Mass-Balance Modelling as a Planning Tool for Water Quality Management at Mine Closure, Premier Gold Project (PGP), Boliden Limited

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Abstract
Boliden Limited's Premier Gold Project (PGP) has been under active decommissioning since 2002. Metal loadings of specific elements are sourced from a variety of historical mining operations, which have been ongoing on the site since 1918. The mining area is situated in a complex watershed characterized by steep terrain, flows impacted by melt water from glaciers and seasonally varying water quality. Historically, watercourses downstream of the mining area have not always met B.C. and Canadian water quality guidelines. Goldsim software was used to build a mass-balance water quality model capable of quantitatively assessing the impacts that various closure activities will have on concentrations of parameters of concern in receiving waters after closure. Modelling activities focus on calibrating flow and loading parameters to current conditions. The model was effective in delineating sources of metal loading and identifying areas where targeted mitigation work will have the highest impacts. Future work includes updating the model functionality to predict changes in water quality over time, under changing climatic conditions, in order to define water quality objectives, and analyzing closure scenarios to develop a cost-effective plan that enables PGP to meet these objectives.

Key Words: water quality model, loadings, mining

Introduction
Premier Gold Project (PGP), wholly owned by Boliden Limited (Boliden) from Sweden, is an underground and open pit gold mine that is currently closed and under active decommissioning. The site is located approximately 12 km north of Stewart, BC (25 km by road), and approximately 2.4 km northeast of the BC/Alaska border. The mine consists of two properties, Big Missouri to the north and Premier to the East. The site has been mined intermittently by a variety of owners since 1918. The mine has been owned by Boliden since 1998 and has been under care, maintenance and reclamation since 2001.

Both mine areas consist of underground workings, open pits and waste rock areas. The Premier mine area also includes a tailings storage facility (TSF) and a mine water treatment plant (MWTP). Seepage into the underground workings in the Premier mine area discharges through the underground mine portal and is currently being treated using a lime-dosing system. The treatment plant effluent passes through two settling ponds to remove suspended solids prior to being discharged into Cascade Creek. Historical mining of the Premier underground disposed of their tailings in two creeks downstream of the Premier pit and waste rock dumps (WRDs) with remnant tailings remaining along these creeks within the project area. Runoff from both mined areas drain into Cascade Creek. Significant mine infrastructure, as well as the creeks that make up the primary flow network, are shown in Figure 1.

With the intention of advancing the PGP to full closure status, Boliden commissioned Klohn Crippen Berger Ltd. (KCB) to develop a water quality model (WQM). The objective of the WQM is to estimate the water quality of PGP runoff and effluent from the pits, waste dumps, TSF, underground workings and historical waste and infrastructure, starting from present conditions, and assess the impact of various closure options.

Site characterization

The PGP site is located in coastal British Columbia, and is characterized by mountainous terrain and high rainfall. The watershed encompasses approximately 80 km^2 of steep terrain, with elevations ranging from 300 metres above sea level (masl) to over 1,100 masl. Mean annual precipitation varies spatially over the site from approximately 1,750 mm/year to 3,400 mm/year, and is influenced by orographic effects. Flow regimes are generally dominated by spring melts during April and May and heavy rainfall in the fall. In the winter the majority of precipitation falls as snow, resulting in relatively low flows, and the summers are typically relatively dry. This climatic seasonal variability results in seasonal fluctuations in water quality.

PGP staff have established several stations on-site where stream flow is recorded, either automatically or by manual measurements. Figure 2 shows seasonal variability of flows at station S-7, in Cascade Creek upstream of the TSF.

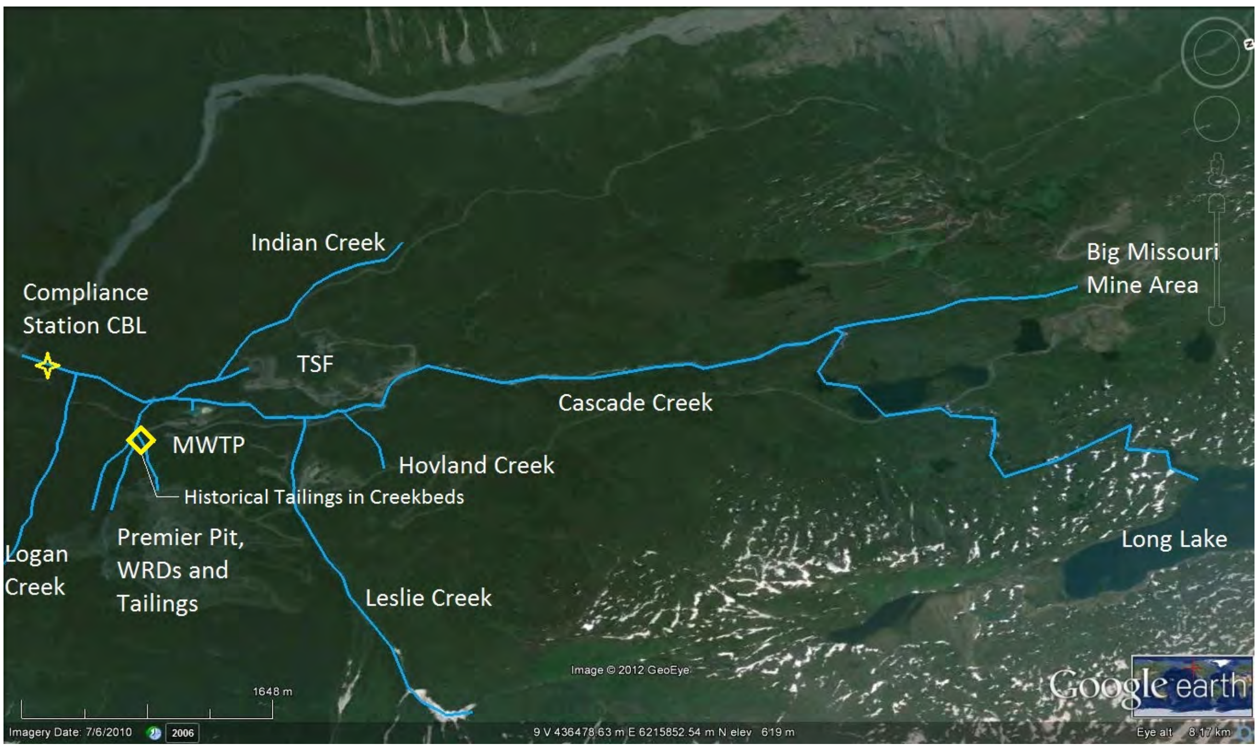

Figure 1. General arrangement of mine infrastructure and watercourses.

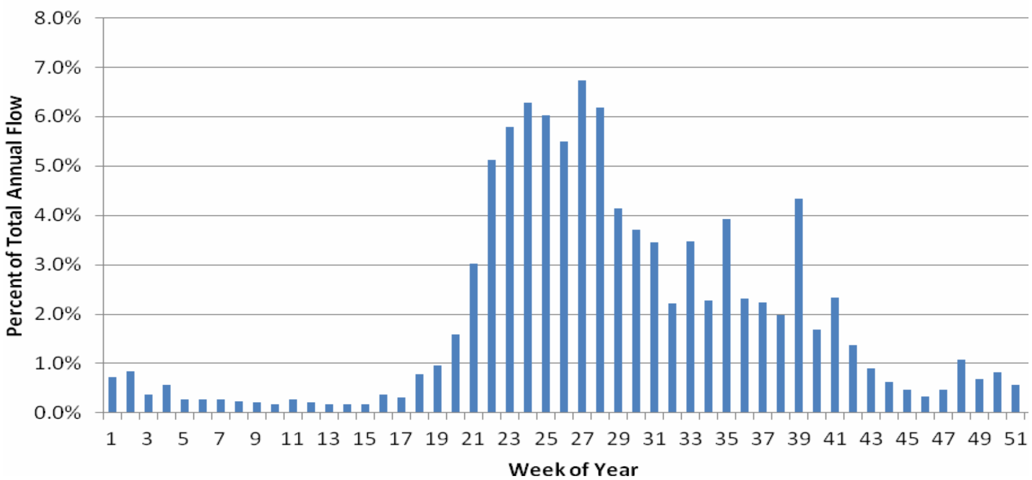

Figure 2. Distribution of average weekly flow in Cascade Creek above TSF over the period of record (2001-2010).

Material & Method

The WQM was developed using Goldsim, an object-oriented software package designed to conduct mathematical operations in time steps. Goldsim was selected for this analysis as it holds several advantages over traditional spreadsheet software, such as ease of use, particularly with respect to use of timesteps, and unit integrity. As with any software model, analysis and interpretation of site data for input into the model is of paramount importance. In addition, a model is, by nature, a simplified interpretation of reality and in order to produce reliable results it must be checked against existing conditions and calibrated appropriately. For this reason, attention is given to analysis of flow and water quality data recorded on-site, as well as calibration of model results.

The methodology used in development of a WQM for this study was:

- Site characterization:
    - Identify major watercourses and hydraulic networks;
    - Quantify average annual and seasonal variations of flows within hydraulic networks;
    - Review water quality data and identify POCs;
    - Differentiate between impacted and non-impacted watercourses; and
    - Identify metal loading sources and quantify loading rates.
- Develop and calibrate a mass-balance model:
    - Develop a site-wide water balance that replicates current hydrological conditions;
    - Develop a mass balance metal loading model using existing flow and water quality data to simulate current loading conditions;
    - Develop loading rates for source terms from kinetic tests and apply loading rates; and
    - Compare modelled flow and water quality at relevant points to measured baseline data.
- Sensitivity analysis and closure scenarios:
    - Examine the sensitivity of downstream water quality to variations in flow conditions caused by hydrological conditions or development of a proposed upstream hydroelectric project.

- Examine the impact of various closure strategies. Specifically, routing an upstream creek (Indian) into TSF, changing flows and qualities of water streams within the system.

The model is run on a weekly time step in order to provide sufficient data points to delineate short term seasonal peaks, such as spring freshet.

Assumptions and limitations

A mass balance approach has been used for this modelling exercise. This approach was selected to account for limited and/or unreliable geochemical source term data available for the site, including:

- Lack of representative information for loadings under acidic pH conditions;
- High detection limits for many of the water quality samples;
- Limited suite of parameters tested in humidity cell leachate;
- Limited background water quality sampling data; and
- Relatively short duration of humidity cell testing under circum-neutral pH conditions.

These factors significantly limit the ability of the method to predict long-term geochemical trends or changes. However, a mass-balance approach can be used to assess relative contributions of contaminants from different sources to downstream water quality under current, neutral-pH conditions or compare the relative impacts of different closure activities or circumstances. Additionally, the WQM allows for the input of acidic pH source term data representing the potential onset of ARD.

Water quality

An EQWin database was provided by PGP containing 86 on-site water quality stations with both total and dissolved concentrations.

Parameters of concern (POCs)

Water quality data recovered from sixteen selected stations at the PGP site between 1988 and 2010 was reviewed to identify target parameters of concern (POC's) for further assessment using the WQM. For this assessment, POC's are species which have an average concentration greater than the minimum of the corresponding guideline value. Where applicable, guideline limits were corrected for hardness and considered the pH and salinity of the stream and receiving environment. The process for selecting the most appropriate guideline for each parameter and site was judicious, with the most conservative value selected in most cases. For each POC, the number of samples, average concentration and maximum/minimum concentrations for the historical data set were examined. Representative weekly concentrations for POC's were defined and input into the model. Initially, total concentrations were considered in correspondence with the mine's site-specific effluent permit. Subsequently, however, the analysis was expanded to include dissolved concentrations, which are considered as more bio-available and therefore more important for impact assessment. The WQM does not specifically consider partitioning of metals into dissolved and non-dissolved fractions; this is accounted for by using input data which corresponds to the fraction of interest. In general, it was found that the dissolved concentrations were equivalent to the total concentrations in all of the samples evaluated, except at the MWTP. Therefore, as a conservative measure, the values of the total concentrations were maintained as inputs for the WQM, with the exception of the MWTP discharge.

The POCs are D-Cd, D-Cu, D-Zn, D-Pb and SO4. In addition, cyanide has been identified in PGPs permit as a key discharge parameter for the TSF, and at the request of Boliden, was also included. Note that due to the limited speciation data for cyanide in the TSF, a conservative measure was taken and the total fraction was considered as a mass balance parameter. All references to Cd, Cu, Zn and Pb in this paper therefore refer to the dissolved fractions, while any reference to CN refers to the total fraction.

Selection of data
For simplicity, and to account for a lack of water quality sampling data, a single set of water quality inputs are used to represent water from sub-catchments that are considered to be not impacted by mining activity (background stations).

As modelling was required to use weekly time-steps in order to represent key short-duration seasonal events such as pre-freshet flushing, and a very limited quantity of water quality data has been collected at these non-critical water quality monitoring stations, empirical relationships were developed to relate POC loading to flow measurements.

The other advantage of this method is that it enables the model to represent seasonal variations in water quality as well as to be able to predict changes to water quality during high and low-flow periods.

As well, because of the limited number of water quality samples available for these stations, a single set of water quality data was used incorporating data from all the stations listed in Table 1. A comparison of data at non-impacted stations indicates that these stations generally exhibit similar magnitudes and seasonal variations in water quality.

Relationships were calculated for each POC by plotting concentrations vs. flow measurements taken simultaneously, and using the best-fit relationship. It was determined that for each POC, a best-fit relationship existed for the pre-flush period prior to spring freshet that was distinct from the best-fit relationship that was sufficient to represent water quality for the remainder of the year. Therefore for each POC, a separate POC loading vs. flow relationship was used for this period than was used for the remainder of the year.

A selection of water quality monitoring stations in Cascade Creek and tributaries that are not appreciably impacted by mining activity are shown in Table 1.

Table 1. Background water quality sampling stations.

STATION	**NO**	**PERIOD OF RECORD**	**DATA USED**	**NUMBER OF VALID DATAPOINTS (WEEK 13-19/TOTAL)**
LESLIE AT GRANDUC	S-5	1998-2010	Data before 2005 omitted	0/5
INDIAN	S-17	1998-2010	Data from 2002 to 2006 used only	0/5
HOVALAND AT GRANDUC	S-6	1998-2010	All data used	2/11
LOGAN AT GRANDUC	S-26	1998-2010	Data before 2002 omitted	0/9
CASCADE ABOVE TAILS	S-7	1997-2010	All data used	15/64
Total				**17/94**

Impacted stations were represented by applying background water quality over undisturbed catchments, and adding loading rates from mine components. Loading rates were determined from existing kinetic geochemical data for the PGP site, from:

- Waste rock humidity cell data (NDM 1998);
- Tailings humidity cell data (BCRI 1995); and
- Historical tailings humidity cell data (URS 2006).

Loading rates were calibrated to recorded downstream water quality using appropriate scaling factors and in-stream solubility limits. These impacted stations are listed in Table 3.

Table 3. Impacted PGP water quality sampling stations (KCB 2011a).

STATION NO	STATION NAME	LOADING SOURCES	DATES SAMPLED	TOTAL NO. OF WQ SAMPLES
S-2	Fletcher above Cascade	-Historical 4-Level Tailings in Creek -Premier North and South WRDs	1999-2010	45
S-19	Combined Discharge	-TSF Supernatant and Seepage: Sludge deposited in TSF, exposed and submerged tailings	1995-2010	459
S-7	Cascade Above Tailings	-Big Missouri mine area: Dago, S1 and Province Pits and WRDs	1997-2010	159
S-13b	6-Level Before Treatment	-Premier underground workings -Infiltration from Premier Pit	1999-2010	75
S-13a	6-Level After Treatment	-Treated water from S-13b	1997-2010	215

Result & Discussion

A base case mass-balance water quality model was developed consisting of weekly water quality and flows. The methodology used in the base case was:

- Develop a site-wide water balance
  - Define flow-paths and catchment areas;
  - Add flows based on precipitation, catchment area, and runoff;
  - Add reservoir components such as the TSF, Long Lake and MWTP; and
  - Calibrate to recorded flows.
- Add loading rates
  - Compare weekly contaminant concentrations downstream of impacted and background stations;
  - Define loading rates as discussed above. Geochemical mechanisms (e.g. NP depletion) are not applied at this stage;
  - Apply load scaling factors and in-stream solubility constraints; and
  - Compare and calibrate mass balance model results to recorded contaminant concentrations at stations downstream of mine components.

Site-wide water balance

Flow magnitudes were simply generated using average annual precipitation values multiplied by the catchment area of each monitoring station and a site-wide calibration coefficient. Calculated average annual flows are compared to recorded averages in Table 4. Note that all the water quality stations listed fall within the lower part of the catchment, varying from elevation 221 masl to 339 masl, and therefore don’t display a large amount of hydrologic discrepancy. Almost 50% of the overall watershed is dominated by the higher Long Lake watershed (1,000 masl to 1,700 masl). To account for this, the Long Lake watershed was represented using a separate calibration of hydrologic parameters tailored to its specific conditions.

Weekly flow data at each station was used to develop seasonal flow distributions, which differ from precipitation distributions in that they correspond to the seasonal timing of snowfall and melt. These distributions varied from station to station, which is expected as response-times are related to climatic influences and catchment characteristics. For example, catchments at higher elevations tend to experience colder temperatures and spring snowmelts that occur later in the year and over a longer period and smaller, steeper catchments have a faster response time to rainfall events.

Table 4. Recorded vs. calculated mean annual flows at PGP monitoring stations (KCB 2011b).

STATION NAME (NUMBER)	RECORDED MEAN ANNUAL FLOW (m^3/s)	CALCULATED MEAN ANNUAL FLOW (m^3/s)
Fletcher Above Cascade (S-2)	0.38	0.46
Leslie at Granduc (S-5)	1.08	1.02
Hovland at Granduc (S-6)	0.15	0.12
Cascade Above Tailings (S-7)	5.20	4.02
6-Level Before Treatment (S-13b)	0.042	0.042
6-Level After Treatment (S-13a)	0.054	0.056
Indian Creek (S-17)	0.09	0.13
Combined Discharge (S-19)	0.034	0.034
Logan at Granduc (S-26)	0.094	0.08
Cascade Below Logan (S-27)	6.27	5.91

Ponds such as the TSF and Long Lake itself have been represented as reservoirs, with discharge equivalent to the rate of inflow exceeding a maximum discharge elevation such as a spillway invert, with pond evaporation and direct precipitation applied to open pond areas and geometrical factors incorporated such as elevation-area and elevation volume curves.

Flow Calibration

Weekly flow distributions were input into the WQM and the resulting flows calculated. Results were then compared to recorded downstream flows to determine how well the flow network balanced. Downstream calibration stations are shown in Table 5. The same stations were used to calibrate water quality predictions. Because of the limited number of flow measurements at the CBL station, the level of confidence in the calibration is lower than other stations. However it is included, as it is the downstream compliance station for the PGP site; therefore it is useful to compare calculated and recorded values where they are available.

Table 5. PGP flow and water quality calibration stations.

Mine Area	**Calibration Station**
Long Lake and Big Missouri	Cascade Creek Above Tailings (CAT) (S-7)
Tailings Storage Facility (discharge and seepage)	Combined Discharge (S-19)
Premier Mine Area	Fletcher Above Cascade Creek (S-2)
Mine Water Treatment Pond	MWTP Discharge After Treatment (S-13a)
Entire Site	Cascade Below Logan (S-27)

It should be noted that a perfect calibration is not expected, as the model does not represent the effects of groundwater inflow or time-lags associated with the large catchment area, and hydrologic parameters are natural phenomena that are highly spatially and temporally variable. As an example, the recorded and calculated flows, along with the number of weekly flow measurements, at Combined Discharge, downstream of the TSF, are shown in Figure 5.

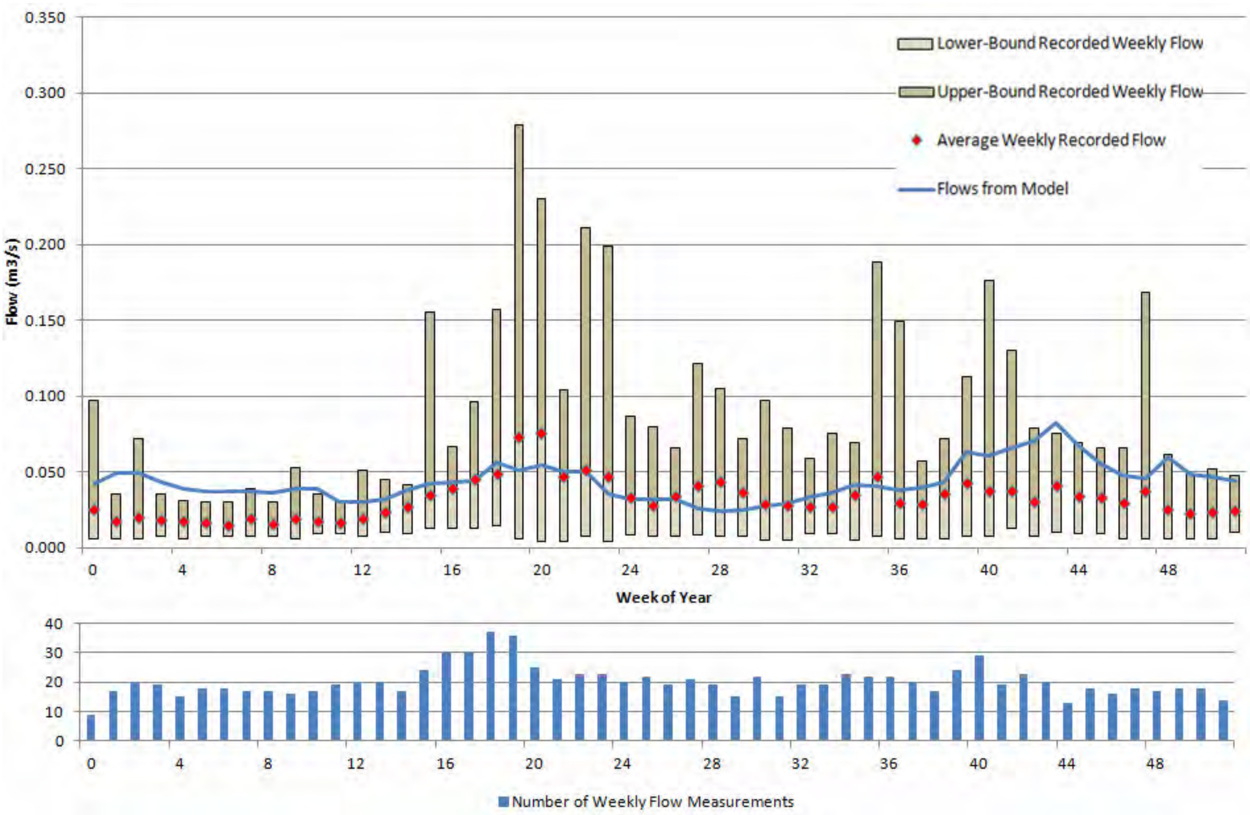

Figure 5. Recorded vs. modelled flow at combined discharge.

Note that the model appears to adequately represent average flows during the pre-freshet, freshet and summer months, while overestimating winter flows. This may lead to underestimations in winter concentrations and will be addressed in future work.

Loading rates

The background and impacted water quality stations all drain into Cascade Creek and eventually report to CBL (Figure 1), located downstream of the TSF. A simplified mass-balance model uses weekly background concentrations for each subcatchment, adds calculated source term loading rates from mine components such as pits, waste rock dumps or the TSF based on calculated parameters such as exposed rock mass, contact factors and surface areas, and multiplies them by weekly flows from the site-wide water balance in order to calculate loadings at station CBL. A composite calibration process was undertaken in watercourses downstream of mine components by applying load scaling factors and adjusting downstream concentrations to empirical instream solubility constraints.

The resulting concentrations calculated at station CBL are compared to measured concentrations in order to determine the effectiveness of the model to represent current conditions on a weekly basis. The results are shown in Figure 6.

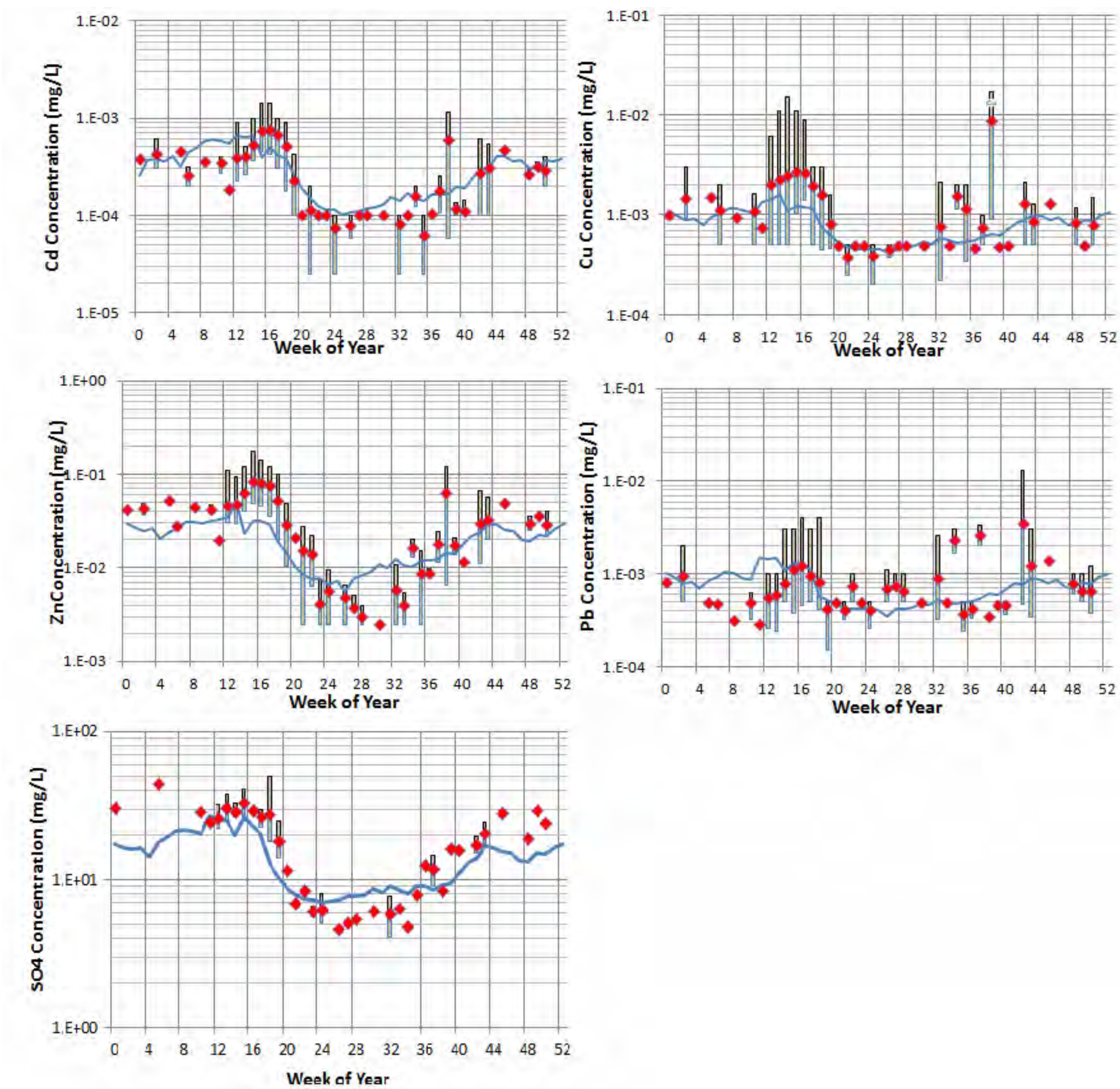

Figure 6. Modelled vs. recorded concentrations of dissolved POCs at station CBL.

Variations are attributed in-part to year-to-year changes in seasonal variability and in-part to lack of consideration of geochemical attenuation processes in the model.

This analysis has proven useful by allowing identification of likely sources of loadings from different areas within the PGP site. Percent contributions from each of the impacted stations are shown in Figure 7.

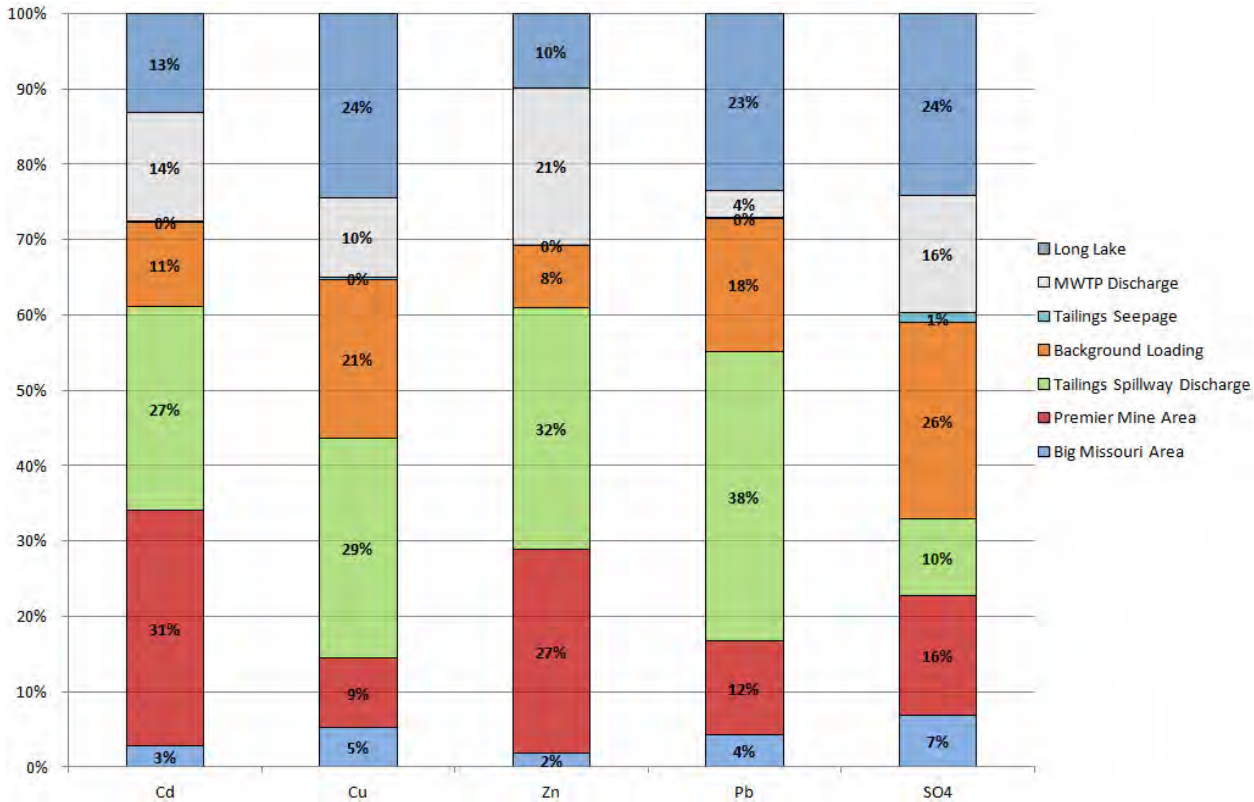

Figure 7. Percent of downstream loading contributed by each impacted station.

Conclusions & Path Forward

Conclusions from analysis of calculated data from loading sources are:

- The 'background' catchment contributes fairly significantly to POC loadings at station CBL.
- The most significant contribution to loadings at CBL is from the MWTP, TSF pond discharge, and the 4-Level Historic Tailings (in the Premier area).
- The open pits and waste rock dumps of the Big Missouri and Premier areas are currently not significant sources of loadings. The only major contributor to loading from these areas is the 4-Level Historic Tailings.
- Total cyanide concentrations in the TSF currently do not contribute significantly to downstream loading, and are expected to steadily decrease over time (assuming equilibrium conditions have been reached and are maintained).

The water quality model has demonstrated adequate correlation to current conditions, as a mass-balance model, to be able to reasonably predict changes in water quality within the PGP hydraulic network if changes are implemented in the short term and under current geochemical conditions. Note that if the system undergoes any significant changes in geochemical processes, the validity of the model results may no longer be accurate. Although mechanisms are built into the model to enable it to represent geochemical conditions, these were not implemented due to lack of available data at the time of modelling. In order to expand the functionality of the model to predict long-term effects of various closure plans or effects of changing geochemical conditions, additional functionalities and data inputs beyond those of a mass-balance model are required.

ARD

Norecol Dames and Moore (NDM 1998) completed short-term kinetic humidity cells of waste rock from the Premier and Big Missouri area. During 2008, new water quality and geochemical studies were carried out by URS that included the identification of data gaps in that are needed for further geochemistry predictions. As discussed above, there are some limitations to the currently available geochemistry data. Additional geochemical data of long-term waste rock behaviour are needed to expand the predictive capabilities of the WQM. Therefore, it is recommended that a testing programme be implemented by Boliden in order to complement previous analysis by NDM (1998) and URS (2008). The programme would give more rigour to predictive modelling using this model for the PGP site.

Sensitivity analysis and closure scenarios

As a mass balance WQM, changing flows within the WQM will result in proportional changes in water qualities at the compliance point CBL. Experience tells us that changing hydrologic and climatic patterns, and attenuation mechanisms result in changes beyond those that can be represented by a mass balance model – for example with relation to accumulation of contaminants during dry periods and high-concentration "pulses" that follow. These effects need to be examined in more detail, using empirical data at the PGP site, in order to more accurately represent scenarios in which changing hydrologic or climatic conditions is a concern. Such scenarios are described in the sections that follow.

Mine Closure

Planned mine closure activities centre on closure of the TSF. A new, more robust, spillway will be commissioned, at a higher elevation than the current spillway, that discharges water directly into Cascade Creek, and diverted tributaries upstream of the TSF will be allowed to flow into the TSF pond. The effects of this should be examined in terms of increased water levels and volumes in the pond, increased spillway outflows, and a decreased exposed tailings beach area.

Extreme hydrologic conditions

The 200-year wet and dry flows were estimated by extrapolating recorded flow data in Cascade Creek upstream of the TSF, at station S-7. The same extrapolations are applied to other catchments to estimate the 200-year high and low flows. These scenarios are useful for examining the sensitivity of the system to variations in hydrologic conditions, including variations in spillway discharge and TSF water levels.

It was examined whether hydrologic 200-year dry conditions would cause a net-negative water balance in the TSF resulting in tailings being exposed. Recent history indicates that this may be detrimental to TSF pond water quality. Data shows that spikes in concentrations of POCs correlate with periods where the TSF pond level was dropped for tailings relocation, as discussed in KCB (2011a).

According to the current water balance analysis, the TSF pond water level is expected to drop by no more than 0.04 m during the 200-year dry year. The lowest water level is expected in week 35 – around mid-August.

Climate change

The Intergovernmental Panel on Climate Change (IPCC 2008) has issued a number of publications relating to the impacts of climate change. Predictive modelling of global and regional climate systems has led to a range of estimates of non-stationarity (i.e. climate change) in aspects such as:

- Extreme and average temperatures;
- Mean precipitation;
- Water vapour resulting in extreme precipitation events;
- Snow and glacier melt;

- Partial pressure and evaporation; and
- Wind patterns.

Based on predictive models and analysis of data from climate monitoring station networks, magnitudes and spatial/temporal distributions of the above will be impacted in ways that have implications for flow magnitudes, patterns and chemical loadings.

Upstream hydroelectric project
A hydroelectric project is currently under construction within the PGP watershed, in Long Lake. This project may have a regulating (seasonal smoothing) effect on flows in Cascade Creek, particularly during extreme climate conditions. The impacts this development may have on water quality in Cascade Creek will be highly dependent on actual operational procedures of the hydroelectric project. Ongoing monitoring of flows and water quality during commissioning of the LLHP will provide data for model validation.

Acknowledgements

The authors would like to acknowledge the contributions of the site team at the PGP for their tireless data collection and sharing their knowledge of the site, as well as the managerial team at Boliden Ltd., for providing support and technical resources for this project, as well as the staff at the Ministry of Environment and the Ministry of Mines and Petroleum Resources for their technical feedback.

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Acronyms

CAT = Cascade Above Tailings, a water quality and flow sampling station upstream of the tailings storage facility, but downstream of Long Lake and the Big Missouri mine area.
CBL = Cascade Below Logan, a water quality and flow sampling station downstream of the project site
KCB = Klohn Crippen Berger Ltd.
masl = metres above sea level
MWTP = Mine Water Treatment Plant
PGP = Boliden Limited’s Premier Gold Project
POCs = Parameters of Concern
RMFS = Root-Mean-Fraction-Square
RMS = Root-Mean-Square
TSF = Tailings Storage Facility
WQM = Water Quality Model
WRD = waste rock dump