

A Case History of Intrinsic Remediation of Reactive Tailings Seepage for Questa Mine, New Mexico

Christoph Wels¹, Shannon Shaw¹ and Michael Royle²

ABSTRACT

Intrinsic remediation is the effect of natural attenuation mechanisms – dilution, dispersion, sorption/precipitation and biodegradation – reducing contaminant concentrations in ground water to specified levels at predetermined compliance points in the aquifer. Current monitoring and modeling for post closure was used to assess the current and long-term potential of intrinsic remediation of contaminated seepage originating from a large reactive (sulfidic) tailings impoundment near Questa, New Mexico. It is concluded that the natural attenuation mechanisms of precipitation within the tailings (as a result of buffering) and dilution/dispersion within the aquifer are currently active and likely sufficient to reduce contaminant concentrations to below state standards in the long-term. Other natural attenuation mechanisms such as sorption and biodegradation within the receiving aquifer(s) were not assessed here, but are likely further reducing contaminant concentrations. Active interception and recovery of the seepage water is being maintained until monitoring demonstrates that intrinsic remediation has successfully achieved the level of water quality control required.

INTRODUCTION

Intrinsic remediation is the effect of natural attenuation mechanisms – dilution, dispersion, sorption/precipitation and biodegradation – reducing contaminant concentrations in ground water to specified levels at predetermined compliance points in the aquifer. The deliberate use of intrinsic remediation is a well-accepted practice in the clean-up of petroleum hydrocarbon contaminated groundwater (e.g. Chappelle, 1999; US EPA, 1997). In contrast, the consideration of intrinsic remediation for the clean-up of groundwater impacted by mine waste (tailings or waste rock) is still met with resistance both by the regulators and the general public. Some of this skepticism towards intrinsic remediation at mine sites may be explained by the potential for acid rock drainage (ARD). Due to kinetic controls, acid rock drainage may develop slowly (often delayed by many years after closure of the facility) resulting in an increase in contaminant concentrations with time. Clearly, the potential and likely magnitude of acid rock drainage needs to be carefully evaluated when proposing intrinsic remediation for groundwater impacted by seepage from mine waste.

This paper examines the potential for intrinsic remediation of contaminated seepage originating from a large reactive tailings impoundment near Questa, New Mexico. The solutes in tailings pore water currently exceeding New Mexico Water Quality Control Commission (NMWQCC) standards at this facility include molybdenum, manganese, sulfate, fluoride, and TDS. The objective of this study was to assess whether natural attenuation mechanisms can reduce those solute concentrations to the extent that NMWQCC standards will be met in the receiving groundwater. For the purpose of this study the toe of the tailings dam(s) was selected as the compliance point. The analysis combined a number of different approaches for characterization of the geochemistry and hydrogeology of the system including:

- acid/base accounting of tailings;
- kinetic testing of tailings;

¹ Robertson GeoConsultants Inc., Vancouver, B.C.

² Steffen, Robertson & Kirsten (Canada) Inc., Vancouver, B.C.

- field pH testing at many depths in the tailings to confirm the above;
- geochemical modeling (MINTEQA2) to estimate long-term pore water quality due to sulfide oxidation and secondary mineral formation;
- groundwater flow modeling using MODFLOW (varying in scale from regional to local model using “telescopic” modeling approach) to estimate dilution potential for tailings leachate; and
- tailings seepage modeling (SEEP/W) to identify seepage pathways and estimate leachate flux as a function of time.

The results of the above analyses were combined to predict trends of molybdenum, sulfate, and TDS concentrations over time (after closure) in the most vulnerable, perched groundwater system beneath the tailings impoundments.

An integration of in-depth analyses of the geochemistry as well as the hydrogeology of the tailings impoundment is considered critical for a defensible assessment of the merits of intrinsic remediation of reactive tailings seepage. While the case study presented in this paper illustrates this approach it should be kept in mind that the details of approach and analysis methods will have to be adapted to account for site-specific issues (e.g. size and type of tailings deposit, solutes of concern, climate, state regulations etc.).

SITE DESCRIPTION

Molycorp Inc. owns and operates a large tailings facility located near the town of Questa, New Mexico (Figure 1). Over the last 33 years a total of nearly 100 million tons of tailings from the Questa Molybdenum Mine have been discharged into this facility covering a total surface area of about 260 ha (640 acres) (as of 1997). The tailings originate from a hydrothermally altered molybdenum porphyry deposit of volcanic origin. After crushing and grinding the ore is extracted using froth flotation while the tailings are buffered to about pH 8.5 by adding lime and are pumped to the tailings impoundment in a pipe line.

The tailings are impounded in two deeply incised valleys (so-called “arroyos”) behind two major earth fill dams (Dams 1/1C and Dam 4, respectively) (Figure 1). Currently, tailings are discharged behind the smaller Dam 5 in the northwestern corner of the facility. The tailings facility lies in an alluvial plain at an elevation of about 7600 feet a.m.s.l., bordered by the Sangre de Cristo Mountains to the east and the Guadalupe Mountains to the west. To the south, the Red River and its tributary, Cabresto Creek, have cut a prominent valley 100 to 200 feet below the level of the alluvial plain (Figure 1).

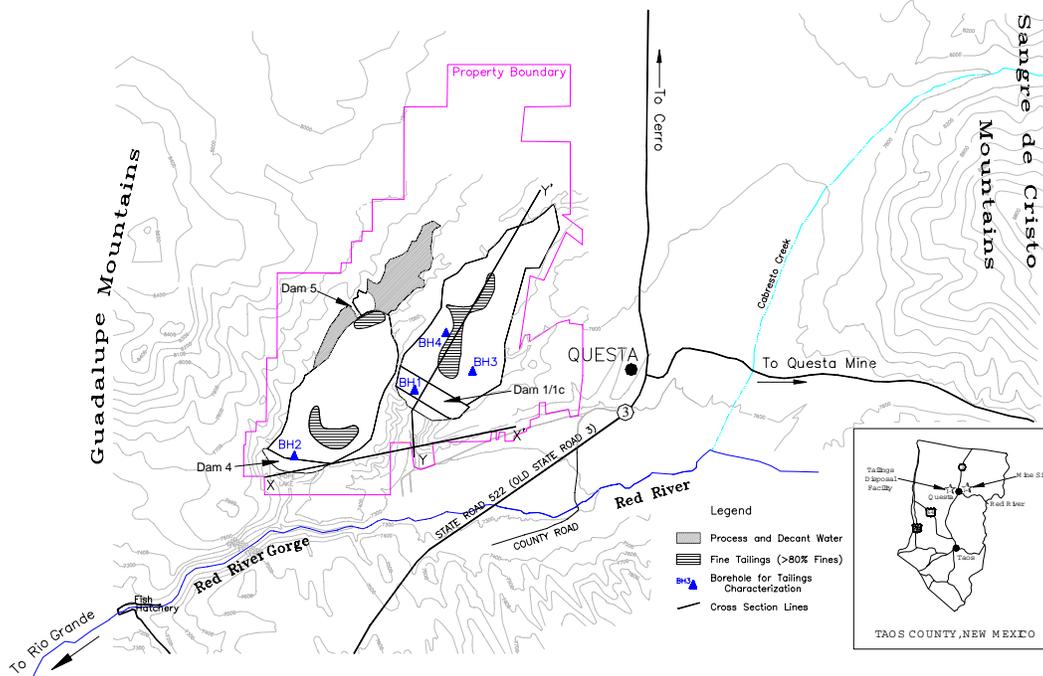


Figure 1 Overview of Questa tailings facility, Taos County, New Mexico.

The eastern section of the Questa tailings facility was entirely constructed on recent alluvial sediments, whereas the western sections were constructed partially on alluvial sediments and partially on volcanic rocks of the Guadalupe Mountains (Figure 2). Beneath the tailings facility the basalt flows from the Guadalupe Mountains gradually dip eastward, interfingering and underlying the recent alluvial sediments. The surficial alluvial sediments are composed of materials ranging in size from clay particles to large cobbles. Usually the alluvial sediments are unsorted, but locally they are fairly well sorted, and contain lenses of gravel, sand, or clay. Owing to the large range in possible degrees of sorting and coarseness of the alluvial sediments, the permeability of this material varies greatly. The volcanic activity of the Guadalupe Mountain has emplaced a variety of volcanic lithologic types including dacites, colluvial and surge breccias, rhyodacite and occasional cinder beds. Hydraulic testing suggests that the volcanic rocks of the Guadalupe Mountain have a very high formation permeability, in large part due to the presence of fractures and bedding planes (Dames and Moore, 1987).

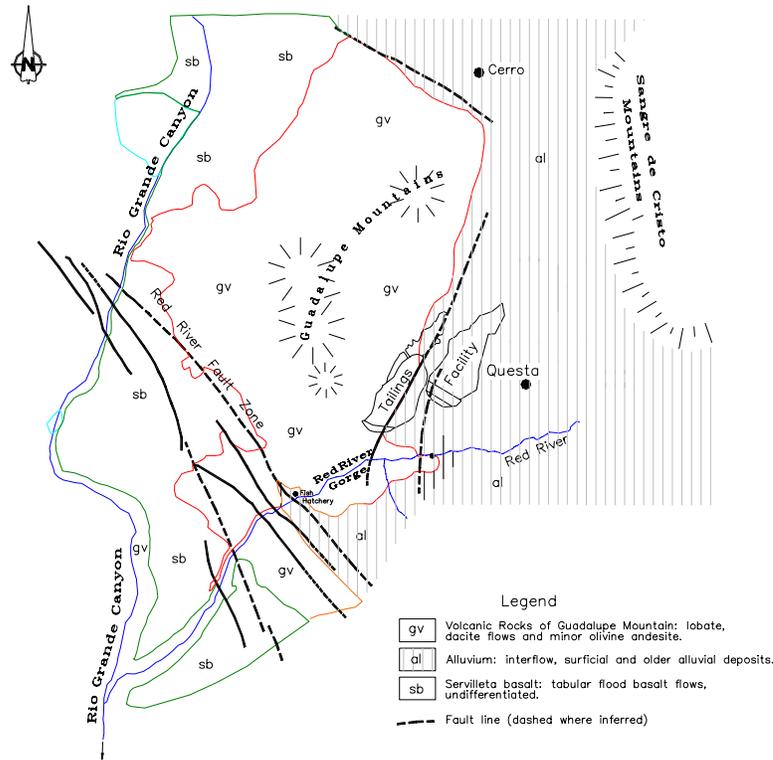


Figure 2 Surficial geology in study region (after Vail, 1987).

The climate of the study area is semi-arid. Annual precipitation at near-by Cerro averages about 310 mm/yr (12.2 inches per year) with much of this precipitation occurring as summer thundershowers (43% of total precipitation occurs from July to September). The summers are moderately warm with maximum daily temperatures around 27°C (80°F). The winters are long with temperatures dropping below freezing almost every night from October through to April. However, typically clear skies bring sunshine during most days with temperatures rising to above the freezing point. During the winter much of the precipitation falls as snow. Nevertheless, a significant snow pack rarely develops due to intermittent snow melt and/or sublimation. Based on frost data collected by the U.S. Weather Bureau at Cerro a growing season of 120 days is average for the study area. As expected for this semi-arid climate, the potential evaporation rates far exceed precipitation rates during all months on record. The annual potential (pan) evaporation is estimated to be about 65-70 inches per year.

ASSESSMENT OF CURRENT INTRINSIC REMEDIATION

An initial review of available data suggested that no significant ARD has developed in the tailings despite their reactive nature (0.5–1.5% pyrite). Several geochemical and hydrological studies were subsequently conducted to better understand the mechanisms resulting in this apparent intrinsic remediation.

Geochemical Controls in Tailings

A series of field and laboratory tests were performed to assess the reactivity of the tailings and the current extent of oxidation in the field. Prior to sampling, the mining, milling and tailings depositional history was reviewed and a three-dimensional geometric model developed (Robertson GeoConsultants, 1997a). Based on this model, a sampling program was designed to collect samples from the tailings surface and from four boreholes located in areas such that every year of tailings deposition within the impoundment was intersected. The boreholes penetrated the entire tailings deposit to a maximum depth of 55 m (180ft). Throughout the impoundment, the Questa tailings are geochemically similar mixtures of aplite and andesite tailings. The tailings are extremely homogenous and represent only tailings produced from ore milled at the Questa mill and only ore processed from the Questa Mine. Therefore the 463 tailings samples collected are considered to be statistically representative of the entire tailings facility. Subsets of these samples were subjected to various testing procedures as shown in Table 1.

The mineralogical composition of the tailings consists predominantly of quartz, plagioclase feldspar, potassium feldspar and biotite with lesser amounts of chlorite, amphibole, calcite and sulfide minerals (SRK (U.S.), 1997a and 1997b). The sulfide minerals include pyrite, sphalerite, chalcopyrite and molybdenite with trace amounts of galena, covellite and pyrrhotite. The minerals that are considered potential sources of acidity and dissolved metals are pyrite, chalcopyrite, molybdenite, sphalerite and pyrrhotite. Very minor alteration of pyrite and chalcopyrite were detected in some of the samples (5 of 10 samples) characterized by mineralogical analysis. These samples also contained excess calcite and had near neutral paste pH values indicating acid production is effectively neutralized. One sample showed slight dissolution of molybdenite. The minerals that likely contribute to the laboratory neutralization potential, determined using a concentrated strong acid, include calcite, biotite, plagioclase feldspar and minor clay. Of these, calcite is the most important since it is currently buffering the porewater in the tailings to near neutral values.

Table 1 Summary of geochemical testing of Questa tailings.

Testing Method	Number of Samples Tested			
	Acid Generating Potential Assessment (SRK 1996)	Geochemical Testing Program Phase I (SRK 1997a)	Geochemical Testing Program Phase II (SRK 1997b)	Geochemical Speciation Modeling (SRK 1997b)
STATIC TESTS				
Paste pH	42	402		
Paste Conductivity	42	402		
Acid Base Accounting	42	36	10	
Metals Concentration by ICP	12	14		
Petrographic/XRD	4	6		
Leach Extraction	18	16	7	5
KINETIC TESTS				
Humidity Cells			9	8
Enhanced Peroxide Oxidation test			5	

Acid/Base Accounting (ABA) tests have been conducted on a total of 88 representative samples to assess the potential for acid generation. For the homogeneous tailings at Questa, ratios of neutralization potential to acid generation potential (NP/AP) above 1.5 were considered to be likely acid consuming. The validity of this assumed cut-off value was checked by performing kinetic tests on samples with NP/AP ratios greater and less than 1.5:1 (see below). Figure 3 summarizes the results of the ABA testing. Based on the distribution of all the samples tested for acid/base accounting (ABA), using a defining NP/AP ratio of 1.5, approximately 80% of the tailings were initially characterized as acid consuming, 14% were considered uncertain, and 6% were considered to be potentially acid generating. The overall mean NP/AP ratio of the tailings was 2.42 (ranging

from 0.42 to 5.00; standard deviation 1.34) and therefore the tailings are considered net alkaline. The predominantly andesitic tailings have higher sulfide-sulfur contents and a higher potential to generate acid than the slimes tailings or aplite tailings.

Despite the oxidation potential of sulfide minerals, the Questa tailings are currently not acid generating. The surface tailings, which have been most susceptible to oxidation processes, have remained grey in color and are consistently circum-neutral with respect to paste pH. Figure 4 shows a typical profile of paste pH and conductivity for borehole BH 3 located on the tailings beach of the older Dam 1/1C impoundment. The paste pH of the tailings was found to be near neutral for all samples (surface and at depth). The depth profiles of paste conductivity were significantly more variable exhibiting several peaks (Figure 4). The elevated paste conductivity values are likely caused by seasonal flushing of stored oxidation products/secondary minerals (e.g. gypsum). Historic fluctuations in the solution chemistry of the process water may also have contributed to the variation in TDS of the tailings pore water with depth. These field observations suggest that the tailings are reactive, i.e. that some oxidation is occurring in the desaturated tailings (or at least occurred in the past), while at the same time, providing sufficient buffering to maintain a near-neutral pH in the pore water.

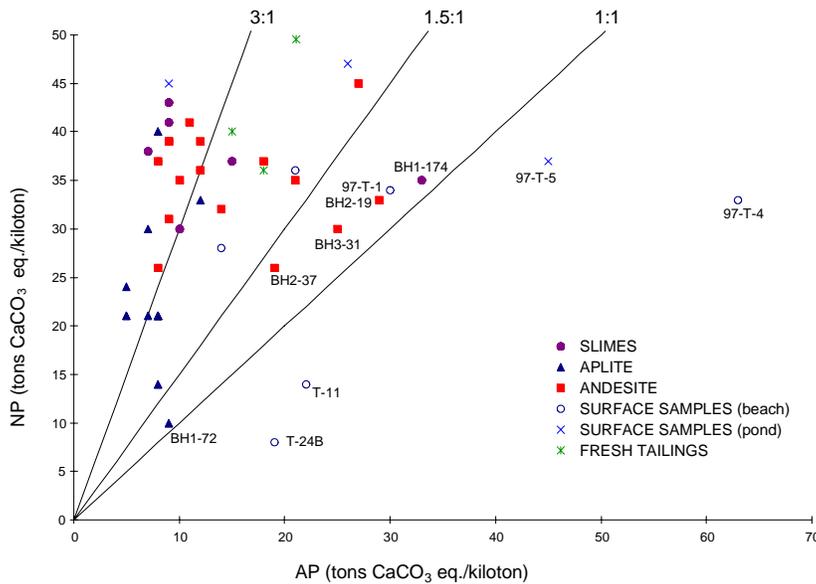


Figure 3 NP versus AP for the Questa tailings samples (from SRK (U.S.), 1997b).

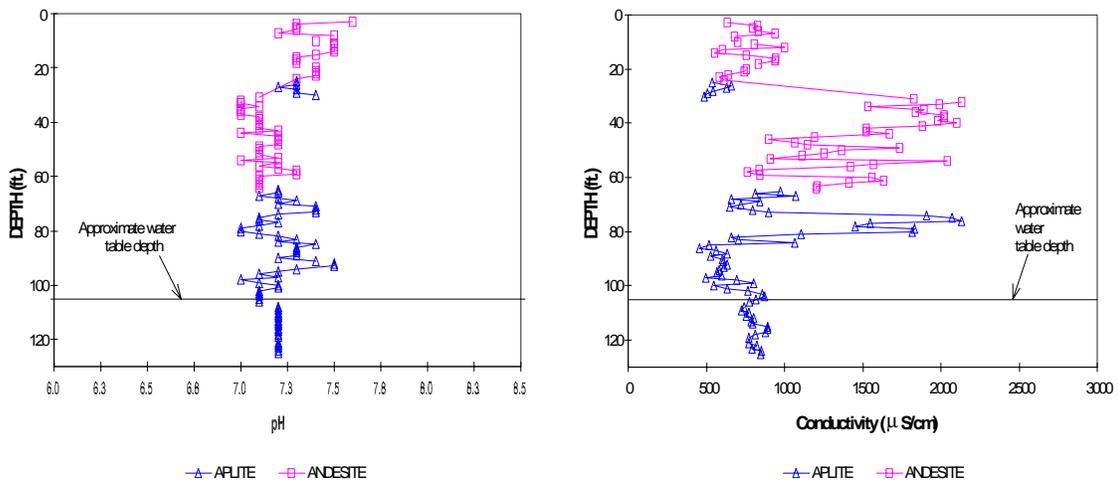


Figure 4 Observed paste pH and paste conductivity in borehole 3 (from SRK (U.S.), 1997b).

Leach extraction tests indicated that readily soluble constituents associated with the tailings include Al, Ca, Mg, Mn, Mo, K, Na, Sr, and SO₄. The primary “contaminants” (i.e. elements with concentrations greater than those defined by the New Mexico groundwater standards) occurring in the tailings leachate are F, Mn, Mo and SO₄ and TDS. These leaching results are consistent with tailings pore water taken from the base of the four boreholes drilled into the tailings (Table 2).

Table 2 Selected water quality results for tailings seepage and groundwater.

Location	Well-ID	Concentration in mg/l				
		F	SO ₄	TDS	Mn	Mo
<i>New Mexico Ground Water Standards</i>		1.6	600	1000	0.2	1.0
Tailings Pore Water (average)	BH1-BH3	5.07	1130	2000	3.5	5.2
Groundwater downstream of Dam 1/1C Impoundment						
at toe of Dam 1/1C (Shallow Alluvium) ¹	EW5A	1.34	832	1694	0.82	2.53
	EW5B	1.36	772	1578	2.38	1.77
50 ft downstream of Dam 1/1C (Shallow Alluvium) ¹	MW-A	0.40	737	1307	0.15	0.74
2,000 ft downstream of Dam 1/1C (Shallow Alluvium) ¹	MW-2	0.58	598	947	0.55	0.17
2,000 ft downstream of Dam 1/1C (Deep Alluvium) ¹	MW-12	0.42	67	234	0.01	0.01
Groundwater downstream of Dam 4 Impoundment						
at toe of Dam 4 (Volcanics) ¹	MW-11	1.05	170	342	0.02	0.21
	MW-13	0.82	149	355	0.00	0.11
Ambient (Background) Groundwater						
Volcanic Aquifer ²	various	1.1-1.2	19-50	154-167	0.002-0.01	0.006 - <0.002
Alluvial Aquifer ²	various	0.8	9-43	136	N/A	N/A

Notes:

1. average of six samples (from 1st Quarter 1998 to 2nd Quarter 1999)
2. data from Dames & Moore, 1987

In summary a comprehensive field survey and static laboratory testing program suggested that the Questa tailings are currently net acid consuming. The data suggest that the buffering capacity of the tailings is sufficient to maintain circum-neutral pH in the tailings pore water thus preventing the potential acceleration of acid production and release of metals. In other words, internal buffering within the tailings currently represents a key mechanism for preventing/attenuating ARD.

Geochemical Controls in Aquifer

The only constituents currently found in tailings seepage emerging at the base of the impoundment that exceed the New Mexico Ground Water standards are F, Mn, Mo, SO₄ and total dissolved solids (TDS) (Table 2). The potential for geochemical attenuation (precipitation and/or adsorption) of these constituents in the local aquifer materials was evaluated using published data. The adsorption potential of the above constituents on volcanic rocks found in the area had previously been studied as part of a feasibility study for a proposed

new tailings facility located immediately to the east of the existing facility (Dames and Moore, 1987). Batch adsorption tests were conducted with volcanic breccia and volcanic bedrock (broken to gravel size, but not screened) covering a wide range of rock-to-solution ratios (see Roy et al., 1985 for procedure). The volcanic rocks used are typical for the aquifer material found below the western part of the Questa tailings facility.

The test results indicated that the anions, fluoride and sulfate, and TDS did not exhibit any adsorption. In contrast, molybdenum adsorption was observed at all rock-to-solution ratios ($K_D \sim 37\text{ml/mg}$ for 1:20 rock-to-solution ratio). The bivalent cation lead also showed significant adsorption ($K_D \sim 37\text{ml/mg}$) but only at the highest rock-to-solution ratio (1:20). Manganese was not tested, however, this bivalent cation was assumed to have the same adsorptive properties as lead due to chemical similarities (Dames and Moore, 1987). No adsorption experiments were conducted specifically with the alluvial soils found beneath the eastern portion of the Questa tailings facility. However, the alluvial materials (interbedded layers of clayey and sandy gravels) likely show a greater adsorptive capability than the volcanic rocks tested by Dames and Moore (1987) owing to the significant clay content and the overall much greater surface area of the unconsolidated material.

The adsorption test results obtained by Dames and Moore (1987) are consistent with findings at other sites. Fluoride is known to be highly mobile under all environmental conditions (Levenson, 1980). Similarly, sulfate is typically considered mobile since it has only a negligible potential for adsorption (by ion-exchange) at circum-neutral pH (Drever, 1988). However, both constituents may be subjected to precipitation/dissolution reactions in the aquifer. Geochemical modeling using MINTEQA2 suggests that there are no solubility constraints for sulfate in the range of concentrations currently observed in tailings seepage ($\sim 1200\text{ mg/l}$). However, secondary mineral formation (namely gypsum) will control sulfate concentrations at elevated levels of sulfate ($>2000\text{-}3000\text{ mg/l}$). Fluoride may precipitate as fluorite at the elevated concentrations currently observed in tailings seepage ($\sim 5\text{ mg/l}$) (see below).

Molybdenum is highly mobile in oxidizing, alkaline environments, however has low mobility in acidic or reducing environments (Levinson, 1980). In conventional water treatment technology, molybdenum is typically co-precipitated from solution with ferric or aluminum oxy-hydroxides (CCREM, 1991) and a similar process may also occur naturally in the alluvial soils. Similarly, the dissolved concentration of manganese is dependent on changes in redox potential, dissolved oxygen, pH and organic matter content. Molybdenum and manganese are therefore not considered to be conservative groundwater components in the aquifer.

Groundwater quality monitoring results downstream of the tailings dam generally support the laboratory findings. Table 2 compares tailings seepage concentrations with those measured in several monitoring wells located in the shallow and deep alluvial aquifer (downstream of Dam 1/1C) and in the deep volcanic aquifer (downstream of Dam 4). The observed reductions in concentrations of the reactive constituents (F, Mn and in particular Mo) with distance from the tailings dam are typically significantly greater than for the conservative constituents (SO_4 and TDS) suggesting that geochemical attenuation is occurring in the aquifers. The monitoring data further suggest that the other anion of interest, fluoride, is significantly attenuated in the aquifer material. Geochemical modeling suggests that fluoride might be precipitated out as fluorite.

In summary, there is significant potential for attenuation/co-precipitation of molybdenum, manganese and fluoride in the aquifer. On the other hand, sulfate and TDS are not likely to be attenuated by adsorption/precipitation reactions in the aquifer material. The observed reduction in concentrations of the non-reactive constituents with distance from the tailings impoundments is likely caused by dilution/dispersion discussed below.

Hydrological Controls

Figure 5 shows an idealized geological cross-section running east-west with observed water levels immediately downstream of the Questa tailings facility. As a first approximation, the local groundwater system can be divided into an upper (shallow) aquifer system (above an elevation of $\sim 7200\text{ ft}$) and a lower (deep) aquifer system (below an elevation of $\sim 7200\text{ ft}$). The shallow aquifer system consists of a complex mixture of recent alluvial sediments, ranging from coarse, permeable sand and gravel units to very low permeable clay layers resulting in very high spatial heterogeneity at the local scale. The very high vertical gradients between the shallow and deep aquifer systems (near unity) suggest that the shallow groundwater system is perched on top of the deep aquifer system. The deep aquifer system consists of deep alluvial sediments in the eastern parts and volcanic rocks from the Guadalupe Mountains in the western parts of the study area (beneath the Dam 4 arroyo) (Figure 5). The volcanics have a very high secondary permeability (in the order of $K=1 \times 10^{-3}\text{ m/s}$) and act as a drain for shallow groundwater flowing above in the shallow alluvial sediments (Figure 5).

Most of the recharge to the groundwater system probably occurs from ephemeral and perennial streams (and related irrigation ditches) running off the Sangre de Cristo Mountains, which upon leaving their mountain courses and entering the plateau area, lose much of their flow to permeable alluvial sediments. Other sources of recharge are leakage from arroyo flood flows, and infiltration of water pumped for irrigation. Recharge from local precipitation is comparatively small (<25–50 mm/yr). Recharge to the volcanics occurs predominantly though leakage from the overlying alluvial sediments.

In order to estimate the potential for dilution of tailings seepage in the receiving groundwater a groundwater flow model was constructed using MODFLOW (Robertson GeoConsultants 1997b). First, a regional groundwater flow model was constructed to obtain a regional groundwater balance and to provide defensible model boundaries for the local flow model. The regional flow model was calibrated using borehole logs, observed water levels in the region and measurements of accretion and springs flows to the Rio Grande and the Red River. The regional model is considered “robust” due to the fact that both, observed groundwater levels and observed groundwater fluxes (from river accretion studies, see Vail Engineering, 1993) were used for model calibration (see Robertson GeoConsultants 1997b for details).

Using telescoping mesh refinement, a local groundwater flow model was constructed from the regional groundwater flow model (Figure 6). The northwestern model boundary is a no-flow boundary representing a flow line in the regional model. The north-eastern model boundary is a constant-flux boundary representing an equipotential line of the regional flow model with the assumed groundwater flux across this boundary derived from the calibrated regional flow model (Robertson GeoConsultants 1997b). The local groundwater flow model was then used to estimate the volumes of groundwater flowing beneath the tailings facility available for dilution. Note that the simulated groundwater flow rates and thus the potential for dilution are strongly influenced by the local model boundaries (in particular the flux boundary in the NE). However, the estimated groundwater flow rates agreed very well with observed spring flows (to the Red River) and the currently observed dilution of sulfate in the groundwater system.

At least two faults have been inferred from local outcrops in vicinity of the tailings impoundments (see Figure 5). However, there is no field indication that these fault lines represent preferred conduits of groundwater flow. Sensitivity runs with the local flow model suggested that these faults influence groundwater flow by placing differing hydrostratigraphic units in direct contact (Robertson GeoConsultants 1997b). This displacement of hydrostratigraphic units likely causes the large drop in shallow water table across the fault line in Dam 1 (see Figure 6a).

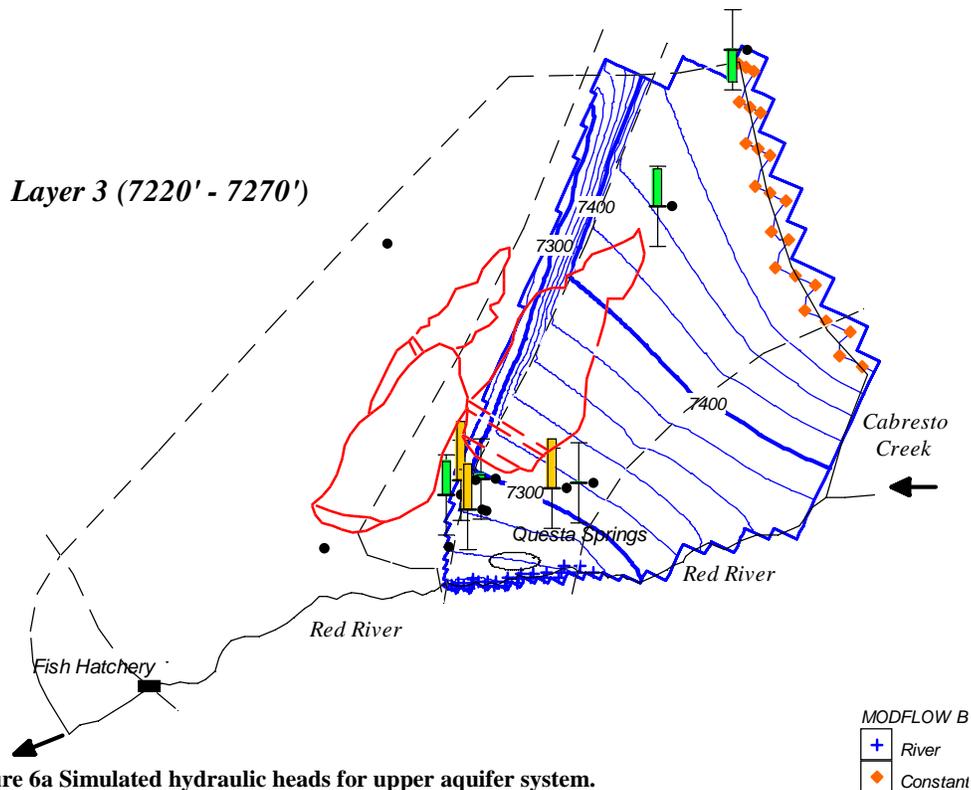


Figure 6a Simulated hydraulic heads for upper aquifer system.

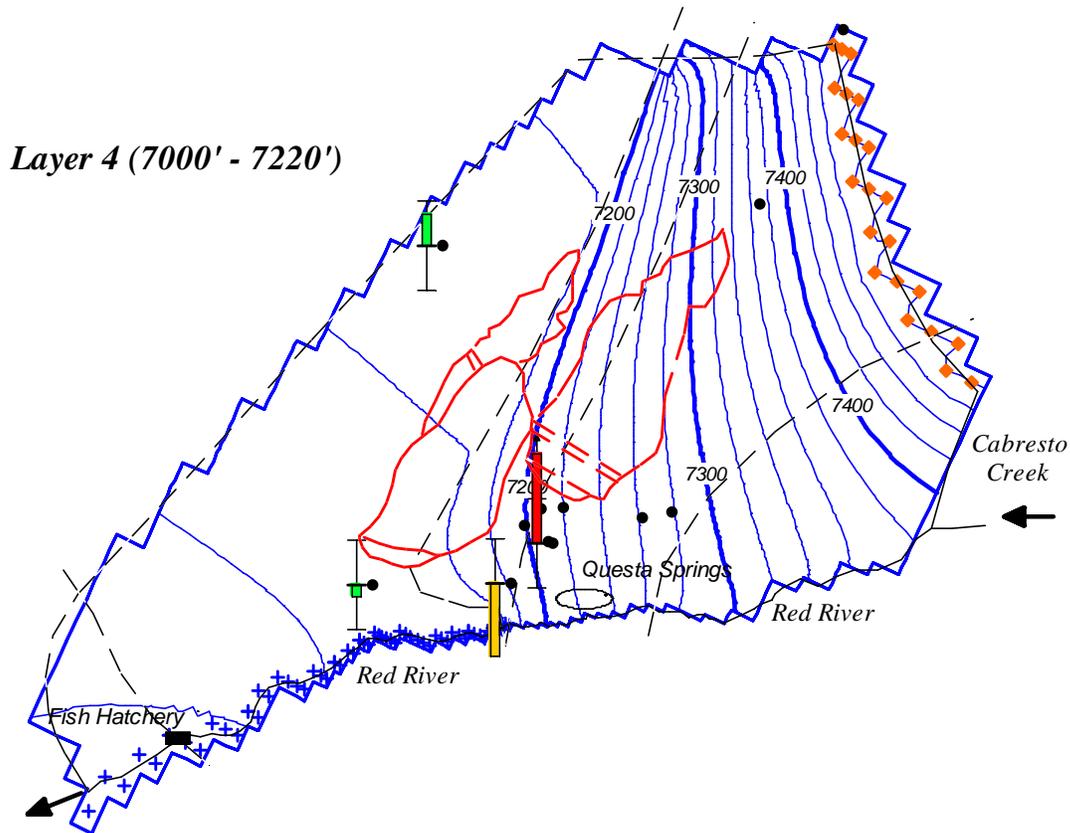


Figure 6b Simulated hydraulic heads for lower aquifer system.

The calibrated flow model indicated that most of the tailings seepage from the Dam 1/1C impoundment would recharge into the shallow aquifer system. The underflow of shallow groundwater directly beneath the Dam 1/1C impoundment is estimated to be about 60 l/s (2.1 cfs). The shallow groundwater flows in a southwesterly direction and discharges near the Red River (“cold springs”) (Figure 6a). In contrast, tailings seepage from the Dam 4&5 impoundments would recharge directly into the deep volcanic aquifer. The underflow of deep groundwater directly beneath the Dam 1/1C impoundment is estimated to be about 153 l/s (5.4 cfs). The deep groundwater travels in a westerly direction beneath the tailings impoundments and assumes a south-westerly direction upon entering the volcanic aquifer, eventually discharging in the Red River Canyon (“warm springs”) (Figure 6b).

The groundwater flow model suggests that there is significantly more potential for dilution in the deep aquifer compared to in the shallow aquifer system due to the higher flow rates in the deep aquifer. Observed water quality results in downstream monitoring wells generally support this contention showing much lower contaminant concentrations in the deep volcanic aquifer downstream of Dam 4 (e.g. MW11&12) compared to in the shallow alluvium downstream of Dam 1/1C (Table 2). The observed concentrations of the “non-reactive” contaminants SO_4 and TDS were used to estimate the relative contribution of tailings seepage to groundwater (Table 3). The results indicate that the deep volcanic aquifer comprises in the order of 8-12% tailings seepage whereas the contribution of tailings seepage to shallow groundwater may range from 42% to as high as 83%.

The very high contaminant concentrations observed near the toe of Dam 1/1C, suggest that tailings seepage is perched above the natural groundwater table and, as a result, does not mix well with shallow groundwater in the alluvium for some distance. Borehole logs and exposed faces along hill cuts indicate that the shallow aquifer system contains low-permeable silt and clay layers which extend laterally (in a north-south direction) up to several hundred feet (Figure 7). The tailings seepage (and water from local recharge in the arroyo) likely moves in the permeable sand and gravel units on top of these silt/clay lenses, gradually ‘cascading’ downward into deeper soil horizons where the regional groundwater is flowing. The heterogeneity of the alluvial material thus results in significant lateral dispersion of the contaminants but limited vertical dispersion. The limited extent of vertical mixing is evidenced by the low concentrations of sulfate or other contaminants (near background levels) observed in monitoring wells screened in the deep

alluvium (e.g. MW12 or EW2, Figure 7). Mixing calculations suggest that groundwater in the deep alluvial aquifer receives only negligible amounts, if any, of tailings seepage (Table 3).

Table 3 Calculated contribution of tailings seepage to groundwater at various monitoring points downstream of Questa Tailings Facility.

Location	Well-ID	Fraction of Tailings Seepage ¹	
		based on SO ₄	based on TDS
Dam 1/1C Impoundment			
at toe of Dam 1/1C (Shallow Alluvium)	EW-5A	0.73	0.83
	EW-5B	0.67	0.77
50 ft downstream of Dam 1/1C (Shallow Alluvium)	MW-A	0.64	0.62
2,000 ft downstream of Dam 1/1C (Shallow Alluvium)	MW-2	0.51	0.42
2,000 ft downstream of Dam 1/1C (Deep Alluvium)	MW-12	0.02	0.02
Dam 4&5 Impoundment			
Toe of Dam 4 (Volcanics)	MW-11	0.12	0.08
	MW-13	0.10	0.09

Notes:

- relative contribution of tailings seepage to groundwater determined using mixing equation: $X_{PW} = (C_{GW} - C_{BG}) / (C_{PW} - C_{BG})$ where X_{PW} is the fraction of tailings pore water ("seepage") in the groundwater and C_{PW} , C_{GW} , and C_{BG} are the current sulfate (or TDS) concentrations in tailings pore water, groundwater, and background groundwater (not impacted by tailings seepage), respectively.

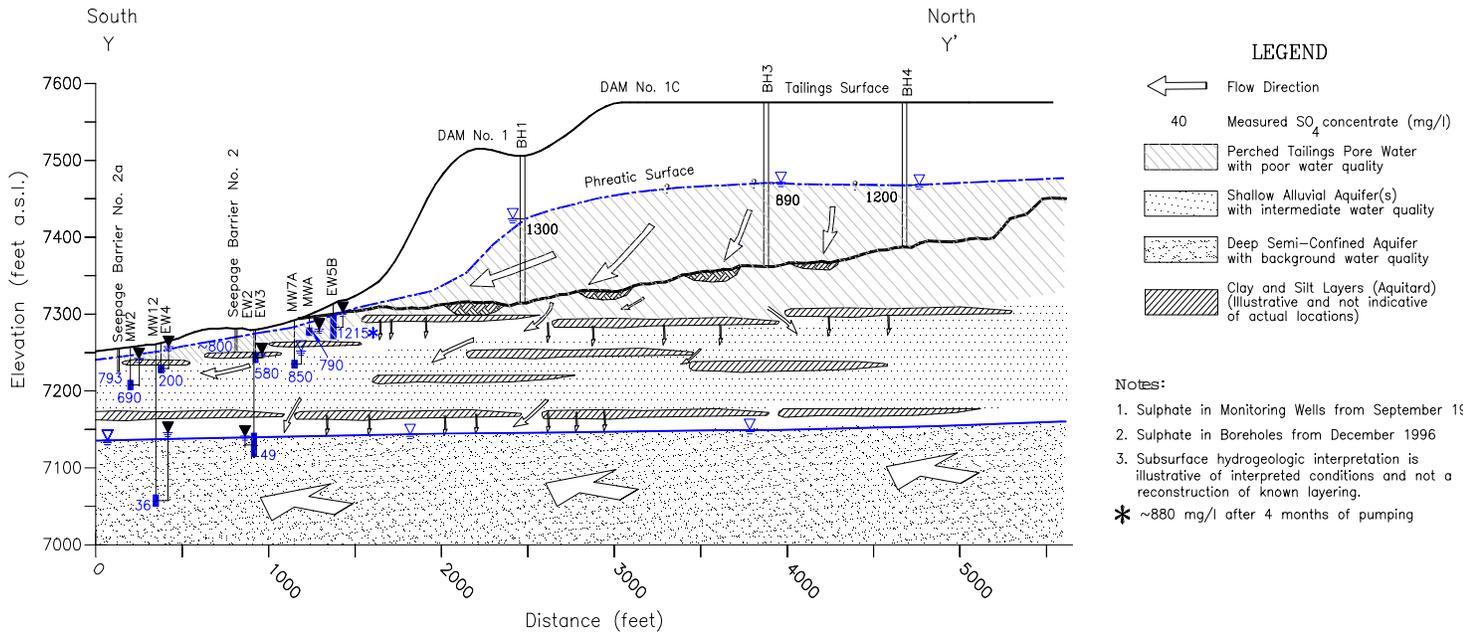


Figure 7 Conceptualization of tailings seepage and ground water flow beneath Dam 1/1C impoundment.

In summary, groundwater flow modeling and water quality monitoring suggest that dilution is effective in reducing contaminant concentrations in the deep aquifer system to concentrations well below state standards. As a result, no interception of tailings seepage is currently required at the toe of the Dam 4 impoundment. In contrast, strong local heterogeneity and anisotropy in the shallow alluvium results in perched tailings seepage downstream of the Dam 1/1C impoundment, preventing adequate mixing of the tailings seepage with groundwater (and dilution of the contaminants) in the shallow alluvium. Since natural attenuation mechanisms are currently not sufficient to reduce contaminant concentrations below state standards, tailings seepage is currently intercepted downstream of Dam 1/1C using extraction wells and shallow drains (see Robertson GeoConsultants, 1998 for details).

LONG-TERM POTENTIAL FOR INTRINSIC REMEDIATION

Predictive modeling was used to evaluate the long-term potential for intrinsic remediation of the impacts of tailings seepage on groundwater quality. The analyses focused on the prediction of long-term tailings pore water quality (seepage) and the prediction of the long-term reduction in tailings seepage rates (and impact on groundwater quality) as a result of closure of the tailings facility.

Prediction of Tailings Pore Water Quality

Five enhanced peroxide oxidation tests (also referred to as Net Acid Generation Tests, or NAG tests, see Miller et al., 1997) were performed on samples characterized as potentially acid generating or uncertain based on ABA tests. The NP/AP ratios for these samples ranged from 1.67 to 0.64. The results indicated that three of five samples tested (NP/AP = 1.67, 1.11 and 0.64, respectively) would in fact be acid consuming, only one sample (NP/AP = 1.37) would be classified as potentially acid generating with low capacity and one sample (NP/AP = 1.14) would remain in the "uncertain" area. These results indicated that the selected NP/AP ratio of 1.5:1 for classification of potentially acid generating tailings is a conservative "cut-off" value for the Questa tailings.

Nine humidity cell tests were conducted on samples with NP/AP ratios ranging from 4.2 to 0.42. The leachate from these cells maintained long term pH values between 7.8 and 8.2. Thus alkalinity release from the dissolution of calcite in the humidity cells is rapid (compared to natural rates of oxidation), and buffers the leachate pH to above 7.0. This indicates that neutralizing carbonates are readily accessible to buffer acidity produced by natural sulfide oxidation. The overall oxidation rates for the tailings were calculated to lie between approximately 2×10^{-8} and 9×10^{-9} kg O₂/m³/s. These rates are low, but similar to those reported elsewhere in the literature for sulfide tailings (Coggans et al., 1991).

These laboratory results are consistent with field observations at the Questa tailings facility. The tailings impoundments are of themselves 'large humidity cells' in that the entire tailings facility has been exposed to surface oxidizing conditions for at least 6 years and a substantial area of tailings (22 acres) for more than 27 years. Yet, the surface tailings at Questa, which have been most susceptible to oxidation processes, have remained grey in color and are consistently circum-neutral with respect to pH. They are net acid consuming and, in terms of kinetics, have been so for 27 years.

Geochemical modeling was performed to estimate the likely quality of tailings pore water (seepage) that could develop in the field as a result of on-going sulfide oxidation in the tailings. The USGS geochemical equilibrium modeling program MINTEQA2 (Allison et al., 1991) was used to calculate saturation indices for selected leachates from the leach extraction tests and the humidity cells ("first flush") in order to identify any secondary mineral phases that may be controlling the dissolved constituent concentrations in the pore water. The possible solubility controlling mineral phases, that may be limiting the release of metals from the tailings under field conditions, include gypsum (Ca, SO₄), fluorite (F), iron oxy-hydroxides (Fe), rhodochrosite (Mn), barite (Ba), celestite (Sr), otavite (Cd), cerrusite (Pb), malachite (Cu), basaluminite and possibly alunite (Al).

The modeling did not indicate any solubility controls for molybdenum, in part due to the lack of thermodynamic data in MINTEQA2 for secondary mineral phases of molybdenum. However, there appears to be a solubility controlling mechanism as indicated by the leach extraction test concentrations, which showed molybdenum concentrations over a fairly narrow range (typically 0-9 mg/L Mo) independent of the solid:liquid ratio. Molybdenum is known to precipitate as ferric molybdenate or co-precipitate with iron-oxyhydroxides (both processes are used in water treatment technology) (Levinson, 1980; CCREM, 1991). The oxidation of pyrite and buffering by calcite likely result in the production of ferric iron and subsequent precipitation of iron-oxy-hydroxides, hence providing an opportunity to co-precipitate molybdenum under field conditions.

In order to obtain estimates of future tailings pore water quality, the leach extraction test results from near-surface samples and from tailings at depth were "scaled" to field moisture conditions. The scaling

accounted for the large dilution that the solution experienced during the extraction tests (e.g. a solid-to-liquid ratio of 1:1 represents a 11-fold dilution compared to a field moisture of 10%). However, this procedure does not account for the possible release of solutes from secondary minerals during the extraction test. Therefore the solubility controls of likely secondary minerals (described above) were imposed in order to arrive at final water quality predictions.

Table 4 lists the tailings pore water quality calculated with this procedure. Although sulfate pore water concentrations are controlled by the formation of gypsum, the presence of magnesium in solution results in sulfate concentrations exceeding typical gypsum equilibrium conditions. Sulfate concentrations in the tailings pore water in the medium and long term are expected to be in the order of 3,000 mg/L. Note that the tailings pore water quality back-calculated for the near-surface samples is significantly poorer than for the deep tailings samples, likely due to greater oxidation of the tailings near the surface (exposed for up to 27 years). Back-calculated pore water quality for the near-surface samples is considered a worst-case scenario for future tailings seepage quality. Note also that the molybdenum concentrations calculated with this procedure are likely too high as no secondary solubility controls were assumed but appear to be active (see above). The molybdenum concentrations in the tailings pore water in the long-term are expected to more likely be in the order of 5 to 6 mg/L.

Table 4 Tailings pore water quality back-calculated from leach extraction tests.

PARAMETERS (mg/L)	Near-Surface Samples (above 20 ft)				Samples From Depth (below 20 ft)			
	T-24B	T-13	VC-3, 10-15'	Average	BH1-135	BH1-40	BH3-69	Average
Aluminum Al ⁺³	0.04	0.07	0.07	0.06	0.12	0.13	0.06	0.10
Calcium Ca ⁺²	330	317	277	308	270	321	291	294
Carbonate CO ₃ ⁻²	256	149	203	203	125	76	212	138
Fluorine F ⁻¹		2.1	2.4	2.3	2.3	1.7	2.0	2.0
Iron Fe ⁺²	0.113	0.113		0.11	0.081			0.08
Magnesium Mg ⁺²	488.5	270.0	263.5	341	175.7	56.1	110.0	114
Manganese Mn ⁺²	5.10	1.57	0.45	2.37	4.12	4.51	4.47	4.37
Molybdenum Mo ⁺⁶	15.24	43.77	85.29	48.1	47.93	4.42	21.42	24.6
Potassium K ⁺¹	108.6	203.7	374.2	229	241.8	163.4	360.2	255
Sodium Na ⁺¹	29.70	48.09	198.75	92.2	288.52	69.20	140.26	166
Strontium Sr ⁺²	11.05	10.42	8.41	9.96	8.07	6.22	9.14	7.81
Sulfate SO ₄ ⁻²	2614	2266	3083	2654	2940	1610	2285	2278
TDS (calculated)	3862.18	3312.56	4496.22	3890	4104.07	2312.77	3436.81	3285
pH (measured)	7.1	7.3	7.3	7.23	7.5	7.5	7.2	7.40

NOTE: For the purposes of this paper, only selected parameters are shown, for details on complete results see SRK (U.S.) (1997b) and Robertson GeoConsultants (1998).

In summary, kinetic testing strongly suggests that the Questa tailings will remain net acid-consuming in the long-term. In other words internal buffering is currently, and will likely remain a key control mechanism in preventing/attenuating ARD at this site. The primary “contaminants” in tailings seepage likely remain unchanged in the long-term (i.e. F, Mn, Mo and SO₄. & TDS) but may increase in concentration. Although solubility constraints by secondary minerals will likely limit maximum concentrations of these constituents, the long-term, steady-state concentrations in tailings seepage are still expected to exceed the New Mexico Ground Water standards.

Prediction of Post-Closure Groundwater Quality

As outlined above, the natural mechanisms of dilution/dispersion are presently not sufficient to reduce contaminant concentrations to below state standards in the shallow aquifer system downstream of Dam 1/1C. However, the groundwater quality is likely to change in time for two reasons. On one hand, contaminant concentrations in the tailings seepage may increase somewhat as all process water is flushed out and the water quality approaches more and more that of “mature” tailings seepage controlled by solubility of secondary minerals (Table 4). On the other hand, the rate of tailings seepage will decrease in time as the process water drains from the tailings resulting in a greater potential for dilution in the long-term. The

transient process of tailings dewatering (after closure) was simulated in order to obtain estimates of tailings seepage as a function of time after closure of the facility. These seepage rates were then used to predict the water quality in the receiving groundwater (shallow alluvial aquifer) assuming conservative mixing, i.e. assuming dilution is the only attenuation mechanism.

A finite element model for saturated/unsaturated flow (SEEP/W) was used to simulate tailings seepage. Figure 8 shows the calibrated flow model for current seepage conditions for the Dam 1/IC impoundment. Note that the model includes groundwater flow in the underlying shallow alluvium. The rates of underflow were taken from the local groundwater flow model and assumed to be constant over time. The seepage model was calibrated, to the extent possible, using estimates of current tailings seepage and observed water levels in the tailings and groundwater (see Robertson GeoConsultants, 1998 for details).

Seepage from the tailings can be subdivided into “shallow seepage” and “deep seepage”. Shallow tailings seepage flows in a perched zone above the regional water table, i.e. has little potential for dilution in vicinity of the tailings dam (Figure 8). Deep tailings seepage percolates through semi-confining beds of clayey silt and mixes with groundwater in the alluvial aquifer system (Figure 8). The calibrated flows for the shallow and deep tailings seepage were 10.5 l/s (0.37cfs) and 6 l/s (0.21cfs), respectively. All tailings seepage eventually mixes with the groundwater of the shallow alluvial aquifer system and discharges at or near the Red River.

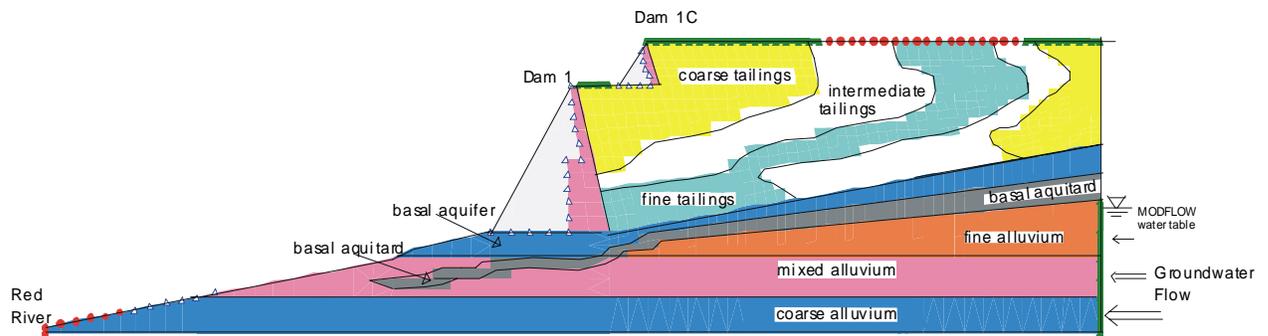


Figure 8a Setup of 2D tailings seepage model.

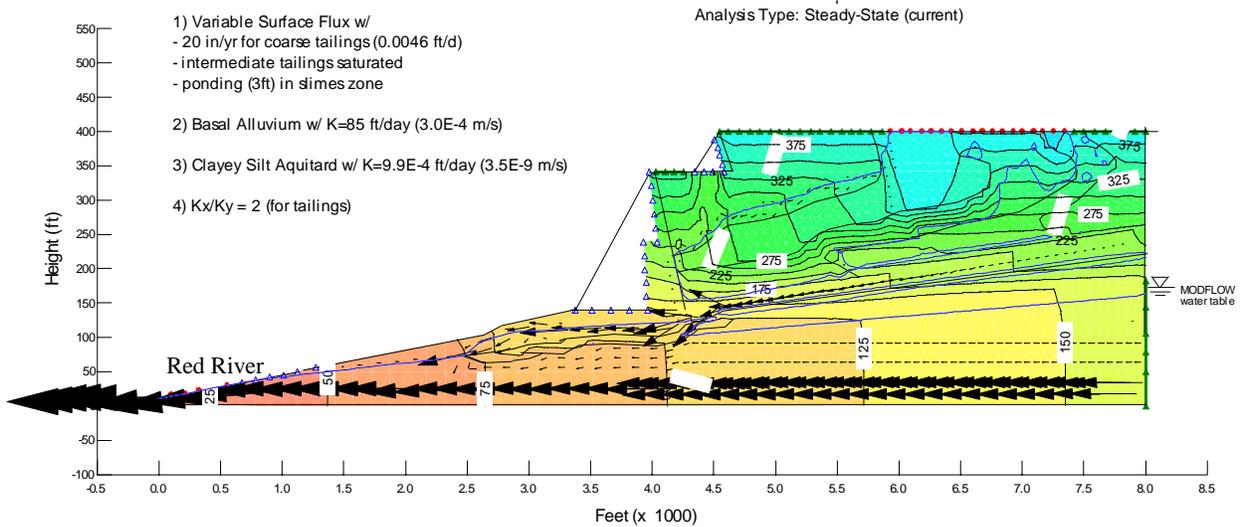


Figure 8b Simulated hydraulic head for calibrated steady-state seepage.

For the transient simulation, a cover was assumed to be present at the tailings surface, thus reducing surface fluxes into the tailings. In practice, the main purpose of this soil cover would be to minimize dusting and act as an initial growth medium for re-vegetation. In addition, this simple cover, together with the upper tailings profile, will act as a “store-and-release” cover, reducing net infiltration due to the semi-arid conditions at the site. Previous cover modeling suggested that the long-term flux through a vegetated alluvial cover (9 inches thick) would be 10 mm/yr (0.4 inches/year) over the fine tailings and 28 mm/yr (1.1 inches/year) over the coarse tailings (Robertson GeoConsultants, 1998). For the purposes of this analysis it was assumed that the placement of the soil cover reduces surface fluxes initially to half of the (calibrated) steady-state flux at the tailings surface. After that surface fluxes were assumed to decline exponentially reaching the long-term fluxes for a mature cover after about 10 years.

The transient model predicts that total tailings seepage flux at the base of the tailings impoundment would decline exponentially in time (Figure 9). The shallow seepage flow decreases very rapidly declining to 10% of its initial flux within ~12 years after cover placement. The transient model further suggests that shallow seepage would dry up completely after about 20 years (Figure 9). Deep seepage is predicted to decline over a greater time period and more gradual than the shallow tailings seepage. The apparent delay in the decline of the deep seepage is caused by the fact that the deep seepage has to move through the (low permeable) basal aquitard and some unsaturated alluvial material before it mixes with the groundwater in the more permeable aquifer units below. The transient model suggests that the system reaches “post-closure steady-state”, i.e. when the deep tailings flux approaches the surface flux entering the tailings, approximately 35 to 40 years after cover placement (Figure 9).

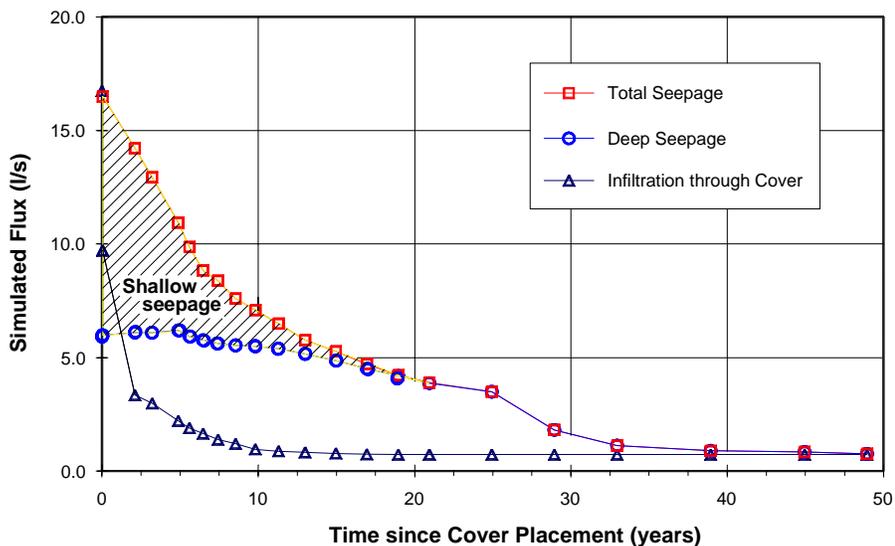


Figure 9 Predicted tailings seepage fluxes using transient 2D seepage model.

The results of the seepage modeling were used to predict water quality trends in the alluvial aquifer system after cover placement. The future concentrations of sulfate, molybdenum and TDS in groundwater were calculated assuming conservative mixing of tailings pore water and receiving groundwater and assuming that the receiving groundwater flows remain constant whereas tailings seepage flows decline (as predicted by the 2D transient seepage model). Water quality predictions were made for three different estimates of future tailings pore water concentrations (C_{PW}):

1. observed concentrations in boreholes completed near the base of the tailings (Table 2);
2. back-calculated concentrations from leach extraction tests for deep tailings samples (Table 4)
3. back-calculated concentrations from leach extraction tests for near-surface tailings samples (Table 4)

The back-calculated constituent concentrations in tailings pore water are significantly higher than those currently observed near the base of the tailings impoundment (c. Tables 2 and 4). It is believed that current

tailings seepage is dominated by process water which, on average, has significantly lower sulfate, molybdenum and TDS concentrations than those back-calculated concentrations from leach extraction tests. The seepage modeling suggests that process water will remain the dominant component of tailings seepage for at least 15 to 25 years after cover placement. Only at that time will unsaturated flow through the oxidized tailings (with potentially higher sulfate, molybdenum and TDS concentrations) become a major component of tailings seepage entering the groundwater system. Hence, the first scenario likely provides a lower bound for seepage water quality predictions (applicable during the early years after cover placement), whereas the third scenario provides an upper (conservative) bound (applicable only many years after cover placement).

Note that scenarios 2 and 3 assume that long-term solute concentrations will be controlled by precipitation/dissolution reactions (notably gypsum controlling sulfate). In other words, solute concentrations are assumed to be independent of pore water flux once the equilibrium concentrations have been reached. This assumption is consistent with field observations of tailings pore water quality observed in borehole BH-1 which is completed in an area of the tailings impoundment which has not received tailings slurry for 27 years.

The water quality predictions generally suggest that, in time, dilution will be sufficient to reduce contaminant concentrations in the shallow alluvial aquifer system downstream of the Dam 1/1C impoundment to acceptable levels. Table 5 lists the estimated times to meet groundwater quality standards in the upper (perched) layer and at depth below Dam 1/1C. The water quality predictions suggest that shallow (perched) groundwater flow, consisting of up to 70-75% tailings seepage, will not meet New Mexico Ground Water standards for at least 5-18 years after cover placement. In contrast, groundwater in the deeper alluvial layers which receive “deep” tailings seepage, will always comply with New Mexico Ground Water standards (as is currently observed, see Table 2).

Table 5 Estimated time to meet New Mexico Ground Water Standards in shallow alluvial aquifer system immediately downstream of the Dam 1/1C impoundment (in years after cover placement).

Constituent	Time to meet New Mexico Ground Water standards (in years after cover placement)	
	in upper (perched) groundwater at toe of Dam 1/1C	in groundwater at greater depth beneath Dam1/1C
Sulfate (NMWQCC standard = 600 mg/l)		
$C_{PW} = 1130$ mg/l	~5	0
$C_{PW} = 2278$	~10	0
$C_{PW} = 2654$	~11	0
Molybdenum (NMWQCC standard = 1.0 mg/l)		
$C_{PW} = 5.2$ mg/l	~11	0
$C_{PW} = 24.6$	~17 ¹	~27 ¹
$C_{PW} = 48.1$	~18 ¹	~32 ¹
TDS (NMWQCC = 1000 mg/l)		
$C_{PW} = 2000$ mg/l	~6	0
$C_{PW} = 3285$	~10	0
$C_{PW} = 3890$	~11	0

Notes:

1. molybdenum concentrations assumed for pore water likely too high (see text)
2. “0” indicates that constituent concentration is estimated to never exceed New Mexico Ground Water Standard

Figure 10a/b shows the predicted trends of sulfate and molybdenum in shallow (perched) groundwater over time. The model calculations suggest that sulfate concentrations in shallow groundwater will improve significantly within 5-10 years after cover placement (Figure 10). As mentioned earlier, the sulfate predictions for scenario 2 ($C_{PW} = 2278$ mg/l) and scenario 3 ($C_{PW} = 2654$ mg/l) are unrealistically high for early times (sulfate concentration in shallow groundwater are presently only about ~800 mg/l). In our opinion the slow dewatering of the tailings (with predominantly process water) will result in only a very small rise in sulfate concentrations for the first 15 years or so after cover placement as indicated by the solid (red) line in Figure 10a/b.

It is emphasized again that these predictions assume that the tailings pore water will be buffered indefinitely by the available alkalinity (in the form of calcite) as suggested by the static and kinetic testing and the actual field response (in particular those areas which have been inactive for 27 years).

According to model calculations molybdenum concentrations in shallow (perched) groundwater will also meet New Mexico Groundwater Standards within 10-20 years after cover placement (Figure 10b; Table 5). Again, the calculated molybdenum concentration values for the first fifteen years are considered very conservative. The molybdenum concentrations are not expected to increase above current concentrations over the next 10-15 years due to the slow dewatering of the tailings (see solid line; Figure 10b). Note that molybdenum concentrations in groundwater may be further reduced due to attenuation in the alluvial aquifer material by adsorption/precipitation (see above). However, there was insufficient data on the magnitude and long-term sustainability of this mechanism; hence adsorption/precipitation was not further considered to provide conservative long-term water quality predictions.

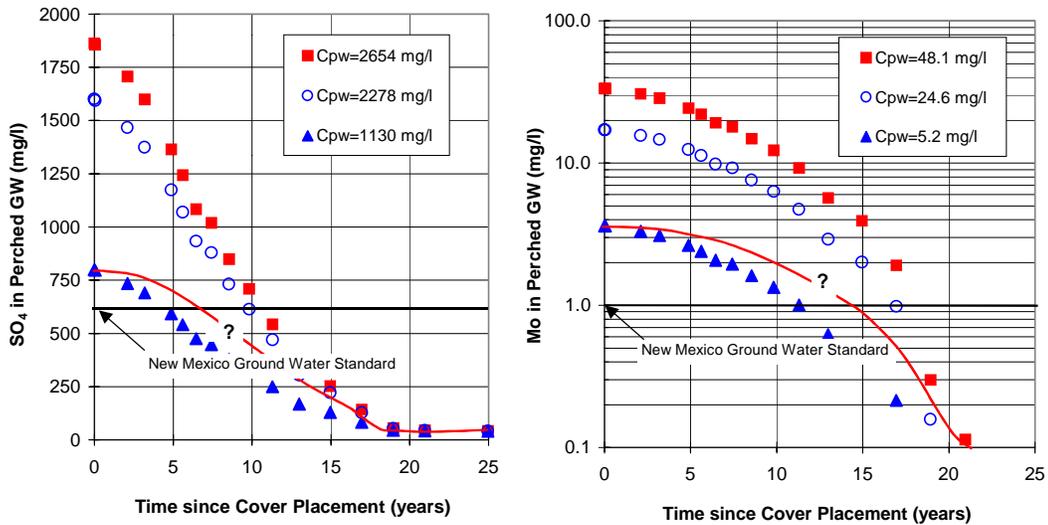


Figure 10a/b Predicted concentrations of sulfate (left) and molybdenum (right) in upper (perched) groundwater versus time. Solid (red) line indicates time trends considered most realistic.

In summary, seepage modeling and simple mixing calculations suggest that dilution of tailings seepage will be effective in reducing contaminant concentrations in the receiving groundwater beneath the Dam 1/1C impoundment to below NMWQ standards in the long-term (i.e. 15-20 years after cover placement). The improvement in groundwater quality is a result of an exponential decline in tailings seepage after cover placement, combined with a delay in the breakthrough of unsaturated flow through the oxidized tailings (with potentially higher sulfate, molybdenum and TDS concentrations).

CONCLUSIONS

Detailed geochemical and hydrological analyses were performed to assess the potential for intrinsic remediation of groundwater impacted by seepage from a large reactive tailings impoundment. It is concluded that the natural attenuation mechanisms of precipitation within the tailings (as a result of buffering) and dilution/dispersion within the aquifer are currently active and likely sufficient to reduce contaminant concentrations to below state standards in the long-term. Other natural attenuation mechanisms such as sorption and biodegradation within the receiving aquifer(s) were not assessed here, but are likely further reducing contaminant concentrations.

The main factors contributing to the potential for intrinsic remediation as a viable closure option for the Questa tailings facility are:

- demonstrated, long-term buffering capacity of the tailings (preventing ARD);
- large reduction in tailings seepage after closure due to semi-arid climate conditions; and
- substantial groundwater flows (recharged in near-by mountain ranges).

Intrinsic remediation, i.e. the reliance on natural attenuation mechanisms for remediation of contaminated groundwater, always requires environmental monitoring to verify that all ground water quality standards are met at the compliance points (Chapelle, 1999). At the Questa tailings facility, active interception and recovery of the seepage water is being maintained until monitoring demonstrates that intrinsic remediation has successfully achieved the level of water quality control required.

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