Factors Influencing Net Infiltration into Mine Rock Piles at Questa Mine New Mexico

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ABSTRACT: From 1965 to 1983 large-scale open pit mining at the Questa mine, located in the Sangre de Cristo Mountains, New Mexico, produced over 300 million tonnes of mine rock, which was end-dumped into several steep valleys adjacent to the open pit. As a result, the mine rock piles are in general at angle of repose and vary in aspect and elevation (2,440m – 3,050m). Results of a detailed drilling program indicated significant variations in moisture contents between different rock piles (Shaw et al, these proceedings). Detailed monitoring of local climate conditions at six sites and measurements of net infiltration into the mine rock profile using four lysimeter test plots at three sites was carried out to evaluate the influence of local microclimate and physical mine rock properties on net infiltration. Initial results for the first year of monitoring indicated large variations in net infiltration. The local micro-climate at the high elevation site, in particular the development of a snow pack during the winter months, was found to result in significant net infiltration (~30% of annual precipitation). In contrast, warmer air temperatures combined with strong winds prevented the development of a continuous snow pack at the mid and low elevation sites resulting in higher actual evaporation and much reduced net infiltration (<6% of annual precipitation). The physical properties of the mine rock (particle size distribution, moisture retention capacity, Ksat) also influence net infiltration but to a lesser extent than the local microclimate.

1 INTRODUCTION

The Questa molybdenum mine, owned and operated by Molycorp Inc., is located 5.8 km east of the town of Questa in Taos County, New Mexico. From 1965 to 1983 large-scale open pit mining at the Questa mine produced over 300 million tonnes of mine rock, which was end-dumped into various steep valleys adjacent to the open pit (Figure 1). As a result, the mine rock piles are typically at angle of repose and have long slope lengths (up to 600m) and comparatively shallow depths (~30-60m). These conditions have large implications with respect to long-term oxidation and acid mine drainage from these rock piles and require definition and evaluation before appropriate mine closure measures can be developed.

Molycorp Inc. initiated a comprehensive characterization program in 1998 for the mine rock piles in order to provide a basis for the development of a closure plan (see Shaw et al., these proceedings). This characterization program included field reconnaissance and sampling of mine rock, physical and geochemical testing in the laboratory, as well as test plot and numerical model studies (RGC, 2000c). This paper focuses on the infiltration test plot study, which was initiated as part of this comprehensive characterization program (RGC, 2000a).

The principal objective of the infiltration test plot study is to collect site-specific data for estimating the net infiltration rate into the mine rock piles (i.e. rate of infiltration into the mine rock to a depth where it is no longer available for evapotranspiration). These estimates will provide the basis for estimating seepage from the rock piles and developing a water and load balance for the mine site.

2 SITE DESCRIPTION

The Questa mine site is located on the south facing slopes of the Sangre de Cristo Mountains in the middle reach of the Red River Valley (Figure 1). The mine rock piles cover a surface area of about 275 ha and extend vertically from just above the elevation of the Red River (~2,470m amsl) to about

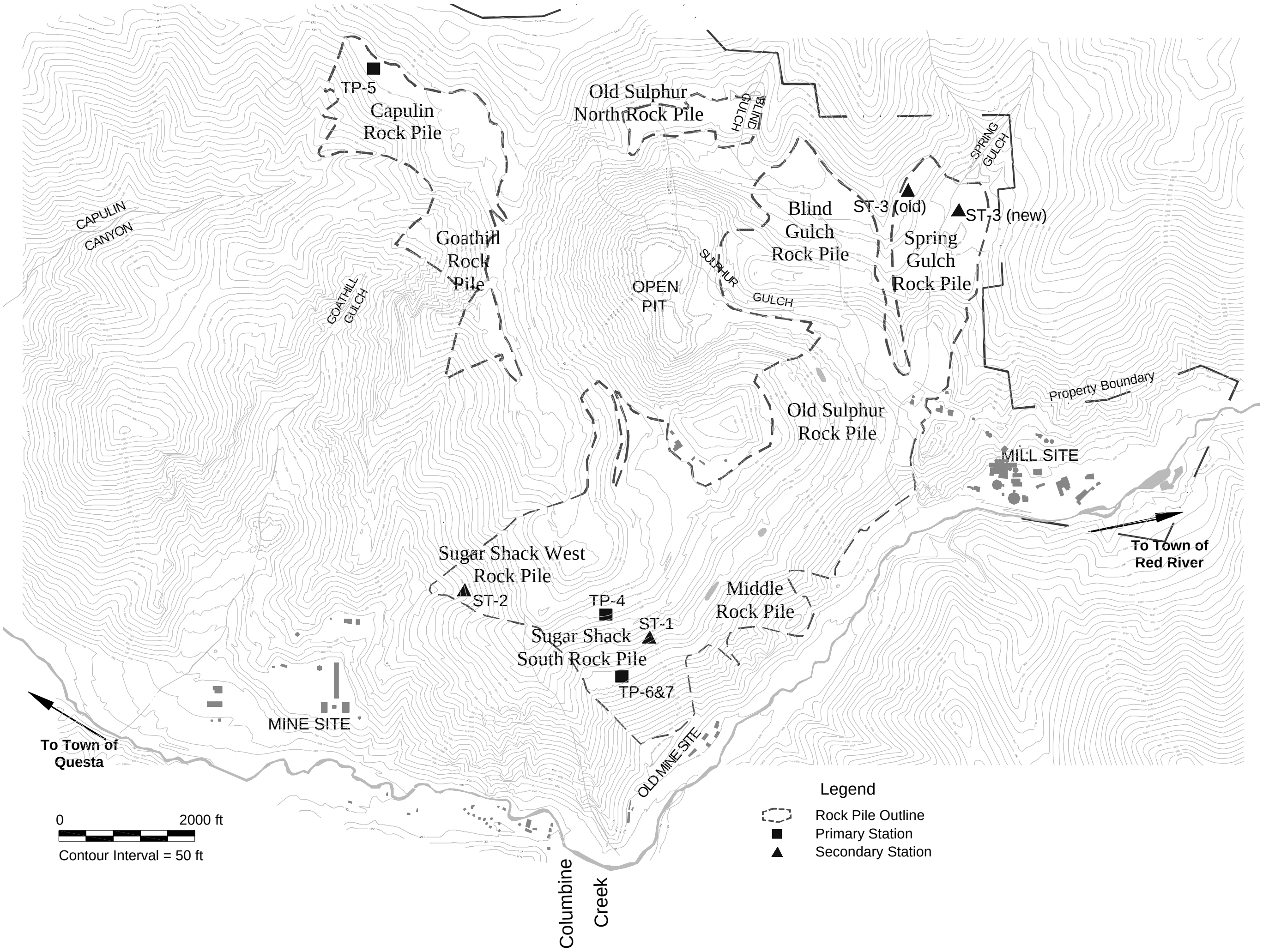

Figure 1. Location map of Questa showing mine rock piles and infiltration test plots.

elevation 2,990m amsl, resulting in some of the highest mine rock piles in North America.

The physical and geochemical characteristics of the Questa mine rock are described in Shaw et al. (these proceedings). Briefly, the Questa mine rock can be divided into four broad categories (i) well-graded (finer) mixed volcanics; (ii) poorly-graded (coarser) aplite/black andesite; (iii) fine-grained erosion material (typically gap-graded); and (iv) very coarse rubble material (predominantly aplite/black andesite). Typically, the ‘mixed volcanics’ are composed of hydrothermally altered and highly weathered andesitic rock (including “scar material”). The erosion material represents mixed volcanic material, which was mobilized upslope and re-deposited further downslope during heavy rainstorm events (RGC, 2000b). This erosion material typically forms a very thin “crust” (~0.3-0.6m) in the up- and mid-slope areas but can be several meters thick near the toe of the rock slopes. The aplite porphyry and the black andesite are relatively competent, coarse rocks with little visual evidence of sulfide oxidation processes and physical weathering.

The climate is semi-arid with mild summers and cold winters. The average monthly temperature is below freezing for five months of the year (November through to March). The long-term average annual precipitation at the mill site (located at the base of the mine site) is approximately 400mm (15.8 inches). Lake evaporation (large free-water surface) and actual evapotranspiration (land surface including transpiration from vegetation) on site are estimated to be 1000mm (39.4 inches) and 400mm (15.8 inches), respectively (RGC, 2000c).

3 DESIGN OF TEST PLOT STUDY

In general, the amount of net infiltration into mine rock piles is controlled by (i) local climate conditions (precipitation and potential evaporation); (ii) physical properties of the mine rock (e.g. grading, moisture retention, permeability); and (iii) geometry and structure of the rock pile (e.g. slope angle, layering).

The key climate parameters influencing net infiltration (i.e. precipitation and potential evaporation) can be expected to vary significantly at a high-relief site such as the Questa mine. Long-term climate data from regional weather stations suggest a general in-

Table 1. Summary of instrumentation at primary and secondary stations.

Location	Station ID	Material	Lysimeter Test Plot Instrumentation			In-situ Monitoring	Met Station Instrumentation (dedicated)			
			Soil Suction Sensors	Soil Moisture Access Tube	Drain flow Monitoring	Soil Moisture Access Tube	PREC	RH & T	W SP	NET R
Primary Stations										
upper bench on Sugar Shack South (near WRD-5)	TP-4	well-graded (finer) mine rock	10	1	yes	1	X	X	X	X
top of Capulin (near WRD-8)	TP-5	well-graded (finer) mine rock	10	1	yes	1	X	X	X	X
lower bench on Sugar Shack South (near WRD-3)	TP-6	poorly-graded (coarse) mine rock	-	1	yes	N/A	X	X	X	X
	TP-7	1ft of finer sediment over poorly-graded (coarse) mine rock	-	1	yes	N/A				
Secondary Stations										
midslope on Sugar Shack South (near WRD-4)	ST-1	poorly-graded (coarse) mine rock covered with fine sediment layer	N/A			5	X	-	-	
midslope on Sugar Shack West (near WRD-6)	ST-2	well-graded (finer) mine rock covered with sediment layer	N/A			5	X	-	-	
plateau area in Spring Gulch (near WRD-1)	ST-3	well-graded (coarser) mine rock	N/A			5	X	-	-	

Legend
N/A = not applicable
X = to be installed
- = not to be installed
5 = number of sensors/instruments

Abbreviations:
PRECIP = Precipitation (tipping bucket w/ snowfall adaptor)
RH & T = Relative humidity and temperature (RH/T sensor)
W Sp = Wind Speed (Wind Monitor)
NET R = Net Radiation (net radiometer)

crease in precipitation with elevation (approximately 43mm for every 90m increase in elevation, Wels et al, 2001). In addition, the duration of snow cover and the depth of snowpack generally increases with higher elevations, which may also significantly increase the amount of net infiltration (RGC, 2001b). Potential evaporation also shows a relationship with elevation (i.e., a decrease with increase in elevation) at a regional scale. However, potential evaporation is influenced by a variety of climate parameters (air temperature, relative humidity, net radiation and wind speed) and as such can be expected to deviate from this regional trend depending on local site conditions (e.g., aspect, ground cover, location along slope).

The physical properties of the mine rock near the surface are also expected to influence the amount of net infiltration. Field reconnaissance and laboratory testing indicated that the particle size distribution and associated hydraulic properties (soil water characteristic curve (SWCC) and hydraulic conductivity function) of the Questa mine rock varied significantly (see RGC 2000b, Wels et al., 2001). Hence, the rate of net infiltration can also be expected to vary significantly among those material types.

Finally, the geometry of the mine rock pile, in particular slope angle and layering, may also influence the amount of net infiltration. The major difference between infiltration on a sloped surface and a flat surface is the potential for greater surface runoff and capillary break effects on the slope resulting in lateral flow parallel to the slope. These factors would tend to result in lower rates of net infiltration along the slopes relative to the flat top of the mine rock piles.

The test plot study was designed to evaluate all three factors controlling net infiltration, i.e. climate conditions, physical material properties and rock pile geometry. A total of three primary stations and three secondary stations were instrumented (see Figure 1 for locations). Table 1 summarizes the instrumentation at the various locations. At each primary station, an instrumented lysimeter and a detailed weather station were set up. The lysimeter tank, which has a diameter of 2.4m and a depth of 2.3m, was placed in an excavation and backfilled with mine rock material from that location (Figure 2). The base of the excavation was prepared as a conical depression (about 5-20cm dip over the radius of excavation) to allow the tank to develop a slight slope towards the 50mm diameter drain in the center of the tank. The lysimeters are free-draining and outflow is monitored continuously using a tipping bucket and a data logger (see RGC, 2000d for more details).

Note that construction of such lysimeters was only feasible on flat surfaces. Attempts were made to install moisture content sensors into the angle-of-

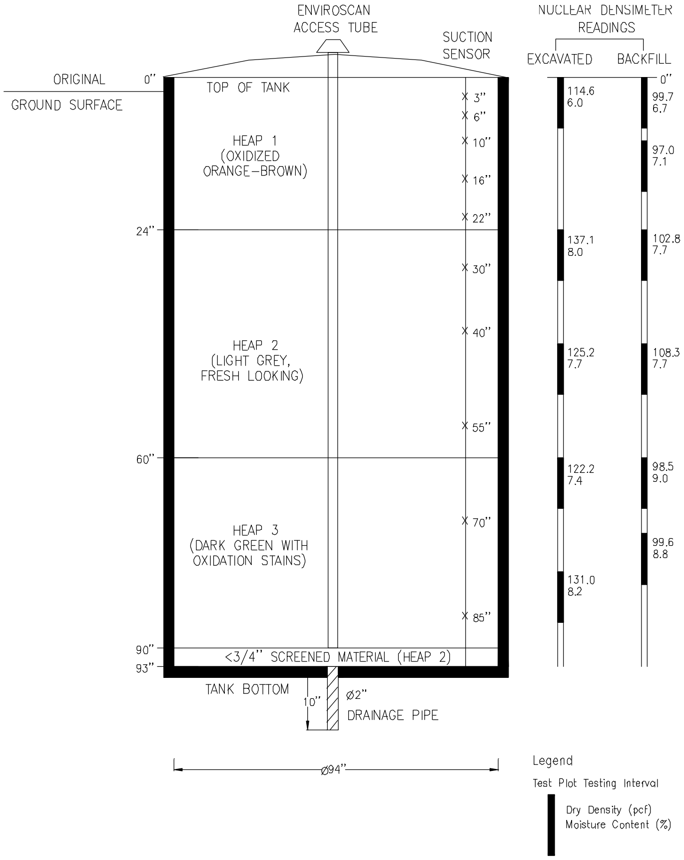

Figure 2. As-Built drawing for test plot lysimeter TP-5.

repose rock slopes (at the secondary stations) in order to measure in-situ moisture contents. However, these sensors did not provide reliable field data (Wels et al, 2001). Therefore, the net infiltration for sloped surfaces will have to be modeled using a soil-atmosphere model calibrated using the soil monitoring data from the lysimeter test plots and climate data from the secondary stations.

The four lysimeter test plots at the primary stations were designed to allow a detailed assessment of net infiltration of four different scenarios (see Figure 1 for location):

- well-graded (finer) mine rock material at mid-elevation (El. 2820m) (TP-4 at upper bench of Sugar Shack South rock pile);
- well-graded (finer) mine rock material at high-elevation (El. 2990m) (TP-5 on top of Capulin rock pile);
- poorly-graded (coarse) mine rock material at low elevation (El. 2660m) (TP-6 at lower bench of Sugar Shack South); and
- poorly-graded (coarse) mine rock covered with 0.3m (1ft) of fine-grained sediment material at low elevation (TP-7 at lower bench of Sugar Shack South).

Note that the lysimeter test plots were not revegetated. For more details on the design, construction and instrumentation of these test plots the reader is referred to Wels et al. (2001).

4 1ST YEAR MONITORING RESULTS

Table 2 summarizes the monitoring results at the four lysimeter test plots for the first year of monitoring (August 2000 – July 2001). The first year summary data indicate a very large difference in lysimeter outflow ranging from insignificant or no outflow for TP-4 and TP-7 to 115.8mm (4.56 inches) in TP-5. The differences in total precipitation and potential evaporation was comparatively small (<25% between any two stations) and showed no clear correlation with the outflow data (Table 2).

These summary statistics indicate that factors other than precipitation and potential evaporation such as material properties and/or other climatic factors must influence net infiltration into the mine rock piles. A detailed analysis of the climate and lysimeter data (including regression analysis and time trend analysis) was carried out to determine the factors controlling net infiltration into the mine rock.

4.1 *Climate Data*

Figure 3 shows scatter plots of daily precipitation measured at the primary stations TP-5 and TP6&7 versus those measured at TP-4. The results of a linear least square regression analysis are also shown (see solid line). The 1:1 line is shown for comparison (dashed line). The scatter plots suggest relatively uniform rates of precipitation across the mine site. The linear regression explains between 75-82% of the variation between any two sites.

The high elevation site (TP-5) received systematically lower precipitation during the few mid to high precipitation events (>10mm/day); however the opposite trend was observed for low precipitation events (Figure 3). In general, the low elevation site (TP6/7) matched precipitation rates observed at the mid-elevation site (TP-4) very well (Figure 3). However, TP6/7 received significantly more precipitation during some of the winter snowfall events resulting in higher total precipitation for the year (Table 2). In summary, the first year monitoring data do not support the general trend of increasing precipitation with higher elevation observed for the regional climate stations (Wels et al., 2001).

Figure 4 shows scatter plots of daily potential evaporation at the primary stations TP-5 and TP6&7

Table 2. Summary of Climate Data (July 23, 2000 – July 23, 2001).

	TP-4	**TP-5**	**TP-6**	**TP-7**
Cumulative precipitation (mm)[1]	380.0	395.5	462.3	
Cumulative Potential Evaporation (mm)[1]	1213.7	931.7	1143.8	
Lysimeter Outflow (mm)	0.055	115.92	25.90	0

Notes:

1. Missing data were patched with data from nearest weather station where required.

versus those measured at TP-4. Note that potential evaporation was calculated using the Penman method, which requires daily average air temperature, relative humidity, net radiation, and wind speed (Penman, 1948). The scatter plots indicate a very good correlation between the mid and low elevation sites on Sugar Shack South (TP-4 and TP-6&7). In contrast, the high elevation site on Capulin (TP-5) recorded significantly lower potential evaporation rates, in particular during the winter months (circles). The lower potential evaporation rates at the high elevation site are predominantly a result of lower air temperature combined with lower net radiation (due to a continuous snow pack for most of the winter months, see below).

Snow surveys were carried out at the primary and secondary stations between January and May 2001 to estimate the accumulation and ablation of the snowpack across the mine site. Figure 5 shows the measured snow water equivalents (average of 10 point values per site) for the spring of 2001. Note that some snow accumulation occurred in November 2000 (not shown). However, most of this snow had disappeared by early January 2001, when the first snow survey was taken. The snow survey data indicate significant differences in snowpack development across the site. As expected the largest snowpack was observed at the high elevation site (TP-5) with a peak snow water equivalent (SWE) of 107mm (4.2 inches) in late March 2001. Some, albeit smaller, snowpack development was also observed at the secondary station ST-3 (Spring Gulch) (see Figure 1 for location). At the other three primary stations on Sugar Shack South (TP-4 and TP-6/7) the winter snowfall did not result in any significant snowpack accumulation (presumably due to the warmer temperatures/higher net radiation on these south-exposed slopes). These differences in snowpack development were found to have a strong influence on the rate of net infiltration into the mine rock piles (see below).

4.2 *Test Plot Response*

Figure 6 shows the time trends of soil suction at selected depths for the first year of monitoring in test plots TP-4 and TP-5. Soil suction was measured in these lysimeter test plots using a thermal conductivity type sensor (Campbell Scientific Inc. model 229). Similar measurements could not be taken in test plots TP-6 and TP-7 due to the coarse nature of the backfilled mine rock in those lysimeters (Wels et al., 2001).

The time trends in soil suction illustrate the difference in the wetting of the two mine rock profiles. In test plot TP-5, the heavy rains in August 2000 (78.7mm fell between August 13-29) resulted in a rapid wetting of the top 0.75m (note steep decline in soil suction at 0.76m depth around late August). The wetting of the deeper mine rock profile of TP-5 occurred more gradual. By mid-December the entire mine rock profile had "wetted up" and soil suction had reached values near saturation (<1 kPa). Note that the soil suction remained near saturation throughout the spring runoff and early summer 2001, except for some drying in the near-surface layers (<0.30m).

In test plot TP-4, the heavy precipitation in August and October-November 2000 also resulted in a significant reduction in soil suction (wetting) in the near-surface (e.g. at a depth of 0.15m, Figure 6). However, the near-surface layers did not remain near saturation for any prolonged period of time, but instead, increased again within days after precipitation to higher suctions. The drier near-surface conditions resulted in a much slower wetting of the deeper mine rock profile. For example, at 0.76m depth a significant decrease in soil suction was only observed in mid-November. In the deeper mine rock profile (>1.40m below surface) the suction actually increased temporarily during the winter months suggesting a slight drying trend. The soil suction near the base of the lysimeter (at 2.24m depth) at the end of the first year of monitoring was still >70kPa, i.e. well below saturation.

The total outflow observed at the base of test plots TP-4 and TP-5 is consistent with the soil suction trends shown in Figure 6. In test plot TP-4 no discharge was observed in the first 12 months of monitoring (Table 2). In contrast, the total (cumulative) outflow collected from test plot TP-5 was 116mm (or ~30% of total precipitation, Table 2).

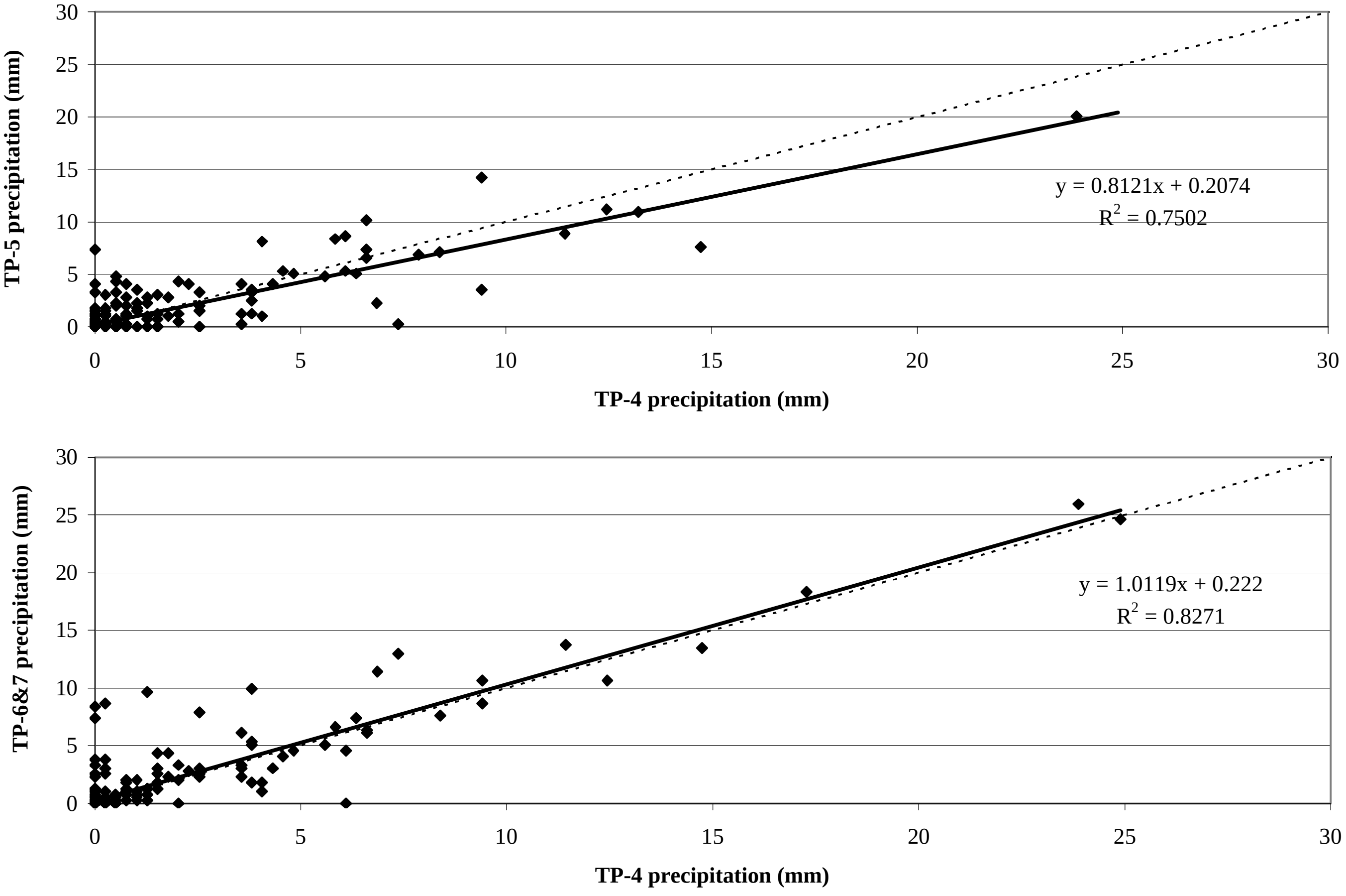

Figure 3. Comparison of daily precipitation at the three primary stations.

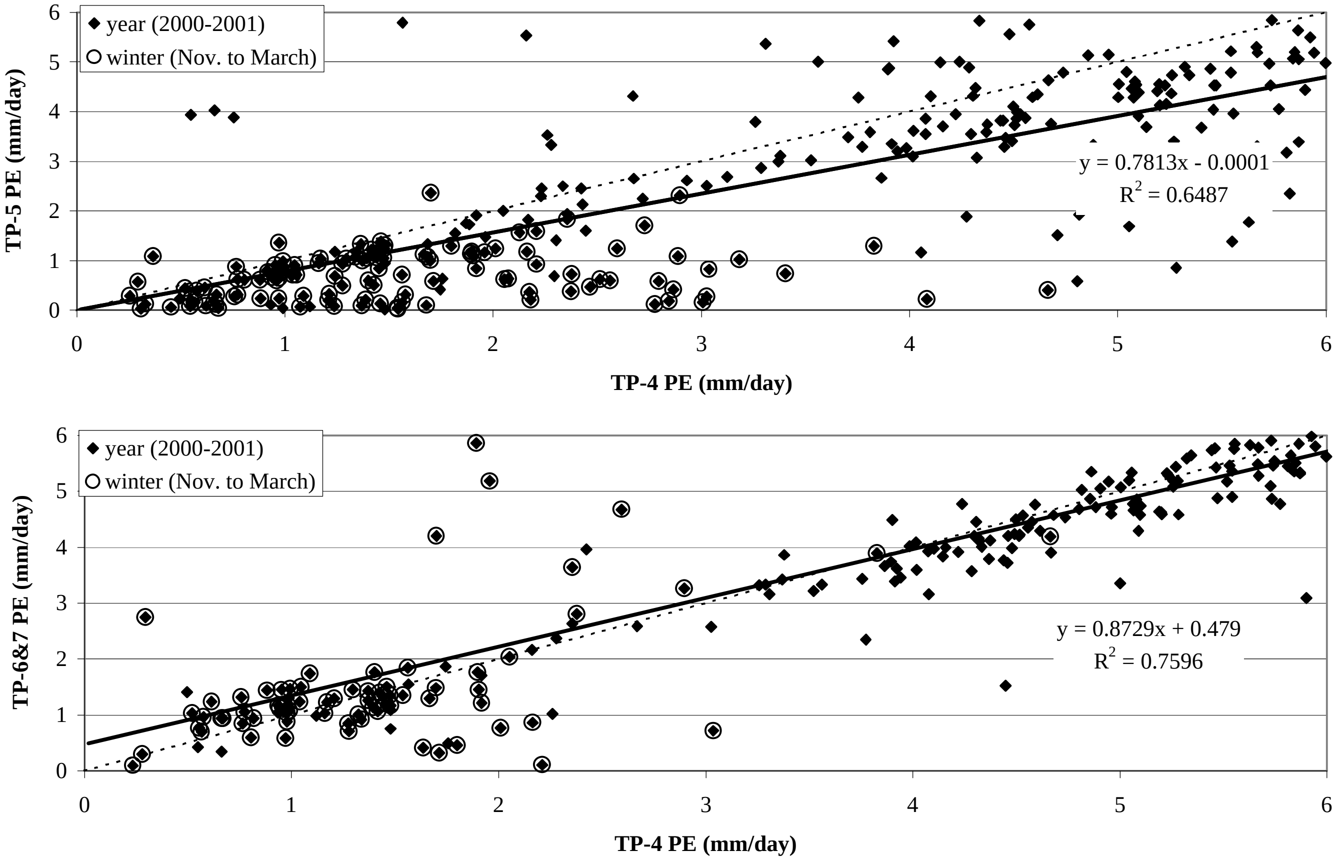

Figure 4. Comparison of potential evaporation at the three primary stations.

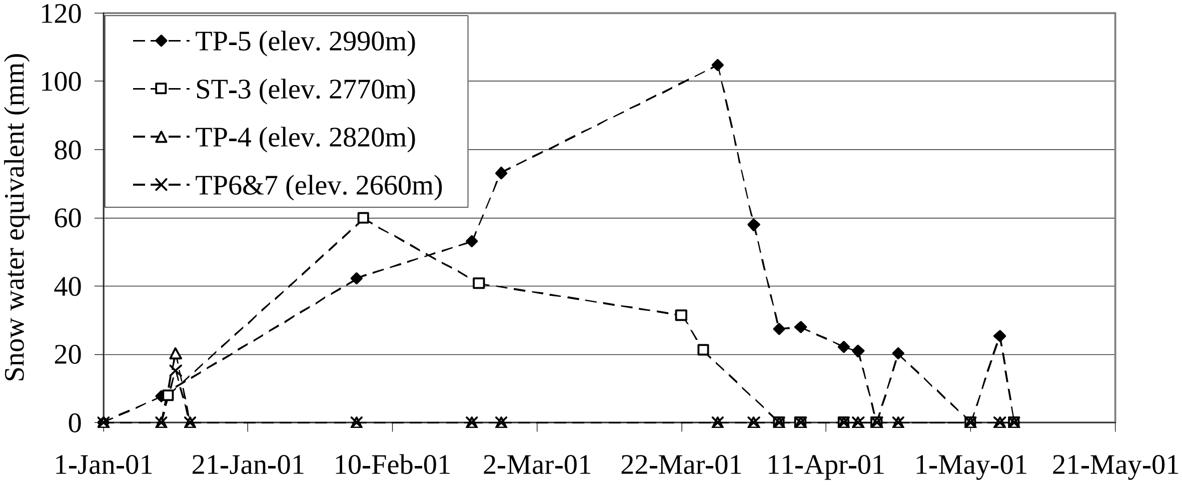

Figure 5. Results of snow surveys at primary and secondary stations (in water equivalents).

Figure 7 shows the daily and cumulative outflow from test plot TP-5 for the period January 1 – July 20, 2001 (lower panel). The snow water equivalent of the snowpack in this area is shown for comparison. Daily precipitation and average air temperature at this site are also shown (upper panel). The first significant outflow from TP-5 occurred in mid-March following several days of air temperatures above the freezing point (Figure 7). A detailed analysis of hourly outflow rates and climate data suggested a lag time of 24-36 hours between days of significant snowmelt and/or precipitation and increased outflow at the base of the lysimeter (RGC, 2001c). The outflow from the lysimeter gradually declined to very low rates (<0.254mm/day) after final depletion of the snowpack in mid-May. Note that the heavy precipitation events in June-July did not produce any significant outflow from the lysimeter. The data strongly suggest that the vast majority of net infiltration into the mine rock profile occurred during the snowmelt period.

Figure 8 shows the outflow data for test plot TP-6, located at the low elevation site. Outflow from test plot TP-6 was significantly lower (33mm) and more delayed than at TP-5 (c. Figures 7 and 8). This result was somewhat unexpected considering that test plot TP-6 was backfilled with much coarser, more permeable, mine rock than TP-5 (Wels et al., 2001). The much lower outflow rates are a result of higher storage requirements in the coarser mine rock and/or higher evaporative losses (relative to TP-5) resulting in reduced rates of net infiltration.

The main difference in climate conditions between the high and low elevation sites was the magnitude and duration of snowpack development (Figure 5). The lack of any snowpack at TP-6 likely allowed significant evaporation to occur from the mine rock surface throughout the winter and spring period. In contrast the development of a snowpack at TP-5 prevented evaporation until late into the spring season while, at the same time, delivering a large amount of melt water (up to 104mm of water equivalent) during a very short snowmelt period (~3 weeks). The amount and duration of a snowpack is believed to have a major control on the rate of net infiltration into the Questa mine rock piles.

Note that no outflow was observed in test plot TP-7 which only differed from TP-6 in the presence of a thin (0.3m) layer of finer-grained erosion material on top of the coarse-grained mine rock (Table 2). A comparison of these two test plots suggests that even a thin layer of finer-grained material can reduce the rate of net infiltration (under these climate conditions).

5 CONCLUSIONS

This paper describes the design and initial monitoring results of lysimeter test plots designed to study the net infiltration into mine rock piles at the Questa mine. Initial test plot data collected during the first year of monitoring illustrate the large variability in infiltration that might be expected under field conditions on the mine rock piles. The lysimeter test plot located at the high elevation site (El. 2990 m amsl) wetted up within 5 months and experienced 114mm (4.5 inches) of outflow during the spring runoff period. In contrast, the lysimeter test plot at the mid elevation site (El. 2820 m amsl) did not show any outflow within the first year despite similar physical properties of the mine rock profile. The lysimeter test plot located at the low elevation site (El. 2660m amsl) showed an intermediate response with some outflow (38.1mm (1.5 inches)) late in the spring runoff period.

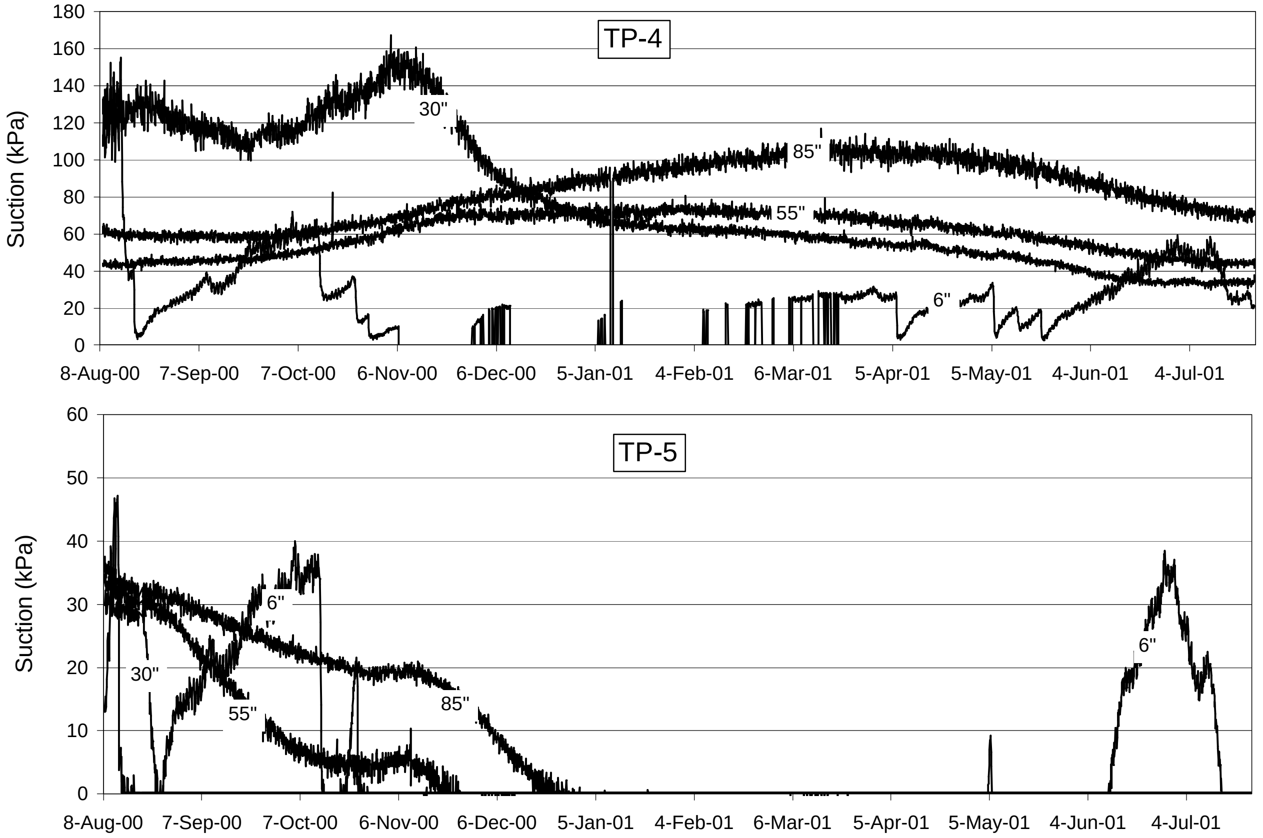

Figure 6. Time trends of soil suction in lysimeter test plots TP-4 and TP-5.

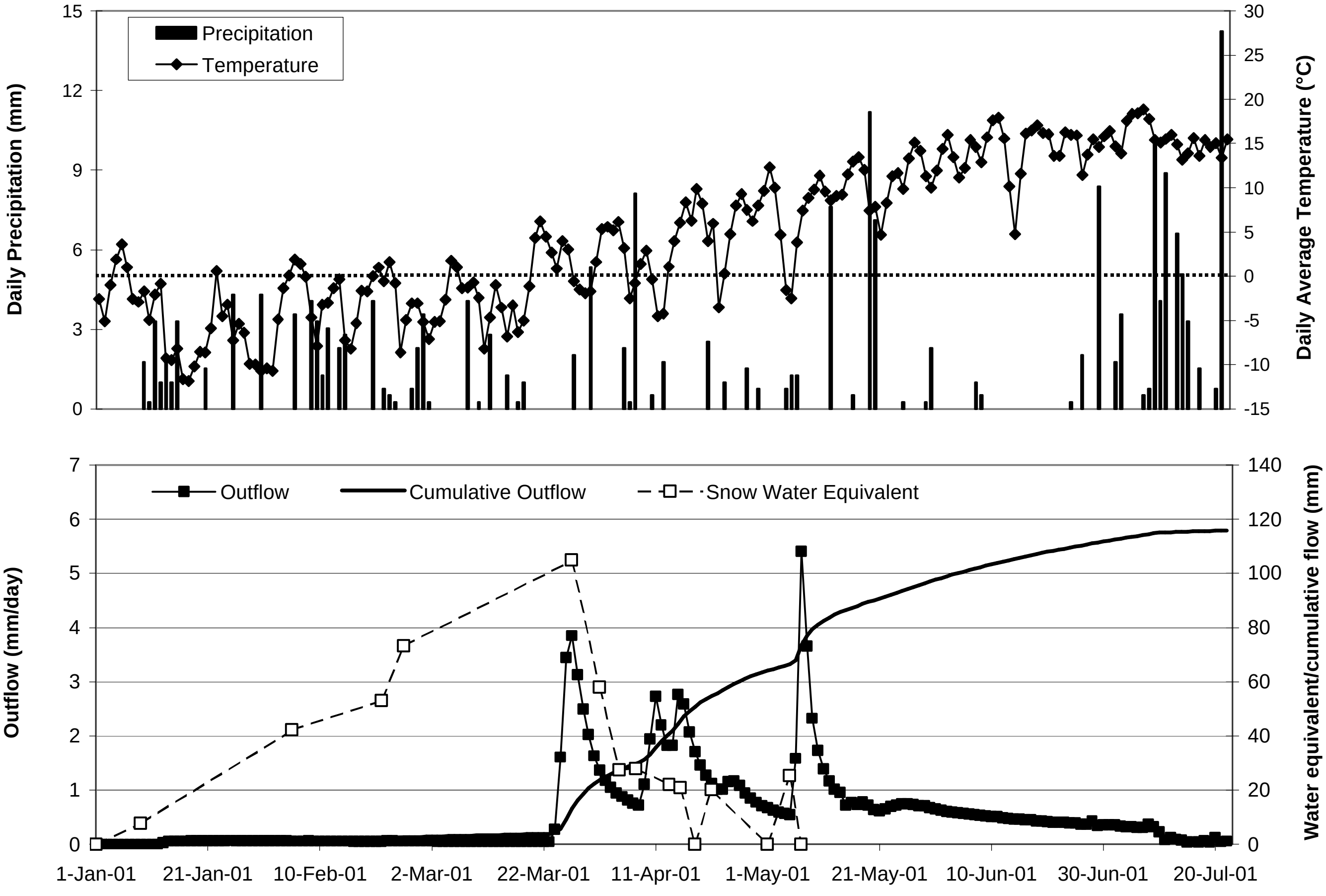

Figure 7. Outflow from lysimeter test plot TP-5 for the period Jan. 1 – July 23, 2001 (lower panel). Relevant climate parameters are shown for comparison.

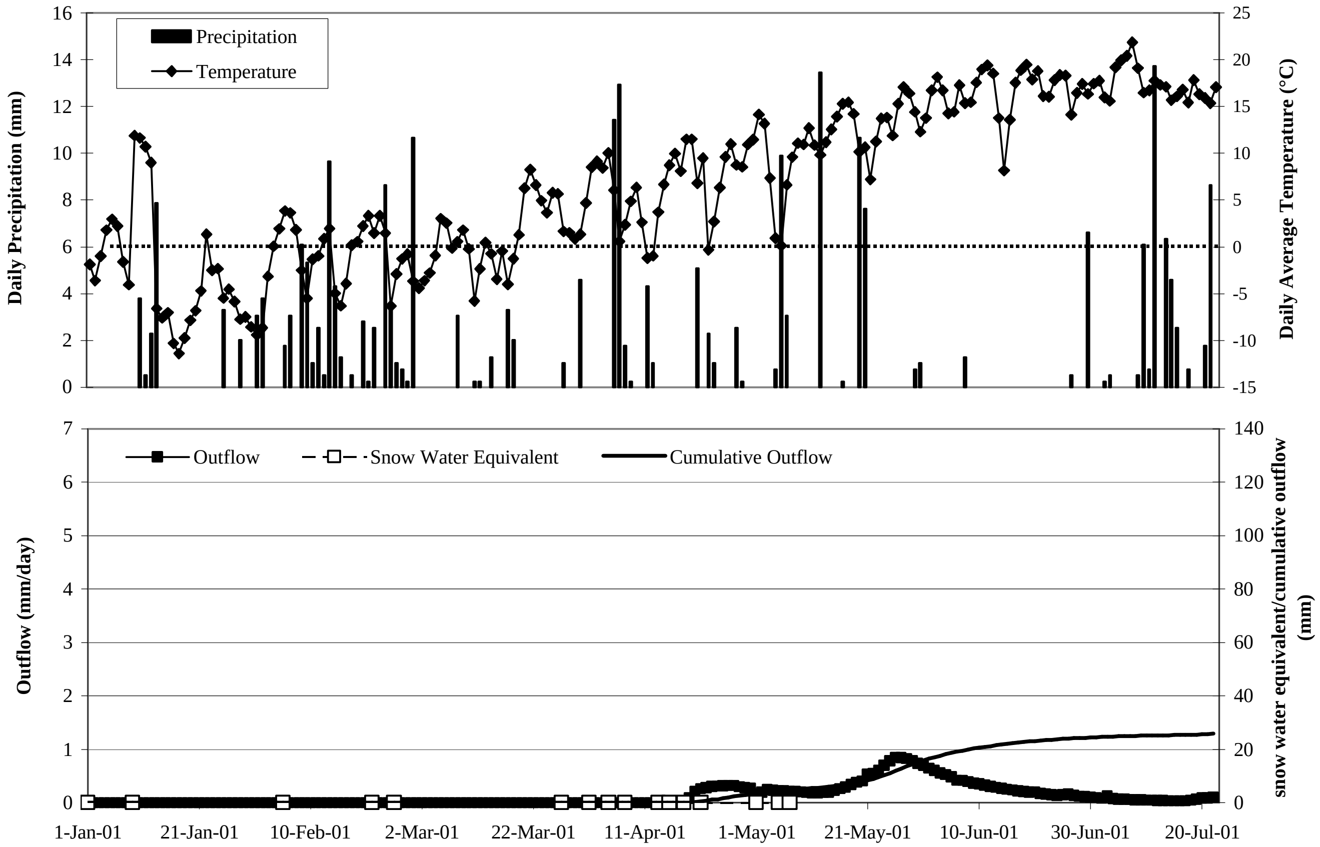

Figure 8. Outflow from lysimeter test plot TP-6 for the period Jan. 1 – July 23, 2001 (lower panel). Relevant climate parameters are shown for comparison.

The much higher rates of net infiltration at the high elevation site are attributed to the development of a continuous snowpack. The snowpack prevents any evaporation from the mine rock surface during the winter and spring months. In addition, melting of the “ripe” snowpack during spring runoff results in prolonged, high rates of infiltration (e.g. 104mm of snow water equivalent melted in ~21days).

This finding is consistent with initial soil atmosphere modeling carried out for the Questa mine rock piles which indicated that the rate of net infiltration is most sensitive to the amount of “effective precipitation” (i.e. snowmelt and rainfall) occurring during the spring runoff period (RGC, 2001a).

The physical properties of the mine rock, in particular in the upper 0.3m, were also found to have an influence on net infiltration, albeit to a lesser extent than the climate conditions. The presence of a thin (0.3m) layer of well-graded (finer) erosion material, commonly found on the slopes of the Questa mine rock piles, significantly reduced the rate of net infiltration at the low elevation site (no outflow has yet been recorded).

The results of this infiltration study are consistent with field observations which suggest significantly lower rates of seepage from the mine rock piles at mid to low elevations (e.g. Sugar Shack South) compared to those at high elevation (e.g. Capulin and Goathill). The spatial differences in local microclimate and net infiltration will have to be taken into consideration when developing a water and load balance for the Questa mine site.

Modeling work is currently in progress to calibrate the soil-atmosphere model SOILCOVER (Geo-Analysis 2000 Ltd., 2000) using the observed test plot data (RGC 2001b). Once calibrated, this soil atmosphere model can be used to assess the influence of local climate conditions, material properties and slope angle on the rate of net infiltration.

6 ACKNOWLEDGEMENTS

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REFERENCES

Geo-Analysis 2000 Ltd. (2000), SOILCOVER User's manual, May 2000.

Penman, H.L. 1948. Natural evapotranspiration from open water, bare soil and grass, *Proc. Royal Soc. London Ser.* A 193: 120-145.

Robertson GeoConsultants Inc. 2000a. Work Plan for Waste Rock Water Balance Study, Questa Mine Site, New Mexico, *RGC Report 052008/4 prepared for Molycorp Inc., February 2000*.

Robertson GeoConsultants Inc. 2000b. Progress Report: Results of Phase 1 Physical Waste Rock Characterization, Questa Mine, New Mexico. *RGC Report 052007/4 prepared for Molycorp Inc., June 2000*.

Robertson GeoConsultants Inc. 2000c. Interim Mine Site Characterization Study, Questa Mine, New Mexico, *RGC Report 052008/10 prepared for Molycorp Inc., November 2000*.

Robertson GeoConsultants Inc. 2000d. As-Built Report – Infiltration Test Plots for Mine Rock Piles, Questa Mine, New Mexico, *RGC Report 052008/11 prepared for Molycorp Inc., November 2000.*

Robertson GeoConsultants Inc 2001a. Initial Soil-Atmosphere Modeling for Mine Rock Piles, Questa Mine, New Mexico. *RGC Report 052008/14 prepared for Molycorp Inc., January 2001*.

Robertson GeoConsultants Inc 2001b. Progress Report on Water Balance Analysis for Mine Rock Piles, Questa Mine, New Mexico. *RGC Report 052008/17 prepared for Molycorp Inc., February 2001.*

Shaw, S., C. Wels, A. MacG. Robertson and G. Lorinczi 2002. Physical and Geochemical Characterization of Mine Rock Piles at the Questa Mine, New Mexico: An Overview, *9th International Conference on Tailings and Mine Waste '02:* Rotterdam: Balkema.

Wels, C., M. O'Kane, S. Fortin and D. Christensen 2001. Infiltration Test Plot Study for Mine Rock Piles at Questa Mine, New Mexico. *Proceedings of the 9th Annual Conference of the American Society for Surface Mining Reclamation, Albuquerque, June 2001:* 195-209. New Mexico: The American Society for Surface Mining and Reclamation.