 31.4 mg/L. Two of the 12 samples collected to date were above the predicted short-term threshold (25.4 mg/L). Therefore, the total zinc concentrations post adit plug have been less than predicted and are within the zinc concentrations observed in 2009 and 2010 pre-adit plug installation. There was no observable trend in the zinc concentrations in 2011. All of the post-adit plug zinc concentrations are above the current effluent quality standard (12.6 mg/L) that is scheduled to come into effect on October 1, 2012. The current effluent quality standard for zinc was established using the 95th percentile zinc concentration from background stations from the 2000 to 2007 data set. The background station data set was updated and the revised 95th percentile zinc concentration is 23.8 mg/L for the 2000 to 2011 data set. The post-adit plug total zinc concentrations would have exceeded the proposed zinc standard 4 of 12 times rather than 100% of the time. Background station T5 is located on a tributary of Sekie Creek #2, has shown elevated natural concentrations in many metals including total zinc with a maximum concentration of 47.4 mg/L during the 2010–2011 fall-winter sampling period

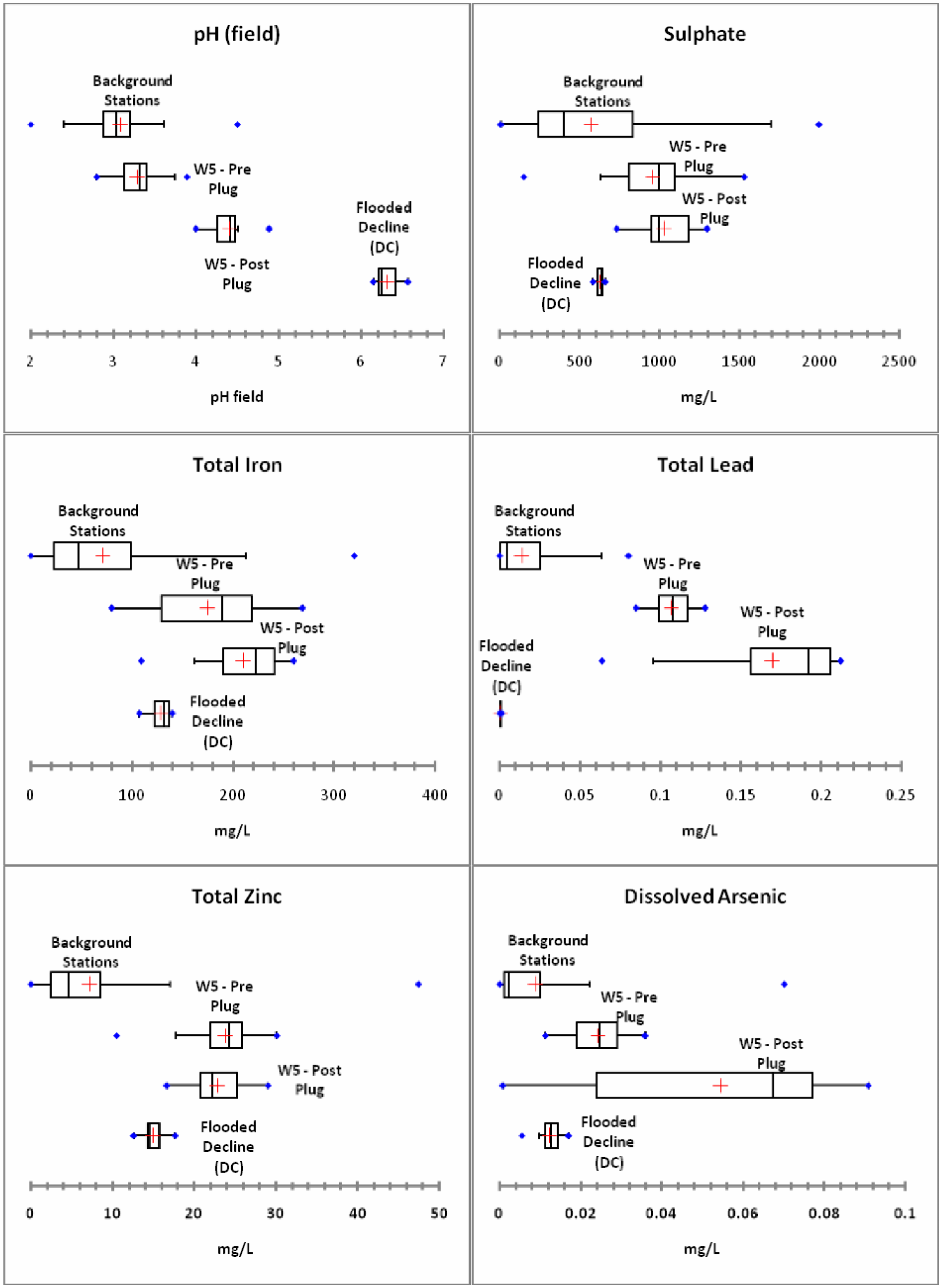

Figure 5 Comparative box plots of pre-plug and post-plug Tom adit discharge quality, background stations and flooded decline from 2000 to 2011

Arsenic
The dissolved arsenic concentrations (0.0009 to 0.0908 mg/L) observed during the post adit plug all monitoring events have been below the flushing threshold of 0.443 mg/L. The arsenic concentrations show a similar increasing trend to lead. The most recent dissolved arsenic concentration (0.0781 mg/L) is approximately double the pre-plug maximum concentration (0.036 mg/L). The dissolved arsenic concentrations are well below the dissolved arsenic effluent quality standard of 1.0 mg/L that is scheduled to come into effect on October 1, 2012. The dissolved arsenic concentrations will continue to be monitored closely to determine if the arsenic concentration has stabilized or will continue to increase.

Nickel
Total nickel concentrations (0.848 to 1.92 mg/L) for all post adit plug monitoring events have been below the flushing phase threshold of 2.78 mg/L. The most recent nickel concentration of 1.54 mg/L is slightly above the short term threshold of 1.45 mg/L. Nickel adit concentrations do not show a trend and are below pre-plug nickel concentrations observed in 2009 and 2010.

Iron and Sulphate
Total iron post adit plug concentrations have ranged from 109 to 260 mg/L and are well below the predicted flushing phase threshold of 858 mg/L. The post adit plug total iron concentrations are within the historic pre-plug adit discharge concentrations. Post adit plug sulphate concentrations have ranged from 730 to 1300 mg/L and have been below the predicted flushing threshold of 3200 mg/L. The latest sulphate concentration of 1178 mg/L is slightly above the pre-plug median adit sulphate concentration (1000 mg/L) from 2000 to 2010.

Oxidation Reduction Potential (ORP)
The pre-plug adit discharge ORP ranged from 374 to 401 mV and the post-plug adit discharge the ORP has ranged from 208to 320 mV. The ORP of the discharge from the flooded decline was measured at -26.6 mV in June 2010. The ORP of the adit discharge has reduced and is expected to continue to decrease as time progresses.

Flow Rates
The adit discharge pre-plug was characterized by a median flow of 9.9 L/s and the post-plug adit discharge median flow of 12.2 L/s.

Discussion
Due to the remoteness of the site and regulatory monitoring requirements, water quality sampling of the adit and background stations was not completed during the late fall and winter periods prior to the installation of the adit plug. It is not possible to confirm if the initial above mentioned trends in adit water quality are a result of the installation of the adit plug or seasonal trends not previously observed during the low flow period. As part of the preparation of the final closure plan for the site, a risk assessment will be completed following the monitoring in 2012 to determine if the adit plug and the other features implemented as part of the remediation plan have reduced the human and ecological risks at the site and in the upper South Macmillan River watershed.

The predicted discharge water quality from the Tom adit post adit plug installation using static geochemical tests and historical adit water quality was a reasonably effective approach in predicting post-plug adit water quality for the first year. The shake flask tests using adit water and adit wall rock used to determine flushing phase predicted water quality was an effective method to establish conservative water quality predictions for the Tom adit discharge with the exception of lead. All seven rock samples used for the shake flask were done using the pyrite rich Tom sequence shale and did not include samples of the pebble chert conglomerate or Tom ore. The predicted water quality thresholds could have been improved by collecting rock samples from all rock units that intersect the underground workings, including those that may have incorporated more galena than the Tom shale. Additionally, testing of the leachability of the iron hydroxide sludge with adit water could have assisted in the development of the post plug adit water quality predictions.

Due to the naturally elevated metal concentrations in Sekie Creek #2 and the South Macmillan River as a result of local natural acid rock drainage and metal leaching the most applicable long term site specific water quality objectives for the Tom adit discharge would be developed using the background method. As part of the final closure plan, the site specific water quality objectives for the Tom adit discharge will be updated using the background method and the 2000 to 2011 background stations data.

The adit discharge was anticipated to have decreased following the installation of the adit plug. The observed increase in flow from the Tom adit discharge could be attributed to a number of factors including the lined discharge channel that collects all of the water that cascades over the bypass raise, whereas the pre-plug discharge measurements may have been subjective to seepage to the adit floor and waste rock pile.

Elevated concentrations of total lead and dissolved arsenic are observed in the post plug adit water quality when compared to the pre-plug median concentrations. The attributed increase in concentrations of arsenic may be a result of the flooded adit water with a reduced oxidation state increasing the solubility of arsenic and the leachability from the iron hydroxide sludge. Further monitoring of the adit discharge is required to identify if the arsenic and lead concentrations will remain at the present elevated concentrations or if they will return to pre-plug concentrations.

Total zinc post-plug adit discharge concentrations remain similar to the pre-plug zinc concentrations observed in 2009 and 2010. If the change in oxidation reduction potential in the adit discharge from ~400 mV to ~250 mV continues to reduce the long term adit discharge may improve to the water quality (zinc ~15 mg/L) concentrations measured in the flooded decline (-27 mV), as shown in Table 3 and Figure 5.

Continued monitoring of the Tom adit discharge is required to determine if the trends observed in the first year of post-plug adit water quality continue or change. Monthly environmental monitoring between June and September, and annual geotechnical inspections at the Tom property will continue to be completed to assess the performance of the Tom adit plug's as a long term passive treatment solution to improve the Tom adit discharge water quality by reducing the oxidation of sulphide minerals resulting in decreased acidity, zinc and other metal concentrations at a remote northern location that has seasonal access and no local power source.

Conclusion

The first year of Tom adit discharge observed during the flushing phase has been within the predicted water quality with the exception of total lead. Future water quality predictions for flushing phases from an adit plug built as a passive treatment system should incorporate static geochemical testing including shake flask tests using all adit wall rock units intercepted by the underground workings with adit water. Additionally, if sludge is present in the underground workings it should be tested for leachability or be removed from the underground workings if possible.

Additional monitoring will be completed in 2012 to further assess the water quality trends identified from the first year of post adit plug monitoring continues or changes. A risk assessment will be completed following the monitoring in 2012 to determine if the adit plug and the other features implemented as part of the remediation plan have reduced the human and ecological risks at the site and in the upper South Macmillan River watershed. The results of the 2012 monitoring events and risk assessment will be used to develop the final closure plan for the Tom property that is scheduled to be submitted in 2013. The current regulatory discharge standards currently developed in 2007 will be updated using all of the background stations water quality data collected to date to reflect the naturally elevated background conditions documented in the late-fall winter period. If the adit plug does not improve to the new water quality standards to be proposed or the risk assessment identifies the need, the construction of a secondary passive treatment system may be required to meet the final closure plan objectives for the Tom Property.

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