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Beneficial Use of Springer Pit Lake at Mount Polley Mine

Jerry Vandenberg[1] · Shauna Litke[2]

Abstract

While pit lakes can pose potential risks to the environment and liabilities to mining companies, they may also present opportunities for sustainable end uses, if managed appropriately. The Springer Pit Lake and Mount Polley Mine provided an opportunity to store mine waste such as tailings and mill process water while the mine repaired its tailings storage facility after a breach in its perimeter embankment, which released tailings to the downstream environment in 2014. 1 year after the breach, a water treatment plant was installed so that the pit lake could be drawn down. Frequent monitoring of water quality in the pit, combined with a calibrated and verified water quality model, shows that water quality is improving. Based on the observations that tailings, suspended solids, and associated constituents are being removed efficiently by the pit, the treatment plant was reconfigured to a "passive" mode, which did not entail the use of reagents or mechanical energy—only in-line instrumentation.

Keywords Passive water treatment · Particulate metals · Copper mine · Mine pit lake · End pit lake

Introduction

Pit lakes can pose potential risks to the environment and liabilities to mining companies (McCullough and Lund 2006). However, they may also present opportunities for sustainable end uses, if managed appropriately. Beneficial use of a pit lake entails the conversion of a post-mining pit into a lake that brings some value to the mining company, local communities, the environment, or combinations thereof. Examples of beneficial uses include recreation, industrial water supply, aquaculture, potable water source, research, and education (McCullough and Lund 2006), and water treatment (Luek et al. 2014).

Beneficial use of a pit lake requires the mining company to understand what is possible, given the pit lake's water quality, morphology, receiving environment, and other characteristics, as well as what is desirable—generally an end use that is lacking in the region or desired by local stakeholders. At the intersection of these two states lies the potential for beneficial uses. If no such intersection is identified, the pit lake may need to be adaptively managed toward a more desirable state (Vandenberg et al. 2015).

Springer Pit at the Mount Polley Mine provided such an intersection, where the mine required a water storage facility and a water treatment system to manage surplus water after the tailings storage facility (TSF) embankment failure and subsequent breach in 2014.

Mount Polley Mine

The Mount Polley Mine is an open pit copper–gold mine with an underground component, and is authorized to process an average of 22,450 t per day of ore on an annual basis. The mine is located 8 km southwest of Likely, BC, approximately 400 km northeast of Vancouver, BC. An aerial view of the mine is provided in Fig. 1.

On 4 August 2014, a breach occurred in the TSF perimeter embankment due to the failure of a glaciolacustrine layer located ≈ 8 m below the embankment's foundation. The embankment breach released tailings, water, and embankment construction materials to the downstream

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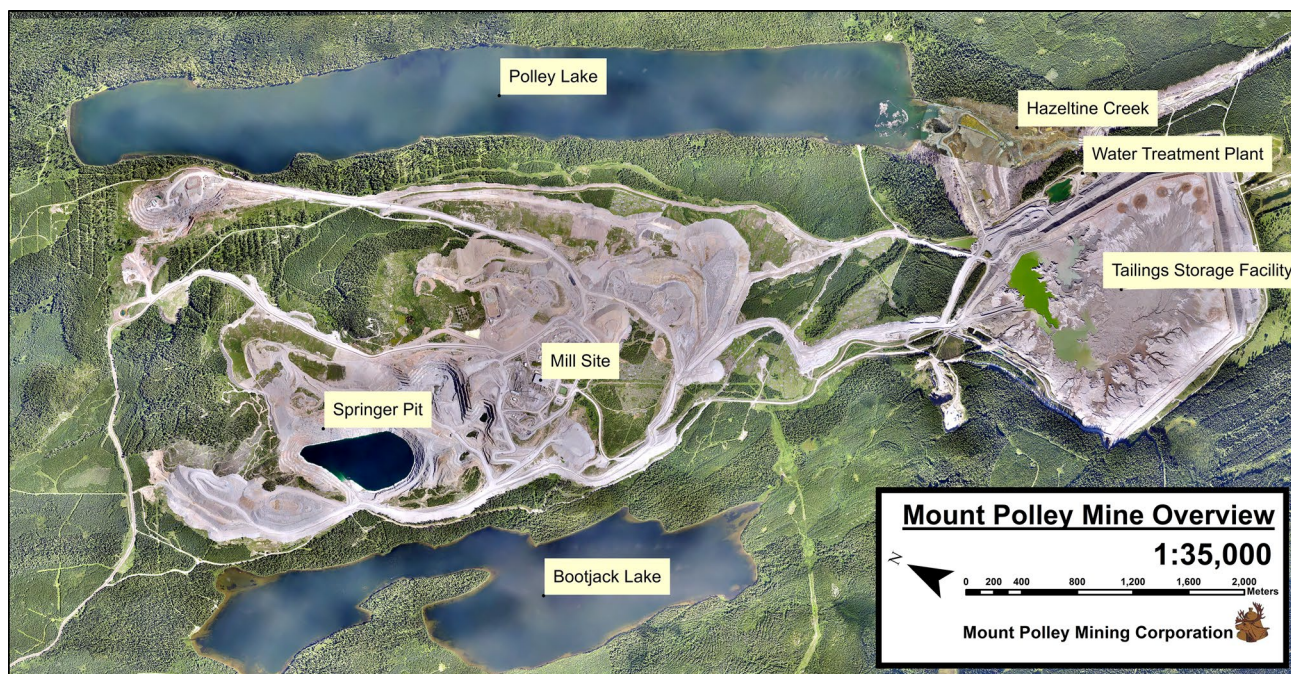2 Mount Polley Mining Corporation, PO Box 12, Likely, BC V0L 1N0, Canada

Fig. 1 Location of Mount Polley Mine in British Columbia, Canada

environments of Polley Lake, Hazeltine Creek, and Quesnel Lake. This event is described in detail elsewhere: the failure mechanism is described by the Province of BC (2015); the environmental assessment by Golder (2016); and a summary of rehabilitation efforts by Nikl et al. (2016). Following the TSF embankment breach, mining and milling operations at the mine were immediately suspended, as well as the authorized mine water discharge. The focus of mine operations shifted to monitoring and remediation work at the TSF, around Polley Lake, and down the Hazeltine Creek corridor to Quesnel Lake. The short-term emergency response to the TSF embankment breach included: addressing health and safety concerns; containment to prevent further release of materials from the TSF; water quality monitoring; cleanup of woody debris on Quesnel Lake; lowering of the Polley Lake water level (which had been increased by the event); assessment of the physical stability of the sediment deposited at the outlet of Polley Lake; and implementation of sediment and erosion control measures in the Hazeltine Creek corridor (Nikl et al. 2016). A timeline showing the events graphically is provided as supplemental Fig. 1.

Residual water in the TSF and accumulating water from precipitation was transferred to Springer Pit for storage, and a water management plan was developed to treat, permit, and discharge the water to the environment. Upon restart of the mine in August 2015, tailings were also deposited as a slurry into Springer Pit while the TSF was being repaired. 5 Mt of tailings were placed into the pit during the temporary restart, which lasted 10 months. During this period, mining was not active, but the mill was re-permitted to process stockpiled ore.

The first priority for the mine during this period was to draw down and discharge surplus water. This had safety implications for long-term water storage, and there were more immediate concerns as well. Once the lake was filled to approximately two-thirds by volume, it was predicted to exfiltrate potentially contaminated water into the surrounding bedrock and towards a nearby lake downgradient of the pit. Additionally, the water and tailings had to be removed from the pit in order to resume mining. Discharge of the water from the mine began on December 1, 2015, the day after a discharge permit was granted by the provincial government.

The water management plan required modelling to predict future water concentrations to manage the discharge in a way that would protect the downstream environment. This information was required to plan for modifications and operation of the water treatment plant. Before proceeding to model the long-term water management plan, post-audit monitoring was conducted to verify the performance of the model during the original, short-term predictions, as described below.

Springer Pit Model

A coupled water-balance and water-quality model was developed using GoldSim™ version 11.1 (GoldSim Consulting Group 2010). The water balance was developed to simulate

mine site water quantities, including Springer Pit volumes under the current and proposed site water management plan. The water quality model was developed to predict Springer Pit Lake water quality for the purposes of estimating effluent quality and identifying constituents of potential concern in this facility and in the discharge. The mine maintains a well-populated database of water quality data for several years at many points of the mine, including all known significant loading sources, and these data were used to derive inputs to the model.

To address uncertainty, the model was developed stochastically using a Monte Carlo approach. The statistical approach to developing such input are described by Lauzon et al. (2011). In the model, each input (including precipitation and source water quality) was defined as a probability distribution function that was randomly sampled over 1000 realizations. This approach provided a range of water elevations and qualities in Springer Pit at each time-step, which were subsequently used to calculate percentiles for each parameter at each model time-step. The predicted maximum of the 95th percentile constituent concentrations, projected over the duration of the model, were used to inform the water treatment plant (WTP) design and to propose effluent limits for the discharge permit. For additional detail on the model, the reader is referred to the Golder (2016).

Model Post-Audit

As the pit lake filled after the model was completed, subsequent monitoring of pit lake water levels and water quality provided an opportunity to audit the original model predictions. Concentrations of 37 modelled constituents were measured in Springer Pit Lake from July 2015 to December 2016, which included restart of operations, pit filling, and drawdown/discharge. A comparison of the model predictions against measured concentrations shows that most constituent concentrations were either within or below the predicted range. Based on the comparison, predictions were grouped into three categories:

Over-predicted concentrations that were observed to be generally below the 5th percentile model predictions, including:

- *Ions and nutrients* Chloride, ammonia, and total phosphorus;
- *Dissolved metals* Aluminum, arsenic, cadmium, cobalt, manganese, and zinc; and
- *Total metals* Aluminum, cadmium, chromium, cobalt, copper, manganese, silver, vanadium, and zinc.

Accurate concentrations that were observed to be between the projected 5th and 95th percentile model predictions, including:

- *Ions and nutrients* Total dissolved solids, calcium, sulphate, and nitrate;
- *Dissolved metals* Antimony, boron, chromium, iron, molybdenum and silver; and
- *Total metals* Antimony, boron and molybdenum.

Underpredicted concentrations that were observed to be greater than the 95th percentile model predictions, including:

- *Ions and nutrients* Magnesium, and nitrate;
- *Dissolved metals* Copper and selenium; and
- *Total metals* Arsenic and selenium.

Figure 2 provides examples of select constituents that were representative of these categories. Observed data on these plots are represented by samples from the Springer Pit dewatering sump, as well as samples collected from near the surface and bottom of the pit lake. Sulphate and molybdenum were two constituents that were observed to be within the model-projected concentration ranges. The good agreement indicates that model inputs were well characterized and that these constituents were not sensitive to differences in water management such as pumping rates that differed from projections at the time of modelling.

The underprediction of water quality constituents, particularly selenium, led to investigations into the water balance and source terms to improve the model. These investigations are described by Beddoes et al. (2016), including the cause attributed to each underpredicted constituent. The overpredicted constituents tell a different story—they are the focus of this paper.

Observed concentrations of total phosphorus and copper in Springer Pit were below the model-projected ranges. There are several reasons why this might have happened, including:

- The model was developed to predict water quality conservatively; where uncertainty existed in model inputs, the inputs were selected to minimize the risk of underprediction.
- Metal concentrations that are far below detection limits may be skewed upward by model inputs where half-detection limits were applied.
- Processes such as the uptake of nutrients, precipitation of dissolved species, and adsorption and settling of particulate materials were not accounted for in the model.

Although these factors led to overprediction, the model was considered valid for developing permit effluent limits because the limits were also derived so that acute guidelines and metal mining effluent limits would be met at the end-of-pipe and so that chronic guidelines within an initial
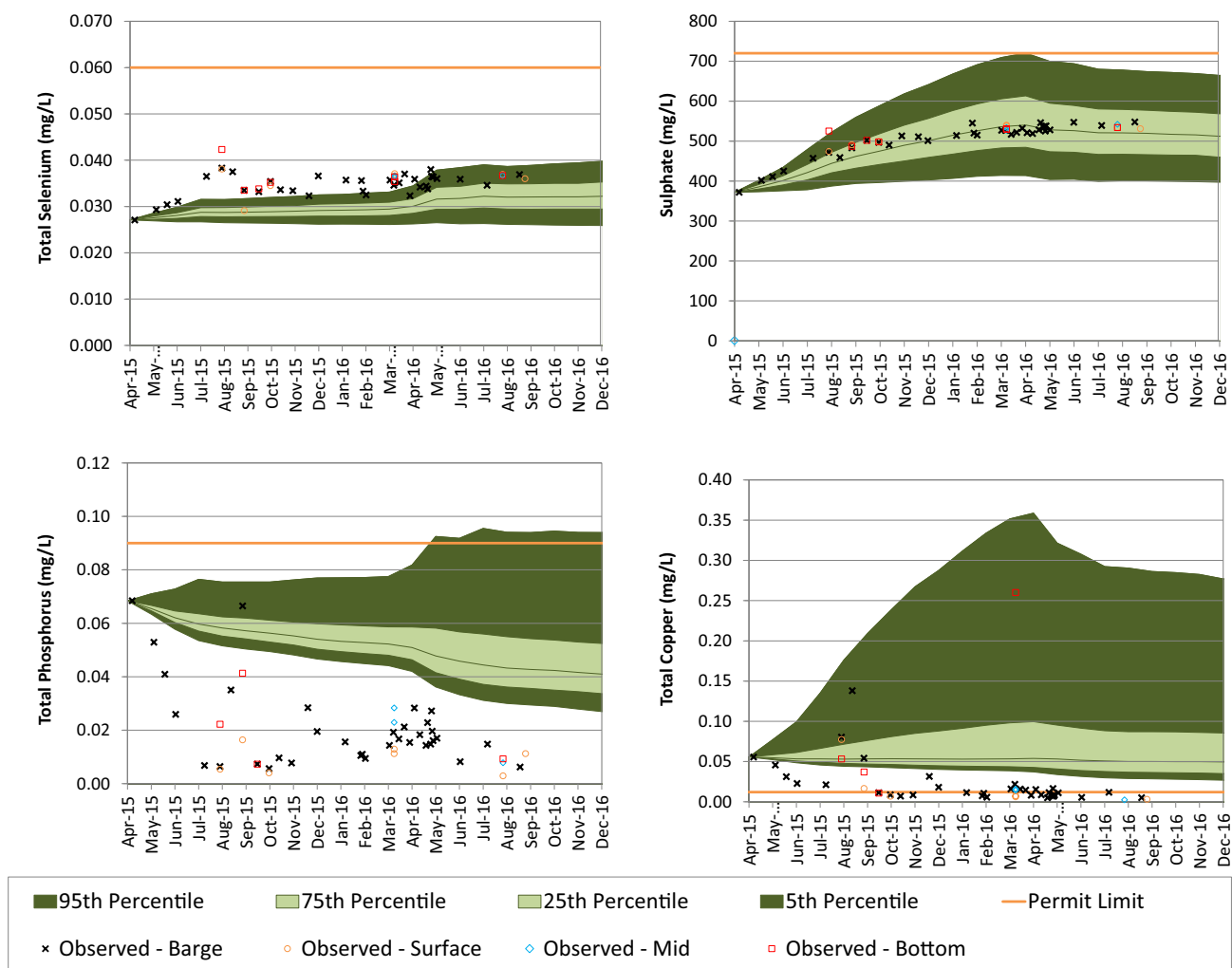
Fig. 2 Representative plots showing model performance **a** under-predicted—total selenium, **b** accurate—total molybdenum, **c** over-predicted—total phosphorus and **d** over-predicted—total copper

dilution zone would be met in the receiving environment. By excluding the settling of total suspended solids (TSS) and particulate metals in the pit lake, the permit effluent limits applied to the discharge cover a range of conditions, including worst-case conditions with respect to settling. Therefore, deviations in model predictions from observed conditions in this category tended to promote the ultimate objective of the model, which was protection of end uses in the receiving environment.

Of the processes listed above, sedimentation was thought to be the dominant mechanism that led to lower-than-predicted concentrations in the pit lake. At that time, it was hypothesized that in-pit sedimentation could be used instead of the WTP to achieve water concentrations below the permitted discharge levels. Before making any changes to the dewatering infrastructure, additional monitoring was completed to verify this hypothesis.

Monitoring Methods

To supplement routine monitoring of water levels and water quality, sampling was conducted on March 9 and May 11, 2016 from an aluminum boat that was launched at the Springer Pit ramp. During this time, tailings were still being deposited into Springer Pit. Water depth was measured along several transects using an Eagle Cuda 128 depth sounder to locate the deepest part of the pit. The water depth at all points except near the pit walls was nearly uniform at 50 m. A few locations, with small spatial extents, were measured at over 60 m deep, but these depths could not be verified due to a light south wind that precluded stationary readings.

Water quality samples were collected and in-situ profiles were measured at six locations: SPP-1 and SPP-3 on
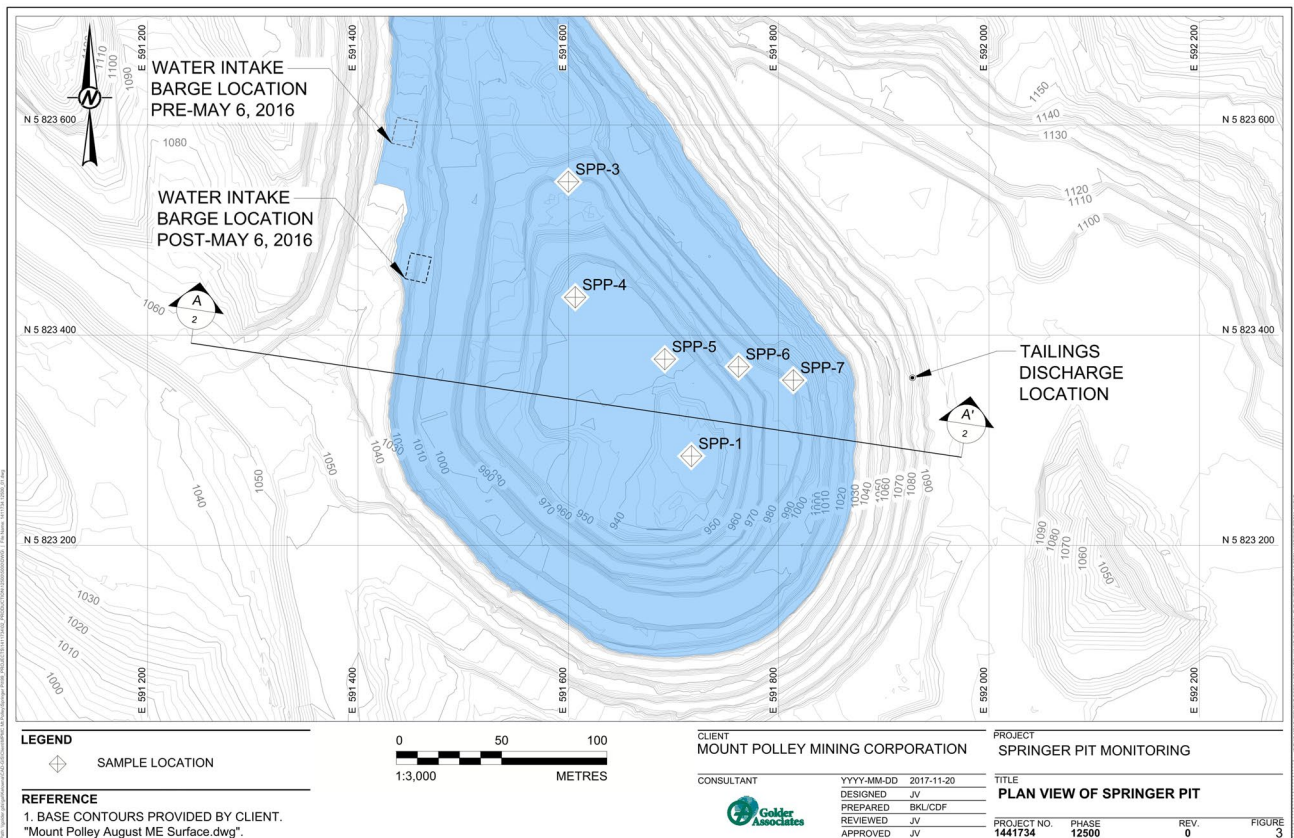
Fig. 3 Plan view of Springer Pit Lake showing sample locations

March 9, and SPP-4, SPP-5, SPP-6, and SPP-7 on May 11 (Fig. 3). In-situ profiles included temperature, electrical conductivity (EC), pH, dissolved oxygen, and turbidity using a YSI EXO1 measured every 0.25 s, which corresponded to readings approximately every 0.1 m.

On March 9, water quality grab samples were collected at the surface and from mid-depth (i.e. at ≈ 25 m) and 1 m from the bottom using a Kemmerer sampler. Samples were shipped to ALS Laboratories in Burnaby, BC, for analysis of physical parameters (EC, hardness, pH, TSS, total dissolved solids, turbidity, and alkalinity), nutrients (nitrate, ammonia, and total and dissolved phosphorus), dissolved organic carbon, anions (sulphate, chloride, fluoride), and total and dissolved metals. On May 11, grab water quality samples were collected for TSS. The objective of the May 11 sampling was to obtain higher resolution information about the spatial distribution of particulate matter than was obtained on March 9.

Surface water quality monitoring results were provided by MPMC for inflows to and outflows from Springer Pit. Up to May 2016, outflows were measured at the Springer Pit sump (sample location E11), which was taken from shore, near the location where water was drawn from the pit by a combination of barges and diesel pumps. A new sampling location was

established in late April 2016 due to concern that surface run-off from the pit ramp or another source may have influenced the water samples. The new sample location was E11a, inline at the Booster Station distribution tank between Springer Pit and the WTP. This location represents the flow sent to the WTP for treatment and discharge.

Inflow to Springer Pit was represented by water collected at sampling location E20. This sample was a slurry sample that was collected from the final tailings box in the mill; a sub-sample of the supernatant was collected after the tailings had settled for approximately 5 h. The E20 sample was considered representative of the liquid fraction of the tailings slurry that was deposited into the Springer Pit.

A cross-section showing measured water level and tailings surface inferred from the depth soundings described above is shown in Fig. 4. During the year of this study, ice did not form on the lake, and macrobiological activity was negligible.
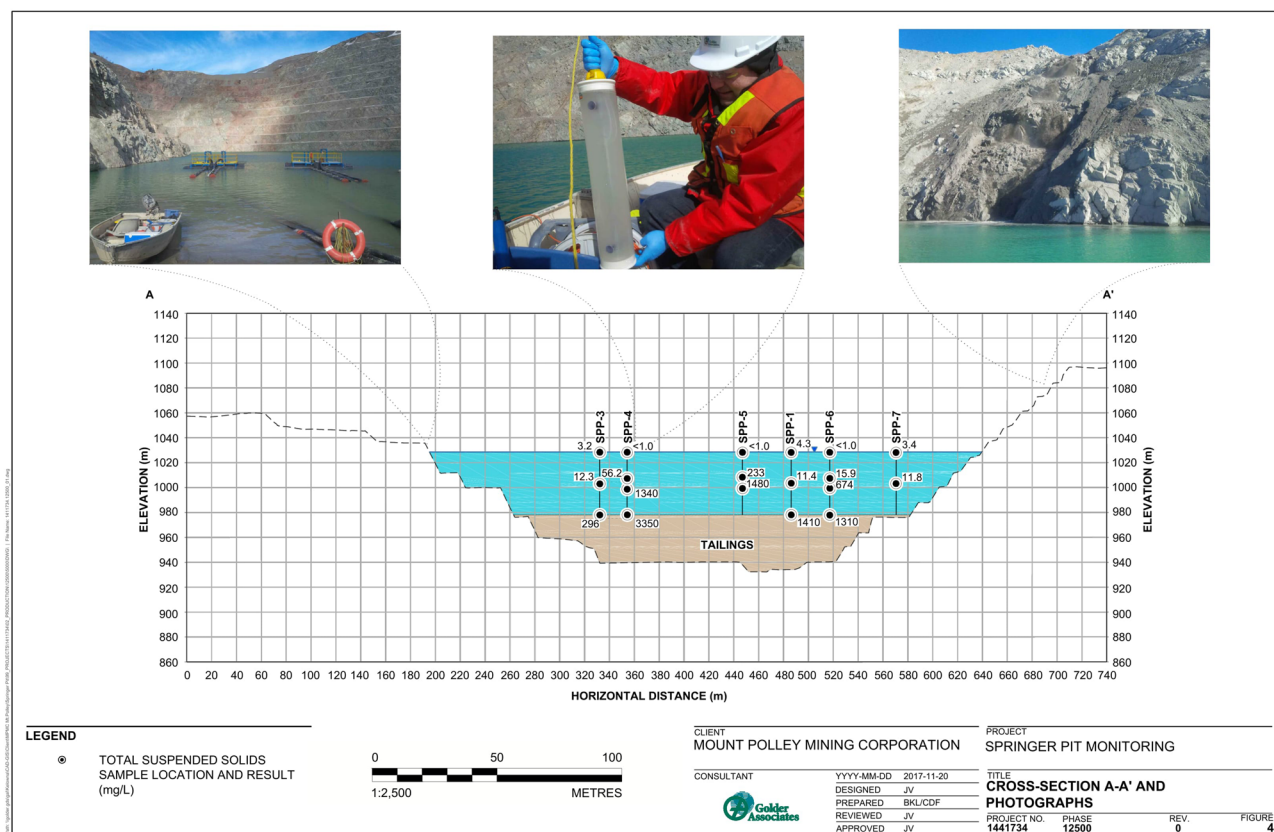
Fig. 4 Cross section of Springer Pit showing tailings and water elevations. The photographs show, from left to right: the boat and barges on March 9, 2016; a sample collected from depth at SPP-3 using a Kemmerer sampler; and, the flow of tailings slurry into the Springer Pit. The numbers shown next to each vertical profile are the TSS values measured at each depth, in mg/L

Results and Discussion

Field Profiles

Vertical profiles of temperature and EC were nearly uniform at all locations, indicating that the Springer Pit water column was both vertically and laterally well mixed on both dates. From March 9 to May 11, 2016, the water temperature increased from $\approx$ 4.4 to 9.0 °C (Fig. 5).

Dissolved oxygen ranged between about 6 and 9 mg/L at depths of less than 30 m, with levels as low as 3 mg/L toward the bottom (Fig. 5). The apparent variation in dissolved oxygen profiles among locations may be due to the speed at which the YSI EXO1 was raised and lowered within the pit lake, which led to different profiles on the downward cast compared to the upward cast. Alternatively, it is possible that the optical probe became fouled in the tailings sediments. In any case, the profiles are typical of deep, temperate lakes with sediment oxygen demand at the lake bed and aeration at the surface (Wetzel 2001).

A strong turbidity gradient was measured at all locations, indicating that fine materials deposited within the tailings slurry remained suspended up to $\approx$ 25 m above the lake bed. In the top 30 m, turbidity was uniformly low at all locations, with the exception of elevated turbidity near the surface at SPP-5 on May 9, 2016 (Fig. 5).

Analytical Data

Based on water quality samples collected during the March 9, 2016 sampling event, most dissolved constituent concentrations were similar at SPP-1 and SPP-3 stations at all depths, similar to the EC profiles. Large differences in concentration were measured at depth for particulate constituents, similar to the turbidity profiles. Concentrations of total phosphorus and 19 of the 31 measured total metals were notably higher near the bottom compared to the mid-depth and surface samples, indicating that the particulate form of these metals was settling in Springer Pit Lake. Favourable conditions for precipitation and settling of some metals were maintained by the slightly basic pH ($\approx$ 8) throughout the water column (Stumm and Morgan 1996). Measured concentrations of constituents with permit limits are presented in Table 1.
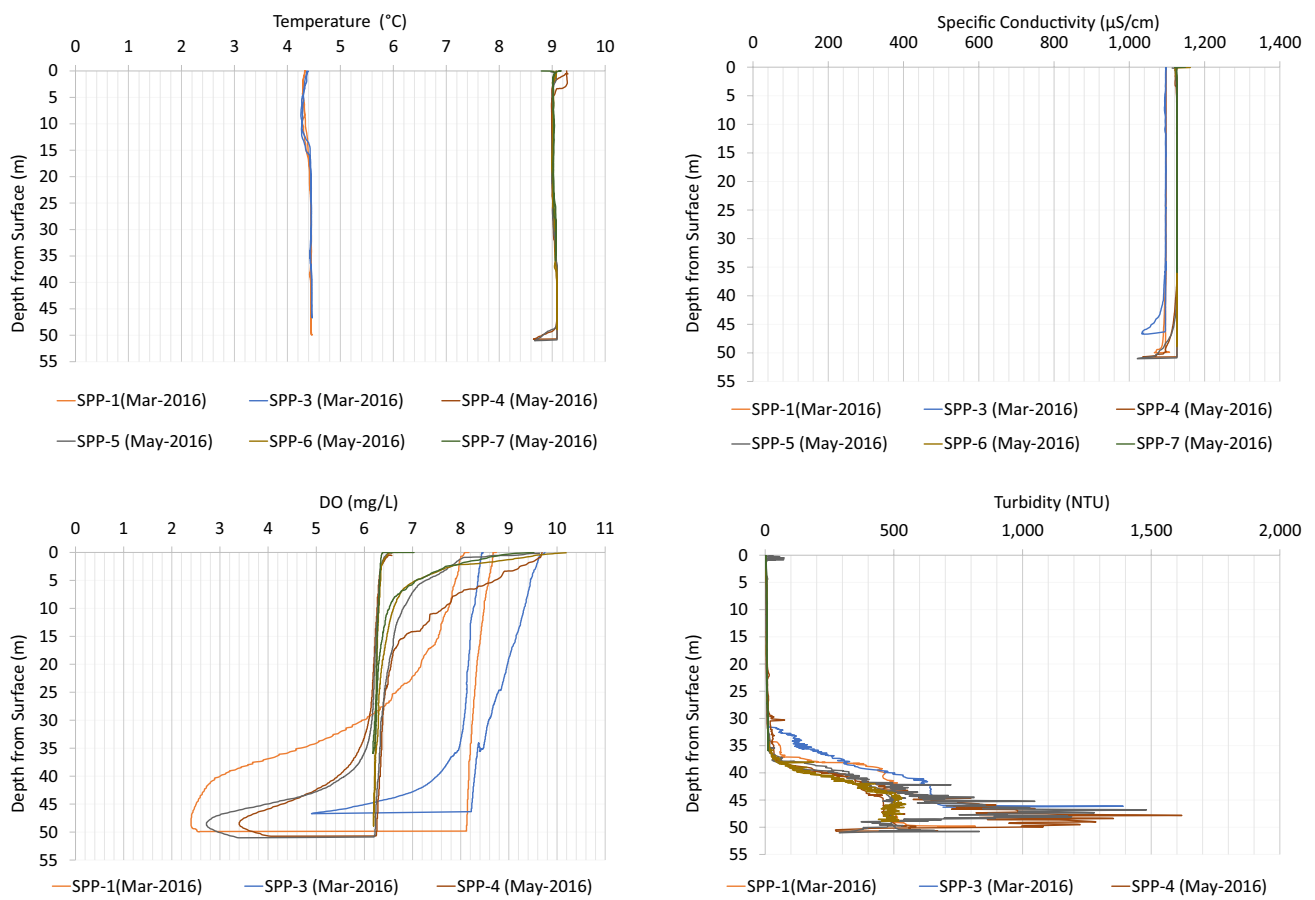
Fig. 5 In-situ profiles **a** temperature; **b** specific conductivity; **c** dissolved oxygen; **d** turbidity

Table 1 Constituent Concentrations in Springer Pit on March 9 and May 11, 2016; concentrations in mg/L

Parameter	Permit limit	SPP-1 bottom 09/03/2016	SPP-1 mid 09/03/2016	SPP-1 surface 09/03/2016	SPP-3 bottom 09/03/2016	SPP-3 mid 09/03/2016	SPP-3 surface 09/03/2016
Physical parameters							
pH	6 to 9.5	7.97	7.96	7.94	8.03	7.98	7.94
TSS	15	1410	11.4	4.3	296	12.3	3.2
Major ions							
Sulphate	720	530	534	538	530	527	540
Nutrients							
Ammonia (as N)	0.41	0.173	0.158	0.162	0.17	0.117	0.166
Nitrate (as N)	9.7	8.64	8.7	8.78	8.61	8.58	8.79
Total P	0.09	2.17	0.0229	0.0112	0.472	0.0283	0.0129
Total Metals							
Arsenic	0.0034	0.0183	0.0012	0.00114	0.00639	0.00124	0.00115
Chromium	0.0011	0.011	<0.00050	<0.00050	0.00333	<0.00050	<0.00050
Copper	0.012	0.827	0.0156	0.00619	0.26	0.0142	0.00743
Iron	1	26.5	0.264	0.046	7.17	0.244	0.071
Molybdenum	0.20	0.152	0.162	0.167	0.159	0.166	0.167
Selenium	0.060	0.0354	0.0363	0.0371	0.0364	0.0366	0.0366
Zinc	0.03	0.078	<0.0030	<0.0030	0.0244	<0.0030	<0.0030

As illustrated in supplemental Fig. 2, for constituents that were hypothesized to be settling out in the Springer Pit Lake, the E20 samples were generally slightly higher in concentration than mid-depth and surface samples, but lower than bottom samples. This indicates that settling of most particulates was rapid, because the E20 samples that settled for 5 h had only marginally higher concentrations than mid-depth samples in the pit lake. A notable exception to this pattern was copper, which may be associated with the colloidal fraction that settled more slowly. The bottom sample concentrations were much higher than both E20 and mid-depth samples for most metals, indicating that, while most of the particulate fraction settled rapidly, there was a significant amount of finer material that had accumulated near the tailings-water interface and had not completely settled out. This information was used to predict water quality during tailings and water drawdown when the dewatering draw point approached these materials.

Based on differences between concentrations measured at the surface and bottom, the constituents listed in Table 2 were apparently being removed from the water column by passive settling in Springer Pit. Table 2 also lists the constituents that were indicated by the conservative mass balance model as being removed. Those shown in this column were below the levels predicted by the model, most likely because of settling. For constituents where both lines of evidence indicate removal, Springer Pit Lake appears to be effectively "treating" the particulate fraction of these constituents. In cases where one line of evidence suggests removal but the other does not, there may be uncertainty due to concentrations being close to detection limits or due to conservatively high input data in the model. Turbidity, TSS, total phosphorus, dissolved aluminum, and 19 total metals appear to be removed by sedimentation.

Ammonia was indicated by the mass balance model validation as being below predicted levels (Golder 2015); however, there was no discernable difference between surface and bottom stations. It is possible that ammonia is being nitrified or volatilized, but advective mixing exceeds the removal rate and therefore an ammonia gradient was not established. Based on inferred inflow concentrations at E20 compared to all measured Springer Pit water column samples, both ammonia and nitrate appear to be undergoing some level of removal. Further investigation would be required to confirm whether significant rates of nitrification and denitrification are occurring.

Total copper was the topic of particular focus during review of the permit application review. In the model, it was assumed that the WTP would remove up to 85% of the particulate copper, bringing effluent concentrations to 0.012 mg/L or less. At both stations in the Springer Pit Lake, total copper concentrations exceeded this value at bottom and mid-depths, but were well below the permit limit

Table 2 Constituents interpreted as being removed from water column

Constituent	Indicated by measured data	Indicated by mass balance model
TSS	Yes	Not modelled
Turbidity	Yes	Not modelled
Total phosphorus	Yes	Yes
Ammonia	No	Yes
Dissolved aluminum	Yes	Yes
Total aluminum	Yes	Yes
Dissolved arsenic	No	Yes
Total arsenic	Yes	Yes
Total barium	Yes	Not modelled
Total beryllium	Yes	Not modelled
Dissolved cadmium	No	Yes
Total cadmium	Yes	Yes
Total chromium	Yes	Yes
Dissolved cobalt	No	Yes
Total cobalt	Yes	Yes
Total copper	Yes	Yes
Total iron	Yes	Yes
Total lead	Yes	Not modelled
Dissolved manganese	No	Yes
Total manganese	Yes	Yes
Total nickel	Yes	Not modelled
Total silicon	Yes	Not modelled
Total silver	Yes	Yes
Total thallium	Yes	Not modelled
Total tin	Yes	Not modelled
Total titanium	Yes	Not modelled
Total vanadium	Yes	Yes
Total zinc	Yes	Yes
All other dissolved metals	No	No

Constituents that are indicated by both lines of evidence as being removed by sedimentation, or where one line of evidence strongly supports sedimentation and the other is not available, are shaded to show those that are inferred to be consistently settled

at surface stations. However, during the same time period, total copper exceeded the permit limit at the Springer Pit sump (sampling point E11). As noted above, this led to the establishment of a new sampling location (E11a) to avoid potential contamination that may have affected E11 samples prior to May 2016. Samples measured at E11a since May 2016 appear to contain less copper than the previous samples measured at E11 (Fig. 2d).

Suspended Solids Removal

For comparative purposes, the dimensions of Springer Pit were evaluated in the context of the BC Ministry of

Environment's (MoE) guidance on assessing the design, size, and operation of sediment ponds (MoE 2015). The pump barge is at the opposite end of the Springer Pit from the influent, and the pit provides gravity settling. The total surface area is $\approx 220{,}000$ m^2, but the shape is not ideal. Following MoE (2015), it is appropriate to apply a derating factor of 100% or more; therefore, a calculation was performed using a pond surface area of 100,000 m^2. This showed that surface area should not be expected to be the limiting factor in gravity settling.

Based on Stokes' Law, particles larger than about 2 µm (fine silt) that were capable of gravity settling would be expected to completely settle by the time they would reach the intake barge (approximately 500 m from the tailings deposition point at surface). In comparison, sediment ponds are typically designed to capture fine particles of 5–10 µm (MoE 2015). In the case of the Mount Polley Mine, most of the particles are coarser than 5–10 µm; only about 5–7% of the particles from the reclaimed tailings are smaller than 2 µm.

Particles below a certain size (≈ 1 µm) would be expected to remain suspended for extended periods, unless settling aids were used. Therefore, a small amount of turbidity caused by clay-size particles would be expected, and it should not vary significantly across the lake surface.

The tailings water (E20) is shown empirically to settle most of the TSS within 5 h to less than 16.5 mg/L. In contrast, Springer Pit has an additional residence time of over a year. Thus, Springer Pit should be able to provide TSS removal to below the permit limit of 15 mg/L. The observed behaviour of turbidity and TSS concentration in the Springer Pit Lake is consistent with the conceptual model.

Passive Water Treatment

Water samples were analysed to evaluate whether Springer Pit Lake was providing adequate passive settling, such that active water treatment was not required, and to explore the potential to have Springer Pit accepted, under permit conditions, as providing water treatment. Concentrations measured at the stations were compared to EMA Permit 11678 water quality limits (Table 1), which indicated that all constituent concentrations were below permit limits since changing the location of the barge and the sampling point to E11a. Thus, we concluded that Springer Pit Lake was providing adequate treatment of the mine water.

Two conditions that could degrade Springer Pit water quality would be: (1) an extreme wind event that could cause turbulence at greater than normal depths, and (2) draw down of the Springer Pit water column as it approaches the tailings. Surface runoff into the Springer Pit is unlikely to affect concentrations, provided the intake barge remains an adequate distance from shore.

Conclusion

Water quality has been measured in the Springer Pit Lake since discharge from the Mount Polley Mine commenced on Dec. 1, 2015. Outflows have been adaptively managed to maximize flow offsite while meeting permitted water quality limits. Since June 2016, the mine has consistently achieved discharge flow rates exceeding the WTP design flow of 0.23 m^3/s and up to the maximum authorized flow rate of 0.3 m^3/s, without the need for active treatment.

Water quality at the Springer Pit surface and sump was examined to assess which metals and other particulate materials were being passively removed from the water column in Springer Pit. In-situ profiles of turbidity and laboratory-measured values of TSS, total phosphorus, and metals indicated that 23 of the measured constituents were being removed. These results confirmed results from a mass balance model that indicated removal of a similar list of constituents. Both lines of evidence align with expectations of a sedimentation pond of similar dimensions.

Active water treatment at Mount Polley Mine refers to the addition of reagents (e.g. coagulant, flocculant, microsand), and the mixing and settling of ballasted floc particles in the WTP. Passive pre-treatment of the influent water from Springer Pit Lake eliminated the need for active treatment and allowed for discharge over the design flow rate of the WTP, as well as lower electricity, reagent, and maintenance costs. There was also less downtime due to low cleaning and maintenance requirements and no sludge production. Water quality permit limits were met throughout the period of discharging "passively" treated water.

As of the end of 2016, the Springer Pit was achieving the removal of TSS and associated particulate metals that the WTP was installed to attain; based on the lines of evidence presented above, the water management system was altered to take advantage of this passive water treatment. Infrastructure was installed to convey water directly to the WTP as feed water. Throughout the second half of 2016, Springer Pit served as the primary treatment system to achieve the permit limits, with the WTP serving as a redundant, fail-safe system.

The mine is has been subsequently re-approved to continue mining, including its long-term water management plan. As originally envisioned in 2014, Springer Pit is being drawn down and is no longer being used in a water treatment capacity. Springer Pit is planned to be used beneficially again as part of the mine's reclamation and closure plan to store potentially acid generating waste rock and to provide passive or semi-passive water treatment.

References

Beddoes P, Herrell M, Vandenberg J, Richards J, Millar R, McMahen K (2016) Validation of Springer Pit lake water balance and water quality model, Mount Polley mine, British Columbia, Canada. Proc, IMWA 2016 Annual Conf, Leipzig, pp 251–260

Golder Associates Ltd (2015) Mount Polley Mine: Short term effluent discharge; technical assessment report in support of an effluent permit amendment. http://www2.gov.bc.ca/gov/content/environment/air-land-water/spills-environmental-emergencies/spill-incidents/past-spill-incidents/mt-polley/mount-polley-key-information

Golder Associates Ltd (2016) Mount Polley Mine tailing storage facility, perimeter embankment breach—update report: post-event environmental impact assessment report. Prepared for Mount Polley Mining Corporation. June 2016, http://www2.gov.bc.ca/gov/content/environment/air-land-water/spills-environmental-emergencies/spill-incidents/past-spill-incidents/mt-polley/mount-polley-key-information

GoldSim Consulting Group (2010) GoldSim User Manual. Redmond

Lauzon N, Vandenberg JA, Bechtold JP (2011) Probabilistic modelling applied to the mining industry to address water quality uncertainty. Proc, 19th International Congress of the Modelling and Simulation Soc of Australia and New Zealand, Perth, pp 3868–3874

Luek A, Brock C, Rowan DJ, Rasmussen JB (2014) A simplified anaerobic bioreactor for the treatment of selenium-laden discharges from non-acidic, end-pit lakes. Mine Water Environ 33(4):295–306

McCullough CD, Lund MA (2006) Opportunities for sustainable mining pit lakes in Australia. Mine Water Environ 25(4):220–226

MoE (British Columbia Ministry of Environment) (2015) Technical Guidance 7, Assessing the Design, Size, and Operation of Sediment Ponds Used in Mining. Version 1.0. June 2015

Morgenstern NR, Vick SG, Van Zyl D (2015) Report on Mount Polley tailings storage facility breach. Report of independent expert engineering investigation and review panel. Prepared on behalf of the British Columbia government and the Williams Lake and Soda Creek Indian Bands. https://www.mountpolleyreviewpanel.ca/

Nikl L, Wernick B, Van Geest J, Hughes C, McMahen K (2016) Mount Polley Mine embankment breach: overview of aquatic impacts and rehabilitation. Proc, Tailings and Mine Waste. Keystone, pp 845–856

Stumm W, Morgan JJ (1996) Aquatic chemistry, chemical equilibria and rates in natural waters, 3rd edn. John Wiley and Sons, Inc, New York City

Vandenberg J, McCullough C, Castendyk D (2015) Key issues in mine closure planning related to pit lakes. Proc, 10th International Conf on Acid Rock Drainage (ICARD) and IMWA Annual Conf, Santiago: https://www.imwa.info/docs/imwa_2015/IMWA2015_Vandenberg_156.pdf

Wetzel RG (2001) Limnology: Lake and River Ecosystems, 3rd edn. Academic Press, San Diego