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Reclamation of the Silver Bell tailings impoundment, San Juan Mountains, USA

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Abstract

The Silver Bell tailings impoundment is located in south-western Colorado in the San Juan Mountains at an elevation of approximately 2,750 m. The impoundment contains approximately 80,000 cubic metres of sulphidic, acid rock drainage (ARD) generating tailings produced during mining activities that occurred between the 1940s and 1980s. Reclamation was conducted in 1999 and 2000 under the State of Colorado's Voluntary Clean-up Program. Reclamation activities included regrading, placement of a soil cover and riprap, run-on diversions, seepage collection, and other closure activities. Total ARD seepage from the toe of the facility was approximately 0.3 L/s and following reclamation seepage decreased to generally less than 0.1 L/s.

In 2005, the State of Colorado required the seepage discharge be permitted under the State's industrial discharge permitting system. The established limits required water treatment measures to be implemented, which were not part of the initial design criteria. Therefore, hydrogeochemical characterisation and treatability studies were conducted as a follow-up to evaluate options for further dewatering the tailings to reduce seepage and/or to improve seepage water chemistry. These studies pointed to several options and actions including some that may have been undertaken if the discharge permit had been considered as part of the original design criteria.

A major finding of these investigations revealed that a large portion of the acidic and metals loading in the seepage is the result of seepage through the oxidised coarse-grained tailings that formed the shell of the impoundment. Subsequent design modifications to address the stricter discharge quality requirements included the construction of an anoxic limestone drain (ALD), aeration channel, and sedimentation/oxic limestone treatment basins, which discharge to reconstructed wetlands. High iron concentrations in the discharge, e.g. 800 mg/l, have inhibited the effectiveness of the system. Further actions that may affect the long-term water balance of the tailings and seepage loadings have included: (1) upgrading a portion of the cover to reduce infiltration; (2) installation of pilot horizontal drains to provide a more alkaline water source for blending with discharging seepage and to help dewater the tailings; and (3) construction of an upgradient dewatering trench with a solar-powered pump to intercept shallow groundwater flow that was identified as recharging the facility.

1 Introduction

The Silver Bell tailings impoundment is located in south-western Colorado in the San Juan Mountains near the town of Ophir (Figure 1). The tailings impoundment was constructed during intermittent milling of sulphidic gold ores between the 1940s and 1980s and was subsequently abandoned and left unreclaimed. The mining companies that originally constructed and operated the tailings impoundment no longer exist, and PacifiCorp, being the primary historic property owner, initiated reclamation activities beginning in the late 1990s to reduce long-term environmental impacts and increase the geotechnical and environmental stability of the tailings facility.

The tailings impoundment site is located in a remote, high-elevation (approximately 2,750 m above mean sea level) sub-alpine mountain valley that is subject to heavy winter snowfall and has no power or water supply. The impoundment contains an estimated 80,000 cubic metres (150,000 metric tons) of mill tailings within a total disturbed footprint of approximately 2.8 ha. The top surface area of the impoundment is approximately

1.1 ha, and the side slope area is approximately 0.6 ha. The tailings are pyritic (up to 20 percent pyrite) and were generating ARD that discharged during storm and snow melt runoff. A relatively small amount of ARD seepage from the toe of the tailings impoundment was also occurring at approximately 0.3 L/s.

The tailings impoundment is located on a glacially scoured bedrock surface of relatively impermeable quartzite. The tailings either sit directly on the bedrock or on a thin layer of organic soil that was likely present in depressions on the bedrock surface. The upslope areas to the south and west of the site are wooded hillsides. The east side directly abuts an approximately 10 m high cliff. The Howard Fork of the San Miguel River is below the cliff, and historically tailings had eroded over the cliff into the stream. The cliff wraps around the site to the north. However, on the north side of the site a bench is present between the Howard Fork and the impoundment that contains wetlands that also have been impacted by eroded tailings.

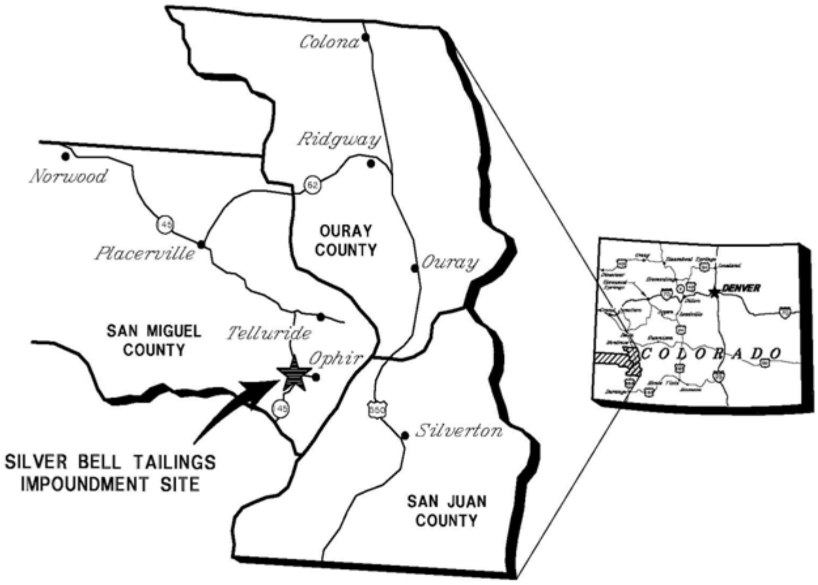

Figure 1 Site location map for the Silver Bell tailings impoundment site, Colorado, USA

PacifiCorp initiated reclamation on May 1999 by submitting an application to the Colorado Department of Public Health and Environment (CDPHE) entitled *Voluntary Cleanup and Redevelopment Act Application for Silver Bell Tailings Impoundment, Ophir, Colorado*. Based on the approval of this application, PacifiCorp hired MWH Americas, Inc. (MWH) to perform activities to both characterise and reclaim the tailings impoundment, to decrease erosion, and to achieve increased geotechnical stability. A goal of the project was to reduce sediment and chemical impacts from the impoundment to Howard Fork. However, when the voluntary cleanup application was initially approved, a stormwater discharge permit was the only water quality related requirement (so long as tailings were left exposed). A more restrictive industrial discharge permit was not required for the relatively low volume of tailings seepage that was occurring.

The following reclamation activities were performed between 1999 and 2000 as a means to reduce long-term environmental impacts and create a more stable facility:

- Installation of sediment and erosion control measures.
- Collection and placement of eroded tailings on the upper surface of the impoundment.
- Tailings regrading.
- Installation of a seepage collection drain system.
- Topsoil placement (minimum of 0.8 m of organic-rich top soil) on the upper surface and revegetation.

- Riprap placement.
- Construction of stormwater diversion channels.
- Wetland reconstruction.
- Construction of sediment ponds.

Opposed to a soil cover, a geotextile and riprap cover was placed on east facing slopes directly abutting the cliff and Howard Fork stream. This was because the cliff and stream resulted in the inability to push the tailings down making regrading difficult. In addition, there were concerns of cover soil erosion on the steep slope to Howard Fork. The resulting features and configuration are shown on Figure 2. The focus of remedial and reclamation activities at the site has been on passive remedies due to the remote location and difficult winter conditions. Visibility from the State highway is an additional consideration, and efforts have been made to reduce the visual impact of the facility because of its location in a scenic area. For example, efforts have included items such as camouflaging stairways and reducing overall visual impacts.

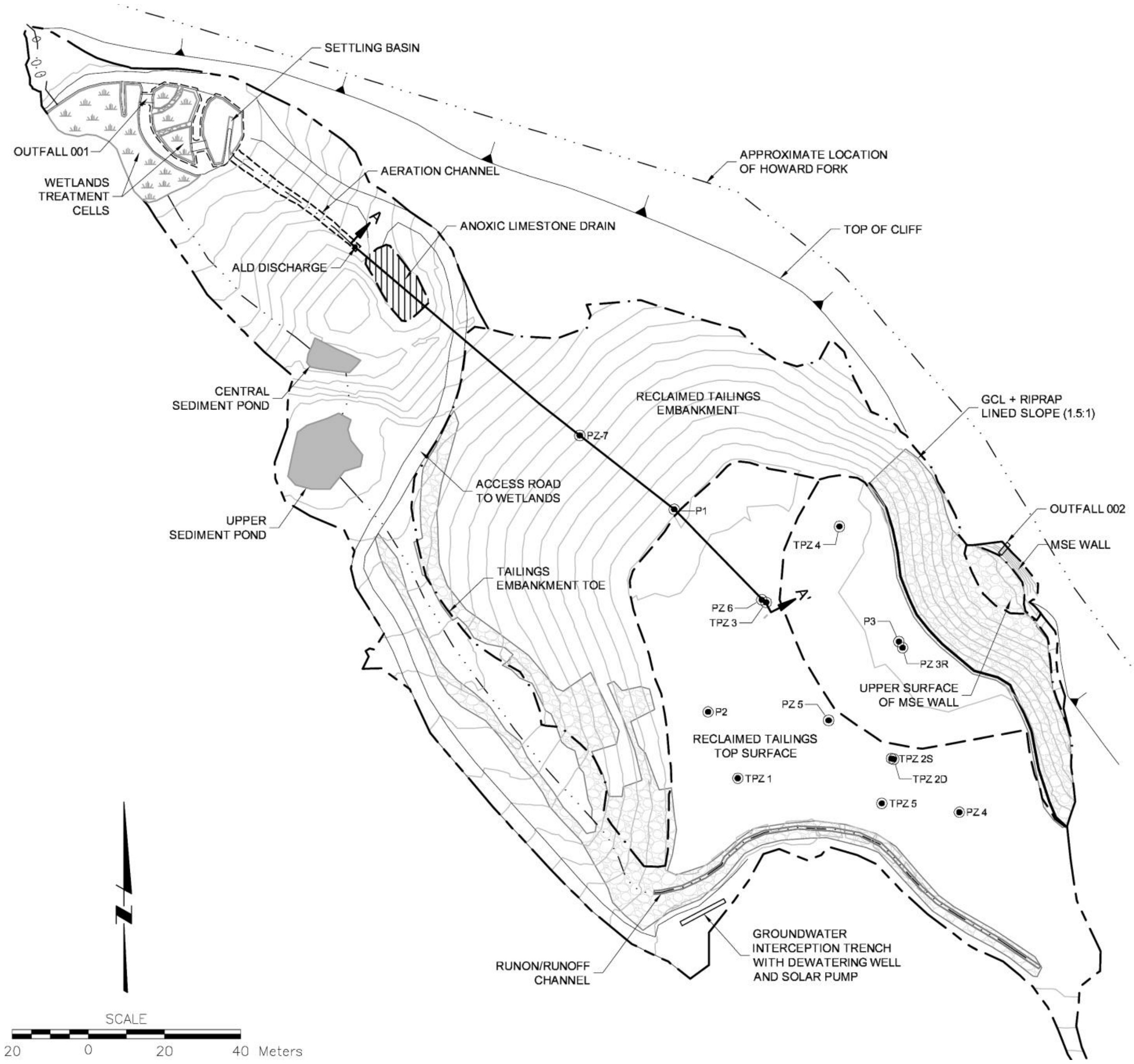

Figure 2 Schematic of Silver Bell tailings impoundment configuration following initial and follow-up reclamation activities; piezometers (P, PZ and TPZ) are shown, as well as the location of cross-section A – A' that is presented as Figure 3

The State of Colorado issued an industrial discharge permit for the site regulating two seepage discharges from the tailings facility on October 1, 2005. The discharge outfalls were identified as Outfalls 001 and 002, which included the North Seep and East Seep discharges, respectively. The Outfall 001 monitoring location included discharge from the original toe seep (Seep-4) and from the perimeter seepage collection system that was routed to the toe seep location. Collectively these flows are now know as the North Seep and are routed through an Anoxic Limestone Drain (ALD). Flow from the North Seep location had dropped from approximately 0.25 to 0.06 L/s as the result of the reclamation activities completed between 1999 and 2000. The Outfall 002 location is associated with seepage occurring along the cliff face on the eastern boundary of the site. Historically, discharge from this area has been diffuse and difficult to monitor. However, the average discharge appears to have been less than approximately 0.03 L/s.

The key permit limits for the seepage discharge at Outfall 001 are:

- 433 mg/L iron.
- 883 mg/L manganese.
- 18.7 mg/L zinc.
- 30 mg/L total suspended solids (TSS).
- 0.18 L/s flow.

Outfall 002 is under a ‘monitoring only’ condition without permit limits because of the lower, difficult to monitor, discharge.

The Outfall 001 compliance point is generally located between the ALD discharge and the receiving water (Howard Fork). The limits were set relatively high because of the ability of Howard Fork to assimilate the relatively low flow and loadings from the site. The pH limit was originally set at between 6.5 and 9. However, PacifiCorp and MWH were able to demonstrate that the acidity could be assimilated by Howard Fork, and the pH limit was adjusted to 3.9–9.5 in 2010.

Best management practices (BMPs) were incorporated into the initial closure design to address site seepage discharges. These included the seepage collection system, a small limestone drain, sediment basins, as well as reconstructed and enhanced wetlands. However, because the new permit limits were not included as design criteria, these measures were not intended, nor were they sufficient, to meet the permit limits imposed in October 2005. This was recognised in the permitting by the State of Colorado, and PacifiCorp was given slightly more than four years to monitor and modify the site to achieve the limits. This paper describes some of the supplemental characterisation studies and actions taken to retrofit the tailings closure to account for the imposed discharge limits that were established after reclamation activities had largely been completed.

2 Supplemental site characterisation

During the summer of 2008, in response to the modification of the discharge requirements, an additional hydrogeochemical characterisation programme was initiated. The focus of this characterisation programme was to identify the sources of water and ARD contributing to the tailings seepage. The data from the characterisation programme helped develop additional remedial measures to improve water quality and/or reduce seepage rates. The previous characterisation efforts were largely focused on geotechnical properties.

The primary characterisation tool used in 2008 was direct-push soil sampling and piezometer installation within the direct-push boreholes. The piezometers are PVC plastic pipe with short screened sections. Five new permanent piezometers were installed to complement three existing piezometers to provide long-term piezometric data. In addition, six temporary piezometers were installed to provide more complete coverage during the characterisation period. Nested pairs of piezometers were installed at two locations to evaluate vertical hydraulic gradients. Tailings samples were collected from the borings and submitted for chemical analyses that included acid-base accounting (ABA), paste pH, and synthetic precipitation leaching procedure (SPLP) metals analyses. In addition, tailings porewaters were collected from the piezometers for water quality analyses.

2.1 Hydrogeological characterisation

A key objective of the hydrogeologic characterisation of the tailings impoundment was identification of potential areas of recharge to the impoundment. Water balance calculations suggested that discharge from the facility was in excess of what was anticipated given the climatic factors, reclaimed impoundment configuration and cover material. It had been hypothesised for some time that the facility was being recharged by a buried spring that was contributing to the tailings seepage. The vertical gradients at key locations were downward, which did not suggest a major source of recharge from beneath the tailings. However, piezometric water levels in TPZ-1 located in the south-western corner of the impoundment appeared elevated (see Figure 2 for piezometer locations). In addition, difficulties in establishing vegetation on the embankment near TPZ-1 may have been related to tailings ARD seepage into the soil cover.

The piezometric mound at TPZ-1 was adjacent to a swale in the hillside where bedrock atypically is not exposed. A trench was excavated in this area just outside of the tailings impoundment during summer 2009 (Figure 2). An approximately 5.5 m deep soil-filled incision was found in the bedrock surface. At the time of the excavation, groundwater was flowing into the trench from the uphill side. It appears that groundwater in this soil-filled bedrock incision is channelled and flows beneath the surface run-on diversion and recharges the impoundment. Subsequent dewatering system piezometric monitoring in the spring of 2010 indicated that the water level at this location was a mere 0.3 m below ground surface, but dried up in the late fall.

2.2 Geochemical and hydrochemical characterisation

Six tailings samples were collected during the drilling of piezometers and submitted for the analysis of ABA parameters and metals using SPLP extraction. The pH of the tailings was measured using the paste pH method along with the pH of the SPLP leachate. The samples were collected from the boreholes for piezometers PZ-6 and PZ-7. The PZ-6 borehole is located at the top of the northern embankment above the ALD, and PZ-7 is located about midway down the embankment slope between the ALD and PZ-6 (Figures 2 and 3). Table 1 presents the analytical results for these samples.

The PZ-7 borehole was advanced at a slight angle from vertical into the tailings impoundment. Oxidised tailings were noted to a depth of approximately 4.0 m below ground surface. Two samples were collected in the oxidised tailings, and a third sample was collected in the deeper unoxidised tailings. This is expressed in the analytical results with the shallower two samples being depleted or nearly depleted neutralisation potential. The presence of unoxidised tailings is indicated in the deep sample by the occurrence of both acid neutralisation and acid generation potential. Neither is depleted. The shallower samples also have acidic pH and higher concentrations of SPLP leachable metals.

The PZ-6 borehole is located on the crest of the tailings embankment and has only a thin layer of oxidised tailings. This is evident by a depleted neutralisation potential in the shallow sample and an acidic pH, whereas the deeper samples have significant neutralisation potential remaining. The concentrations of SPLP leachable metals are between one and two orders of magnitude higher in the oxidised tailings sample except for manganese.

Figure 3 also shows water quality data for pH, iron and sulphate for piezometers PZ-6 and PZ-7, as well as the older P-1 piezometer, the ALD discharge, and historical pre-2006 data for Seep-4. Seep-4 was the tailings seepage discharge location prior to construction of the ALD. Table 2 presents data for additional analytes and includes additional piezometer locations in the central portion of the impoundment (P-2, PZ-3R, PZ-4, and PZ-5 as shown in Figure 2).

Table 1 ABA and SPLP results from Silver Bell tailings piezometer borings

Analysis	Boring	PZ-7			PZ-6		
	Depth (m):	0.6–1.2	3.0–3.7	6.0–6.7	0.9–2.1	3.0–4.6	10.7–12.2
Acid Base Accounting							
Sulphur Residual (%)		1.53	1.79	0.34	6.15	0.76	0.55
Sulphur Pyritic Sulphide (%)		2.73	3.21	1.08	8.88	8.07	2.12
Sulphur Sulphate (%)		1.31	0.79	0.34	0.67	0.36	0.27
Sulphur Total (%)		5.57	5.79	1.76	15.7	9.19	2.94
Total Sulphur minus Sulphate (%)		4.26	5.00	1.42	15.0	8.83	2.67
Neutralisation Potential as $CaCO_3$ (%)		< 0.1	0.7	7.2	<0.1	8.8	5.6
Acid Generation Potential[1] (t $CaCO_3$/Kt)		133	156	44	469	276	83
Acid Neutralisation Potential (t $CaCO_3$/Kt)		<1	7	72	<1	88	56
Acid-Base Potential[1] (t $CaCO_3$/Kt)		-133	-149	28	-469	-188	-27
Paste pH (s.u.)		2.7	4.1	6.6	4.0	7.1	7.0
Synthetic Precipitation Leach Procedure (pH and Metals)							
pH (post extraction/pre-filter) (s.u.)		3.1	4.5	6.7	4.5	7.2	7.9
Aluminium (mg/L)		5.55	2.54	<0.03	2.24	<0.03	0.04
Iron (mg/L)		3.93	13.1	0.03	9.99	<0.02	<0.02
Manganese (mg/L)		8.76	25.2	5.05	10.70	11.7	0.369
Zinc (mg/L)		1.45	2.83	0.05	11.40	1.78	0.07

Boring depths are measured in meters below ground surface.

[1] - Acid Generation and Acid-Base Potential calculations are from total sulphur minus sulphate.

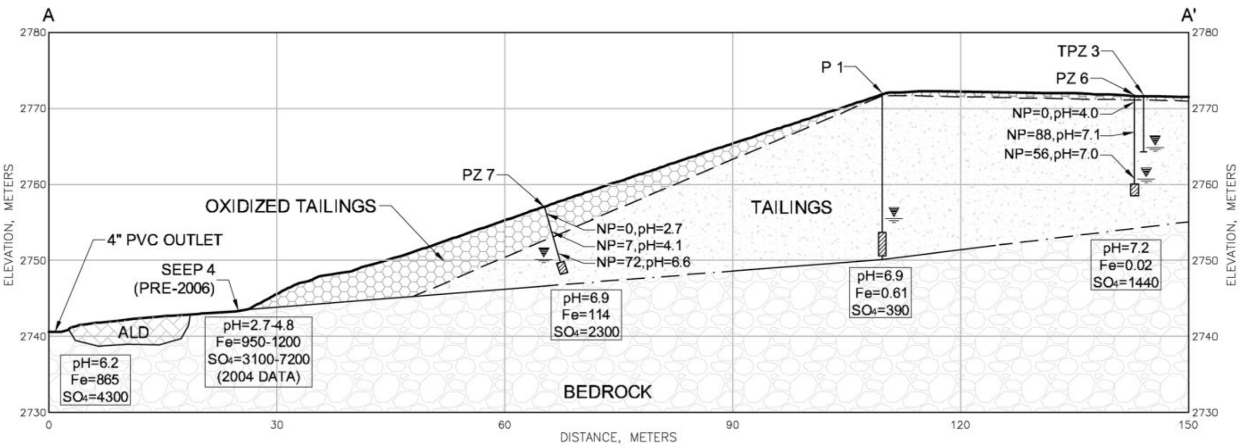

Figure 3 Longitudinal cross-section through northern Silver Bell tailings embankment showing ABA neutralisation potential (NP) and paste pH and water quality results (in boxes); cross-section location is shown on Figure 2 and is oriented in a northwest to southeast direction

Table 2 Porewater chemistry of tailings within the impoundment

Sample Location	Analytical Results (mg/L)						
	Aluminium	Calcium	Iron	Manganese	Zinc	Sulphate	pH (s.u.)
P-1	0.04	98.4	0.61	1.99	<0.05	390	6.90
P-2	0.49	343	26.7	14.0	0.36	1,910	5.80
PZ-3R	<0.03	453	46.8	1.11	<0.05	3,900	6.78
PZ-4	<0.03	466	165	5.79	0.55	2,800	6.80
PZ-5	0.05	538	17.9	3.07	0.09	1,910	6.83
PZ-6	0.07	470	0.02	1.11	<0.05	1,440	7.22
PZ-7	<0.03	550	114	12.8	0.36	2,300	6.85
ALD	1.3	466	865	306	16.4	4,300	6.18

Samples collected in July 2008.
P and PZ locations are piezometers, ALD is north anoxic limestone drain discharge.
All analyses are dissolved fraction (field filtered) and pH was measured in the field.

The tailings porewater is generally characteristic of anoxic, neutralised ARD that contains elevated concentrations of calcium, iron, and sulphate. It may contain pre-reclamation water given the fine-grained and relatively low permeability of the tailings. Water discharging from the ALD has notably higher acidity, metals and sulphate concentrations. Seepage flows from hydraulically upgradient of the ALD are no longer accessible for sampling. However, data from the Seep-4 location, which was the seepage discharge location prior to construction of the ALD, exhibited pH measurement in the range of 2.7 to 4.5, iron from 950 to 1,200 mg/L, and sulphate from 3,100 to 7,200 mg/L. It appears that the water that discharges as seepage picks up substantial metals loading from the oxidised tailings. It is possible that much of this loading is related to the dissolution of existing ARD products stored in the oxidised tailings as opposed to new ARD generation within the finer grained saturated tailings in the impoundment. The organic-rich soil cover should have greatly restricted the influx of oxygen and water; however, this has not been verified by data other than the reduction in seepage flows.

3 Follow-on remedial actions

Even though discharge permit limits are relatively high for the site, reliable long-term compliance with the limits for iron, pH and TSS remained uncertain. The difficulty in compliance with pH was largely resolved when the lower pH limit was dropped to a pH of 3.9. However, to reliably meet all the permit limits, and possibly terminate the permit altogether at some point in the future, additional remedial measures were evaluated and implemented. These measures fell into two broad categories: source controls and treatment.

3.1 Source control measures

New or modified source measures were constructed between 2008 and 2010. These measures included:

- Modification of the cover system on the eastern portion of the impoundment where riprap was utilised as cover.
- Installation of horizontal drains.
- Construction of a dewatering system that included a cutoff trench and dewatering well.

In 2008, a retaining wall was constructed on the eastern edge of the impoundment where the impoundment ran directly up to the edge of the cliff above Howard Fork. Tailings had eroded and deposited along the stream, and the tailings adjacent to the stream were relocated back to the impoundment as part of the construction efforts. Riprap had been placed over the geotextile where runoff reported to the eastern impoundment edge. As part of the retaining wall construction, the riprap and geotexile were removed. A soil cover was placed on the area with a shallower slope. On the steeper portion of the slope, a geosynthetic clay liner (GCL) designed for steep slopes replaced the geotextile. Riprap along with protective bedding was placed atop the GCL. These modifications will reduce the infiltration into the tailings and presumably the discharge from the East Seep (Outfall 002) and potentially also the North Seep (Outfall 001).

Because the tailings porewater upstream of the oxidised outer shell of the impoundment contained alkalinity and was of better quality than the seepage, the concept of horizontal drain installation was tested. The horizontal drains would provide two benefits. They would reduce the driving head for the seepage, and the more alkaline water could be blended with the ARD seepage to reduce the acidity of the combined discharge. Hydrogeologic analysis suggested that a few drains might be able to yield sufficient porewater to provide a significant water quality benefit. However, the uncertainty associated with the net permeability of the tailings was large enough that obtaining sufficient yield from a reasonable number of drains was also uncertain. Two drains were installed that screened across most of the impoundment width north to south and upgradient of the oxidised tailings. The combined yield was less than 0.02 L/s, which decreased with time. The decision was made not to install any additional horizontal drains as they were not cost-effective.

The third source control action was the construction of a dewatering system that included the installation of a cutoff trench in which a dewatering well was placed. The trench was constructed in the soil filled bedrock incision described in Section 2.1. The trench was backfilled with gravel around the dewatering well and included a plastic liner placed on the downgradient side of the trench. The State of Colorado Division of Water Resources required a permit for the system, and the discharge had to be routed downstream of the tailings facility to ensure there was no consumptive use of groundwater through evaporation.

The dewatering system well was fitted with a solar-powered pump and discharge pipe during the summer of 2010. This system is designed to reduce the amount of water entering the tailings impoundment that eventually reports as seepage. The effect of this drain will be evaluated during 2011. It is thought that recharge to the tailings in this area has significantly contributed to the tailings seepage. Some difficulty in vegetation establishment in this area may have been the result of mid-slope seepage into the tailings cover. In addition, water flowing into and through the oxidised rind of tailings in this area reports directly to the perimeter drainage system that discharges through the North Seep. The interception of the recharge should directly work to help reduce the elevated piezometric conditions in this area of the tailings impoundment, and therefore, the associated discharge.

It is hoped that the dewatering system along with continued discharge from the horizontal drains and improved cover will eventually reduce the amount of water discharging through the impoundment. Monitoring in 2011 and beyond will determine if these actions have had a beneficial effect. The reduced flow would enhance the water treatment measures and may eventually allow for the termination of the discharge permit.

3.2 Water treatment measures

In anticipation of discharge permit issuance in 2005, PacifiCorp also discussed with the State of Colorado additional BMPs that could be implemented for increasing the pH in water being discharged at Outfall 001. As a result of these discussions, PacifiCorp moved forward with plans to install an ALD that would increase the pH of the tailings impoundment seepage. An ALD was constructed in a location of an existing stormwater pond in June 2006.

The ALD is approximately 7.6 m wide and 10.7 m long (see Figure 2) with an average depth of about 1.8 m. Construction of the ALD in the stormwater pond included dewatering of the pond, installation of piping for collecting and delivering tailings impoundment seepage to the ALD, installation of a seepage distribution header in the pond bottom, filling of the ALD excavation with 40 to 50 mm crushed limestone, and installation of an outlet line. The upper limestone surface was covered with a geotextile fabric and high density polyethylene liner over which 91.4 cm of locally available fill material was placed. By late October 2006, the voids within the ALD had filled with the seepage and discharge from the ALD had begun.

The pH and water quality data have been collected to assess performance of the ALD and the overall discharge system. Data show that the ALD is increasing the pH of the seepage passively from as low as 2.5 to consistently greater than 6.0. However, the discharge through Outfall 001 was monitored at the outlet of the wetlands, and the limits for pH and flow were commonly exceeded, prior to 2010 the lower pH limit was 6.5. In a large part this was due to flows entering the wetlands from off-site areas.

Additional reclamation activities were completed in 2007 and 2008. The focus of these activities was to construct the retaining wall and to improve on existing water treatment systems. One of the main objectives of the 2007/2008 construction was to eliminate any significant remaining areas of stormwater contact with the tailings material. This was accomplished through the retaining wall and GCL placement described in Section 3.1. As a result of these actions, the stormwater permit was terminated for the site.

The other water treatment improvements that were implemented in 2007/2008 included:

- Construction of additional treatment cells to provide further passive treatment prior to the seepage entering the wetland area.
- Integration of an additional limestone drain as a BMP for the East Seep discharge (Outfall 002).

To specifically address the discharge through Outfall 001, treatment cells were constructed in the area between the wetland and ALD to provide additional passive treatment for the seepage prior to entering the wetland and mixing with the off-site flows. Two treatment cells were created. The first receives the ALD discharge and is intended to settle the iron and other metals that precipitate as the result of increased pH from the ALD. The second area includes flow-through limestone berms to provide additional water quality polishing. The water from the second cell discharges into the existing well-vegetated wetlands area which also receives other acidic off-site inflows. A weir was placed after the second treatment cell for Outfall 001 monitoring. This location is identified in Figure 2.

Primarily due to the effectiveness of the ALD and settling time prior to the discharge, the three regulated metals (iron, manganese, and zinc) have successfully been reduced to below permit limits in the seepage. Manganese and zinc in particular have consistently met the permit limits and are expected to continue to do so as long as the ALD and treatment (settling) cells are functioning and iron is precipitating. The reported iron concentrations have generally been below the permit limit downstream of the ALD. However, because the total recoverable fraction is being monitored, iron has exceeded the permit limit when TSS is high. This has not occurred since 2009. It is anticipated that the ALD will have to be rebuilt in the future to address the accumulation of precipitants within the unit.

The occurrence of elevated TSS and iron is a function of settling. The settling function was disrupted in the spring of 2009 when additional flow seeped into the settling and treatment areas apparently through the berms constructed of low permeability materials. The increased flow resulted in exceedances of the permit limits for flow, iron and TSS. When TSS and iron are above permit limits at Outfall 001, the additional settling capacity in the wetlands assists in lowering these constituents before the flow enters the Howard Fork. However, flow also exceeds the permit limit in these areas downstream of the current Outfall 001 monitoring locations (the weir) especially during spring runoff. The flow limit is an important consideration, because the relatively high concentration limits are based on a low discharge from the site. Consistently exceeding the flow limit could result in lower permit limits for metals. Therefore, limiting the monitored flow to only seepage is an important consideration.

In addition to the TSS issues discussed above, it was difficult to meet the pH limit of 6.5 in the discharge because of the iron precipitation. Iron precipitates in the system as a hydroxide (OH^-), e.g. $Fe(OH)_3$. This process generates acidity because of the reaction of water forming hydrogen ions and a hydroxyl ion. Excess hydrogen ions remain in the water decreasing the pH. Water emerges from the ALD with near neutral pH and reduced ferrous iron. When exposed to oxygen, the iron oxidises to ferric iron, combines with hydroxyl ions and precipitates. If the increase in acidity is offset by sufficient alkalinity, the pH will be stable. However, without sufficient alkalinity, the pH drops. This has proven to be difficult to manage in the ALD discharge owing to the iron concentrations that can exceed 800 mg/L. The limited surface area and shallow bedrock restricts the opportunities to construct additional passive elements such as successive alkalinity producing dystem (SAPS) for example.

The modifications conducted in 2008 and 2009 were directed at addressing the TSS issue and increasing the pH of the discharge while continuing to reduce the metals concentrations. To help control TSS during spring snow melt, the setting pond and treatment cells were lined to help direct flow through the weir and control seepage into the settling and treatment cells. Now only minimal surface runoff contributes to additional flow to the settling/treatment cells. To achieve a sustainable pH of between 6.5 and 9.0 at the weir discharge monitoring point (Outfall 001), attempts have been made to add alkalinity to the system prior to or during the iron settling phase. The amount of alkalinity that can be added to the system by the ALD is chemically limited and is not sufficient to offset the decrease in pH caused by the iron precipitation. Therefore, the following additional options were tested:

- Rejuvenation of flow-through limestone berms in the downstream treatment cells.
- Addition of activated red mud to add alkalinity and to adsorb metals.
- Installation of two horizontal drains in the impoundment in order to increase the discharge of water from the non-oxidised portions, which would increase the alkalinity, as well as reduce seepage over the long-term.

None of these options resulted in the ability to consistently maintain the pH above the minimum limit of 6.5. The limestone berms quickly become coated by iron hydroxides and lose their effectiveness. In pilot testing, the activated red mud had almost no effect on alkalinity and did not result in additional iron precipitation. Flow from the horizontal drains was insufficient to increase alkalinity and offset the reduction in pH. The pH issue was addressed administratively in 2010 with a modification of the permit to include a lower pH limit of 3.9. This adjustment was allowed based on PacifiCorp and MWH demonstrating that the assimilative capacity of the receiving water was sufficient and that a lower pH limit could be justified.

The TSS issue (i.e. periodically exceeding permits limits) continues to be a difficulty. The issue is largely confined to sampling during the winter months. Breaking though the ice to sample disturbs the pond sediments raising the turbidity of the water. However, less oxygen being available for iron precipitation also may be resulting in an increase in iron hydroxide precipitation, and thereby, higher TSS once the samples are exposed to the air during sampling. Ways to address the TSS issue will be evaluated in the future.

4 Conclusions

The Silver Bell tailings impoundment voluntary cleanup has been successful and the State of Colorado has indicated that the site will be formally closed with respect to the voluntary cleanup program in 2011. PacifiCorp, the State of Colorado, San Miguel County, and Federal officials all worked together cooperatively to make the project a success and provide a benefit to the San Miguel watershed. The addition of having to comply with industrial discharge permit limits, imposed six years after the initial reclamation, presented some challenges that have been addressed.

Treatment of the seepage from the Silver Bell tailings impoundment was not an initial focus of the site reclamation and closure. The discharge rates were low and tailings erosion and runoff were a far greater concern. However, the subsequent issuance of the industrial discharge permit for the site by the State of Colorado resulted in the need to re-evaluate the reclaimed facility and develop new water management actions. Adjustments to the site reclamation have been made to comply with the permit limits, and the additional actions aimed at addressing the seepage water quality appear to have been largely effective. However, a couple of years of additional monitoring are needed to verify the effectiveness of these additional actions. Had the seepage water quality been a major concern during the initial reclamation, the issue would likely have been addressed more effectively.

Currently, the most significant factor resulting in the ARD issuing from the impoundment appears to be the oxidised tailings that formed the outer shell of the tailings impoundment. Compounding the issue is the normal construction practice of pushing down the tailings to achieve a stable slope. This essentially placed more tailings with ARD products along the toe of the facility in contact with the tailings discharge. Had the seepage water quality issue been anticipated during the initial reclamation of the impoundment, additional measures could have been incorporated into the closure. For example, because of the relatively small size of the facility, it may have been economically possible to neutralise the layer of oxidised tailings with lime or other neutralising agent prior to regrading. The application could have been incorporated into the regrading effort. Such an action is more difficult now considering that regrading has already been completed and the embankment cover has been successfully vegetated and now has a mature cover.

Acknowledgements

PacifiCorp deserves special recognition for the Silver Bell Tailings Reclamation Project for their willingness to go above and beyond as part of the voluntary clean-up of the tailings impoundment and facilitate project success. This has included a willingness to work to improve upon the closure where opportunities have been identified. The State of Colorado and the local officials also should be recognised for their cooperative approach that helped make the project a success.