Assessment of Legacy Contaminant Remediation at the Phoenix Mine, Nevada

Robert M. St. Louis

Newmont Mining Corporation, 1655 Mountain City Highway, Elko, NV 89801

Abstract Groundwater underlying a pre-regulatory gold tailings storage facility (TSF) was impacted when a previous mine operator utilized calcium hypochlorite to neutralize cyanide in the tailings. In anticipation of a planned expansion of the current copper TSF, a desk top study was conducted which examined the effectiveness of on-going chloride remediation, currently being effected through the use of extraction wells. An integrated approach utilizing hydrogeology, water chemistry, geology and geophysics was employed to complete the study, and achieved reduction in the chloride mass is consistent with earlier numerical predictions. Replacement remediation well locations have been selected. Clarification of misconceptions regarding processing limitations with respect to chloride content of make-up water has resulted in a water management plan that allows for better utilization of impacted water in on-going processing operations.

Keywords Gold tailings, groundwater, remediation, hydrogeology, chloride contamination

Introduction

This paper reviews the findings of an integrated study that analyzed the progress made in remediating legacy chloride-impacted groundwater underlying a tailings storage facility (TSF) at Newmont Mining Corporation's (Newmont) Phoenix mine in Lander county, Nevada U.S.A. In addition, with a planned expansion to the TSF being considered, an evaluation of the optimal locations of new remediation well sites has been made and a revised water management plan has been developed that will allow for better utilization of chloride-impacted water in processing operations.

The Phoenix mine is approximately 20 mi (33 km) southwest of Battle Mountain, Nevada (fig. 1). In 1978 a previous mine operator transitioned from copper to gold recovery, utilizing carbon-in-leach recovery technology. The tailings were stored in an un-lined TSF; at the time the facility was constructed, regulations governing construction standards and operating requirements for tailings impoundments had not been promulgated. Furthermore cyanide neutralization, using calcium hypochlorite as the neutralization agent, was commissioned in 1979. Groundwater approximately 75 ft (23 m) beneath the TSF (fig. 1) was soon found to be impacted by chloride, and shortly afterwards a groundwater remediation plan was filed with Nevada environmental regulators. To-date elevated chloride concentrations have not been detected in groundwater deeper than 400 ft (122 m) below ground surface.

Three wells (CM-2, CM-3, and CM-4 on fig. 2) were installed at the downslope toe of the tailings embankment in 1979 to intercept and extract chloride-impacted groundwater that had percolated through the vadose zone from the unlined TSF. An older water supply well (CM-1) near the southwest corner of the TSF (fig. 2) was also dedicated to the remediation effort. Gold processing operations were terminated in March 1993, and the gold tailings were covered and vegetated. A number of hydrogeologic studies were conducted between 1991 and 1996 to assess the extent of the impacted groundwater, and to provide guidance for remediation.

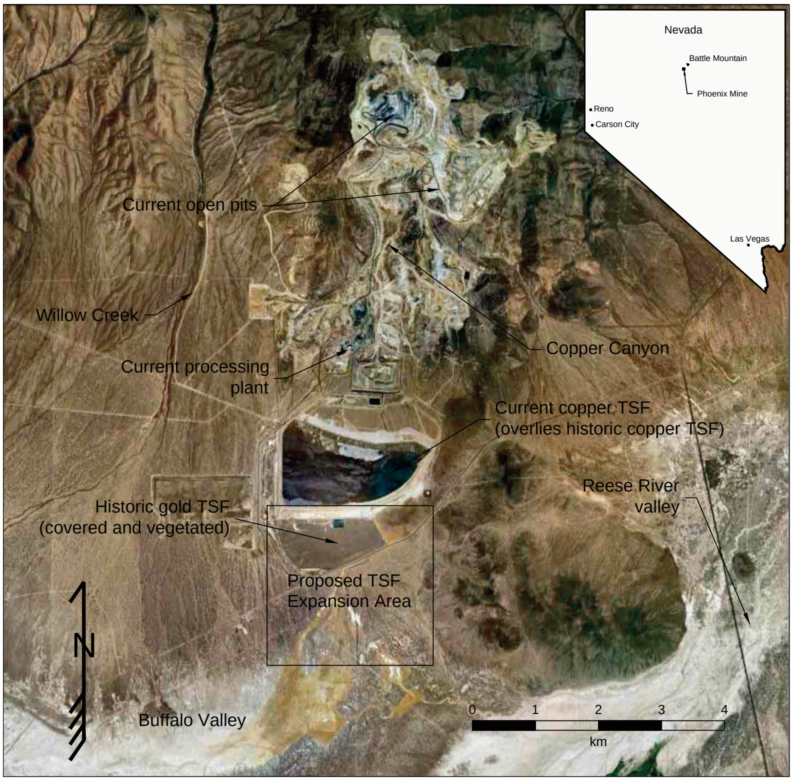

Fig. 1 Location map and 2010 Google Earth image of the Phoenix operations with key points of reference.

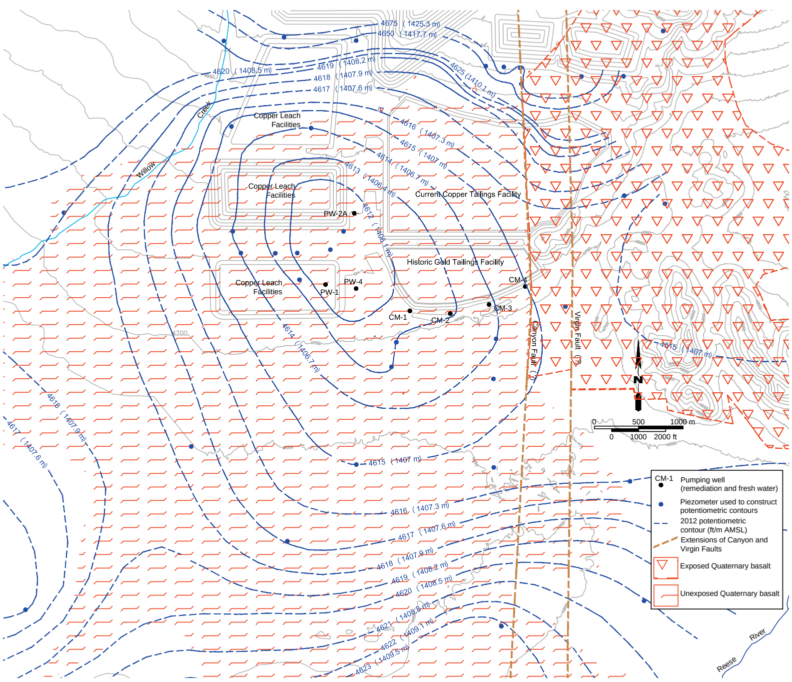

Fig. 2 Potentiometric contours (based on end of 2012 water levels), extent of exposed and unexposed Quaternary basalt, and aeromagnetically-inferred extensions of the Canyon and Virgin Faults. Note that the contour interval changes in the northern portion of the area shown.

Newmont acquired the property in the year 2000 and plans to expand the existing TSF over and to the south of the historic gold tailings. The expanded TSF will employ a synthetic liner with under-drainage leachate collection, which should eliminate future meteoric infiltration through the historic gold tailings. The planned expansion will require the abandonment of the existing remediation wells, and hence the construction of new wells to continue remediation efforts is required.

Hydrogeology

The TSF overlies a broad alluvial fan about 3 mi (5 km) south of the mouth of Copper Canyon, within the Buffalo Valley hydrologic basin (fig. 1). Copper Canyon trends north-south, with its head in the uplands of the Battle Mountain Range, and contains the bulk of the current and historic mines in the district. The hydrologic basin boundary between the Lower Reese River Valley and Buffalo Valley basins is just east of the TSF.

Buffalo Valley basin is a closed desert basin with no surface-water outlet. Lower Reese River Valley basin is open with both surface and subsurface water flow directed northward to the Humboldt River. The climate in the Phoenix mine area is arid, with annual average precipitation of 7 to 12 in (180 to 300 mm), depending on elevation. Pan evaporation exceeds 60 in (1,500 mm) per year in the vicinity of the TSF (JBR Environmental Consultants 2011).

The alluvial sequence beneath the TSF is typical of Nevada's Basin and Range physiographic province, comprising sand, silt, clay and gravel (ranging from very fine to boulders in size). Porosity within the alluvial sequence is generally 30 %. Contained within the alluvial sequence is a Quaternary-aged volcanic sequence consisting primarily of basalts and basaltic tuffs. Basalt is exposed just east of the TSF (fig. 2), but this sequence is covered by 150 to 500 ft (46 to 152 m) of alluvium in the vicinity of the TSF. Depth to groundwater ranges from 18 ft (6 m) down-gradient of the TSF to 160 ft (50 m) in the up-gradient direction. In the immediate vicinity of the TSF, groundwater is 75 ft (23 m) below the original ground surface. Potentiometric contours for water elevations (AMSL) at the end of 2012 are shown in fig. 2.

Simon Hydro-Search (1993) determined that the horizontal groundwater gradient within the alluvial sequence beneath the TSF was 1.6×10^{-4} to the southwest, with an estimated hydraulic conductivity of 55 ft/d (17 m/d). Even though the hydraulic conductivity was determined to be high, the very low hydraulic gradient resulted in extremely slow movement of the chloride plume, estimated to be about 20 ft/a (6 m/a) under steady-state conditions (Simon Hydro-Search 1993).

Sources of data

In addition to reports prepared by and for the previous operator, a significant database of water-level measurements and chloride analyses is available for a number of wells and piezometers. However, gaps in these data sets have resulted from

- inconsistent sampling and water-level measurements,
- abandoned or damaged monitoring points, and
- the lack of any monitoring within the TSF footprint.

In addition, pumping data were available only as monthly averages derived from totalizer readings, and comprehensive pumping data were only available after 2001.

Three of the remediation wells (CM-2, CM-3, and CM-4) produced relatively low volumes of water, ranging from 27 to 60 gpm (2 to 4 L/s). Furthermore these three wells have discharge lines that are exposed and relatively small diameter that could quickly freeze during cold weather if pumping were interrupted. As power bumps are fairly common at Phoenix, these wells are often turned off during the winter months to prevent freezing of discharge lines. In the past, remediation wells had also been turned off during times of high chloride production, because it was then incorrectly believed that the copper flotation circuit could not tolerate the high chloride water.

Geologic logs of borings for the remediation wells, three fresh water wells, two piezometers and five boreholes were used to interpret the upper surface of the unexposed

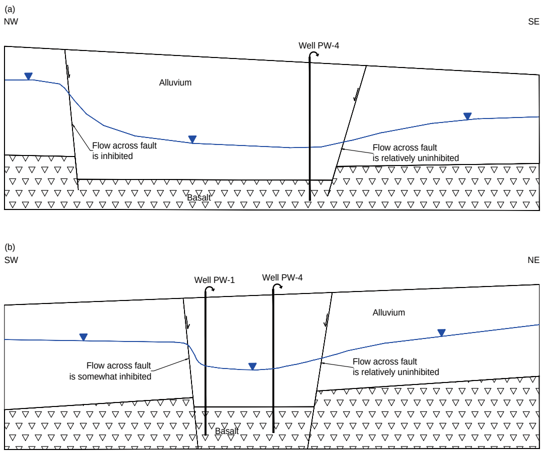

Fig. 3 *Conceptual cross-sections parallel to groundwater flow resulting from the pumping wells (a) and perpendicular to flow (b). Note how fabric developed in alluvium during faulting as well as juxtaposition of different facies across faults creates slightly lower K zones along some faults, but not others. Vertical scale is exaggerated.*

Quaternary basalts. Aeromagnetic data (reduced to pole, with second vertical derivative, rendered in gray) were used to identify the extent of unexposed Quaternary volcanic units, and to identify the presence of probable unmapped faults.

The conceptual hydrogeologic model is shown in schematic cross-sections in fig. 3. Fig. 3a is oriented northwest-southeast through the center of the composite cone of depression (shown in fig. 2), and fig. 3b is oriented northeast-southwest. The two lines of section intersect at fresh water well PW-4. Note that the potentiometric surface in these sections is vertically exaggerated to better illustrate the conceptual model.

The asymmetry in the composite cone of depression (fig. 2) indicates lateral anisotropy. Faulting is inferred to have produced fabrics within the alluvial sequence, and has presumably juxtaposed facies with different K across some faults. These fabrics/juxtaposed facies create preferred flow directions as a result of slightly decreased K across some of the faults.

Methods

Groundwater sampling wells, which included both fresh water and remediation wells, were grouped according to their baseline geometric mean chloride concentrations. Baseline was defined as the period 1993 to 1998 because work performed by Simon Hydro-Search (1993) demonstrated that this represented the time required for residual percolation of chloride-impacted water through the vadose zone beneath the TSF. Five distinct groupings were determined from the baseline data (Table 1). The Well Group High consisted of three remediation wells (CM-2, CM-3, and CM-4). The Well Group Medium included CM-4 and three monitor wells; the Well Group Medium-low contained one monitoring well and a fresh water well PW-4; the Well Group Low included fresh water wells PW-1 and PW-2A and eight monitoring wells. The Well Group Low-low consisted of 14 monitoring wells. In order to minimize the effects of outliers within the data, largely resulting from the sporadic pumping of the remediation wells, chloride analyses were composited for each group over multiple-year increments (1993–1998, 1999–2004, 2005–2009 and 2010–2012).

Chloride-concentration data were contoured for the baseline period, the recent period (2010–2012), and the change in chloride concentrations between the two periods. Change in chloride concentration contours are illustrated in fig. 4. Note that many sampling wells have been constructed after the baseline

Well Group	Wells (n)	1993 – 1998 Composite Max.	Min.	Geo. Mean	2010 – 2012 Composite Max.	Min.	Geo. Mean	Δ Geo. Mean (%)
High	3	4,630	314	3,425	3,110	649	1,631	-48
Medium	4	2,540	835	1,632	1,570	107	326	-80
Medium-low	2	1,550	166	562	538	75	166	-70
Low	10	300	67	158	217	71	106	-33
Low-low	14	196	17	42	66	13	31	-25

Table 1 *Well groupings by chloride concentration (mg/L)*

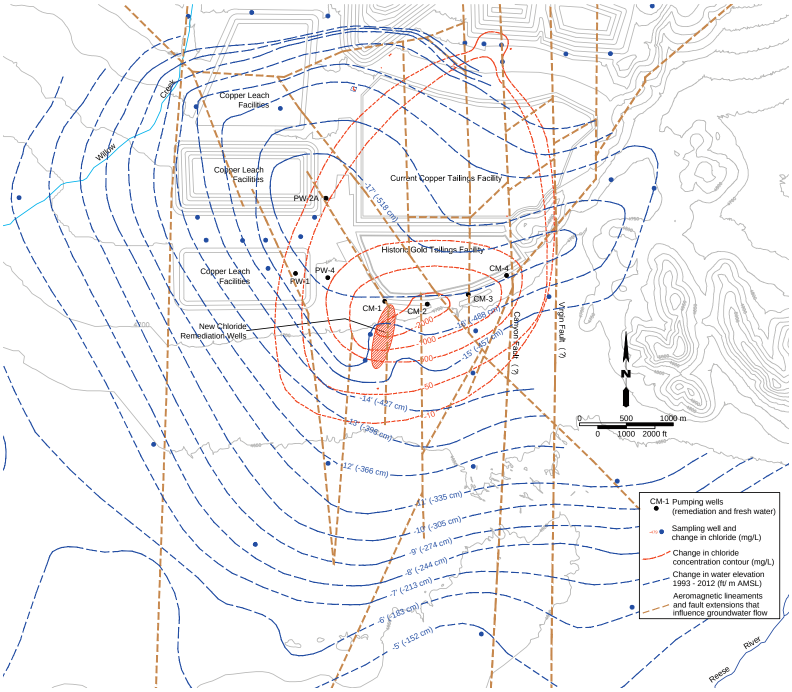

Fig. 4 *Change in water elevation contours from 1993 to end of 2012, and change in chloride concentration contours (1993–1998 vs. 2010–2012 [mg/L]). Key aeromagnetic lineaments that are interpreted to represent faults that have created zones of varying conductivity, and geophysically-inferred extensions of mapped faults that also act as hydrologic boundaries are shown, along with the area selected for replacement remediation wells.*

period, so data from these wells were not used in the change in chloride contours that appear on fig. 4. Contours of the change in water-elevations between 1993 and 2012 are shown in fig. 4. These contour maps provide insight into groundwater flowpaths as well as the propagation of cones of depression over time.

A network of monitoring wells constructed by the previous mine operator and Newmont are distributed over approximately 36 mi^2 (≈ 100 km^2), and were used to establish the background chloride concentration in groundwater within the study area. The previous owner estimated background chloride concentration at approximately 70 mg/L, but a recent reassessment of the data from an expanded groundwater monitoring well network indicates that a concentration of 100 mg/L was a more accurate estimate. This elevated background level was attributed to both the exposed and unexposed Quaternary volcanic rocks in the study area. Sampling wells near the Willow Creek drainage, approximately 1 mi (1.7 km) west of the TSF, showed very low chloride concentrations ranging from 16 to 40 mg/L. within the subsurface flow regime associated with this drainage. This is to be expected, because the bulk of this drainage is within an area dominated by Paleozoic sedimentary rocks. Basalts are interpreted beneath the alluvial fan at the mouth of Willow Creek drainage, at an undetermined depth.

Aeromagnetic interpretations of probable faults were confirmed by comparison with mapped geology wherever possible. Structure contours of the top of the unexposed Quaternary basalt were constructed from somewhat limited, widely-spaced borehole data. Structure contours showed that the top of the Quaternary basalt dips about 2° to the southwest. When overlaid on the aeromagnetic image, the structure contours were judged to be reasonable. The geophysics support the hypothesis that the exposed and unexposed Quaternary volcanic rocks are spatially related to the areas with 100 mg/L background chloride concentrations.

Results and discussion

Examination of chloride concentration data indicated that the centroid of impacted water was beneath the TSF, in the vicinity of CM-1, CM-2 and CM-3 (fig. 4). The baseline chloride contours expressed themselves as concentric ellipses, with their long axes oriented east-west, suggesting that pumping from the chloride remediation and fresh water wells influenced groundwater flow. Contours of the recent chloride concentrations indicated that the three fresh water wells (PW-1, PW-2A, and PW-4), located immediately west of the TSF, have apparently captured chloride-impacted water, although chloride has been decreasing in these wells since 1997. Over time, the three fresh-water wells clearly exhibit an inverse relationship between pumping rate and chloride concentration of the water that they produce. Recent chloride-concentration contours exhibited the east-west elongation observed in the baseline data, and comparison of the baseline and recent chloride concentration contours indicates that the areal extent of the plume of impacted water has not expanded noticeably over time.

Given that chloride impacted water has not been observed deeper than 400 ft (120 m) below the ground surface, that lower boundary and the current static water level were used to determine a saturated thickness of the impacted zone of 238 ft (73 m). Using the area within each of the baseline chloride contours, background chloride concentration of 100 mg/L, the saturated thickness, and the assumed porosity (30 %), the initial chloride mass was estimated to be 1.08×10^8 kg, similar to an estimate provided by Hydro-Search (1996) of 1.16×10^8 kg. The 2010–2012 average chloride contours were then used to calculate a remaining chloride mass of 6.3×10^7 kg of chloride. This indicates a 42 % reduction in the chloride mass with the original remediation goal of 82 % reduction.

Water-elevation contours of 1996 data showed a composite cone of depression around the fresh water and mitigation wells that was elongated northeast-southwest, with a secondary elongation to the south. Contours of 2012 water elevations (fig. 2) exhibited an enlarged composite cone of depression, with a pronounced northwest-southeast elongation, and a maximum drawdown of 17 ft (5.2 m). Drawdown resulting from pumping has propagated into the Lower Reese River Valley southeast of the TSF, and into the Willow Creek drainage to the northwest.

Contours of the change in water elevation from 1993 to 2012 recorded pronounced lateral anisotropy, suggesting the presence of several high and low K areas within the overall area impacted by the remediation pumping (fig. 4). Lineaments defined following aeromagnetic survey evaluation coincide with the apparent limits of these high and low K areas, indicating that the anisotropy is likely related to faulting (fig. 4). Using this interpretation the area selected for replacement remediation wells (fig. 4) was viewed as having minimal impact on the TSF expansion while allowing for continued capture of the chloride impacted groundwater. The potential locations for replacement mitigation wells would target an area downgradient of the centroid of chloride concentration within an area of apparently higher K. This higher K zone has been interpreted from the shape of the change in water elevation contours in the target area shown in fig. 4.

An additional and unexpected outcome of the study occurred when discussions with Phoenix process operations leadership revealed that the previous assumptions regarding operational limits on chloride concentration in make-up water for the existing copper flotation plant were overly conservative. In practice, higher chloride concentrations can be tolerated in the process than had been previously assumed and furthermore, process operations have also planned to implement changes that will result in reducing and may even eliminate the need to use any fresh water from non-remediation wells. Given that the inconsistent pumping of the remediation wells has had the effect of slowing remediation efforts in the past, plans have now been made to prepare these wells for year around pumping. Reducing demand on the fresh water wells for process water coupled with increased utilization of water from the remediation wells is expected to help further reduce the footprint of the impacted groundwater.

To help validate the sites chosen for replacement remediation wells, the conceptual hydrogeologic model developed during this study will be used to construct a numerical groundwater flow model. Once calibrated and accepted as representative, the numerical model will be utilized to determine the optimum locations for the replacement remediation wells as well as the likely volume of groundwater required to be pumped in order to achieve the remediation goal. While the currently-planned life of mine at Phoenix extends well into the 2030s, and it is currently anticipated that remediation will be completed long before the operation is shut down this outcome will be confirmed utilising predictive runs of the numerical model.

Conclusions

By expanding the groundwater monitoring well network, the background chloride concentrations in the groundwater underlying the Phoenix Mine Gold Tailing Storage Facility have been revised up to 100 mg/L from the previous 70 mg/L estimate. Besides the revision of the background chloride concentration, predictions made during previous investigations have been confirmed by the current study. Remediation efforts conducted to-date are estimated to have resulted in the removal of approximately 42 % of the chloride that was introduced to groundwater as a result of historic gold recovery at Phoenix. Due to the groundwater pumping efforts conducted since the commissioning of the original capture system in 1979, the plume of chloride-impacted water has not expanded from its baseline extents. The recent study indicates that more efficient remediation efforts can be achieved by:

1. modification of the copper flotation plant water balance,
2. enhancing emphasis on utilization of water produced from remediation wells instead of fresh water wells,
3. taking steps to allow the low volume remediation wells to pump year around.

New remediation well locations have been selected, and will be assessed by use of a numerical groundwater flow model. The numerical groundwater model will also be used to estimate volumes of pumped water required to meet the remediation target (originally set at 82 % mass removal, but subject to revision based on numerical modeling results). The currently-planned life of the Phoenix operation is currently expected to be more than sufficient to achieve substantial remediation of chloride-impacted groundwater, however this finding will also be confirmed via a pending numerical modeling program.

Acknowledgements

The author thanks Kimra Page for her efforts in gathering the chloride data, Heather Skeen for insights into the aeromagnetics, and Bryce Vorwaller for the Newmont pumping records. Discussions with Karen Tempel and Clayton Prothro were instrumental in arriving at a better approach to utilization of remediation water in process operations. Comments by Bob Sterrett, Tom Byers, Chris Cottingham, Jeff White, Matthew McGann and IMWA reviewers greatly improved this manuscript.

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