INFILTRATION TEST PLOT STUDY FOR MINE ROCK PILES AT QUESTA MINE, NEW MEXICO[1]

by

Christoph Wels[2], Mike O'Kane, Sebastien Fortin, and David Christensen

Abstract. An infiltration test plot study has been initiated at the Questa mine, located in the Sangre de Cristo Mountains in northern New Mexico. The objective of this study is to determine the key processes controlling infiltration into the mine rock piles. This study is part of a comprehensive site investigation carried out in support of the development of a closeout plan for the Molycorp Questa Mine. From 1965 to 1983 large-scale open pit mining at the Questa mine produced over 297 million tonnes of mine rock, which was end-dumped into various steep valleys adjacent to the open pit. 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). Initial analyses suggested that net infiltration might vary significantly across the site due to differences in the local micro-climate (caused by differences in elevation and aspect). In order to account for these differences, test plots were located on sites representative of low, mid and high elevation conditions. The test plots consisted of 2.3m deep HDPE tanks (2.4m ∅), which were backfilled with local mine rock material. The lysimeters are instrumented with suction and temperature sensors as well as access tubes for measuring volumetric moisture content at various depths. The lysimeters are free-draining and leachate from the test plot is monitored using a tipping bucket. An automated weather station was erected at each site to monitor all relevant climate parameters. This paper describes the design and installation of these test plots and summarizes monitoring results obtained to date. The results of this infiltration study will be used to assess the effectiveness of alternative closure measures.

Additional Key Words: Waste rock reclamation, semi-arid climate, net percolation

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 297 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. 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).

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[2]Christoph Wels is Principal Hydrogeologist at Robertson GeoConsultants Inc., Vancouver, BC, Canada, V6C 3B6.

Mike O'Kane is President of O'Kane Consultants Inc., Saskatoon, SK, Canada, S7N 1Z2.

Sebastien Fortin is a Geological Engineer at Robertson GeoConsultants Inc, Vancouver BC, Canada, V6C 3B6.

David Christensen is a Graduate Student at University of Saskatchewan, Saskatoon, SK, Canada, S7N 4L3.

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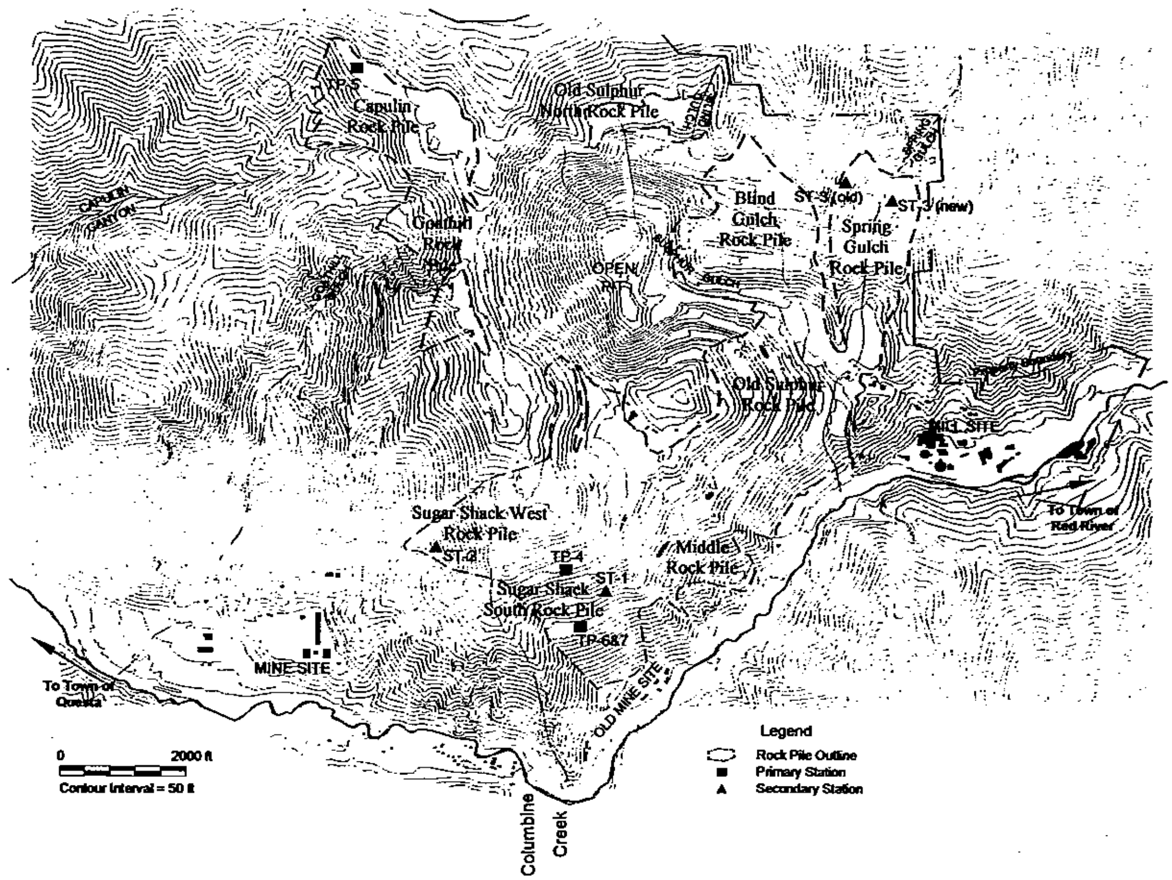

Figure 1. Location map of Questa showing mine rock piles and infiltration test plots.

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). However, it is extremely difficult, if not impossible, to measure net infiltration directly under true and highly variable field conditions (i.e. deep, unsaturated mine rock profile, flat and steeply inclined surfaces; range of climatic conditions). Instead, the test plot study is designed to allow the calibration of a soil-atmosphere model for known (measured) boundary conditions. To this end the test plot study has been designed to meet the following specific objectives:

- measure climatic conditions at the site;
- measure in-situ material properties (characteristic curves); and
- calibrate a soil-atmosphere model in order to predict net infiltration.

The ultimate goal is to use the calibrated soil-atmosphere model to predict with a high degree of confidence the net infiltration rates for (true) field conditions at various representative locations throughout the Questa mine site (RGC, 2000a).

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 a.m.s.l.) to about elevation 2,990m a.m.s.l., 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 RGC (2000c). 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

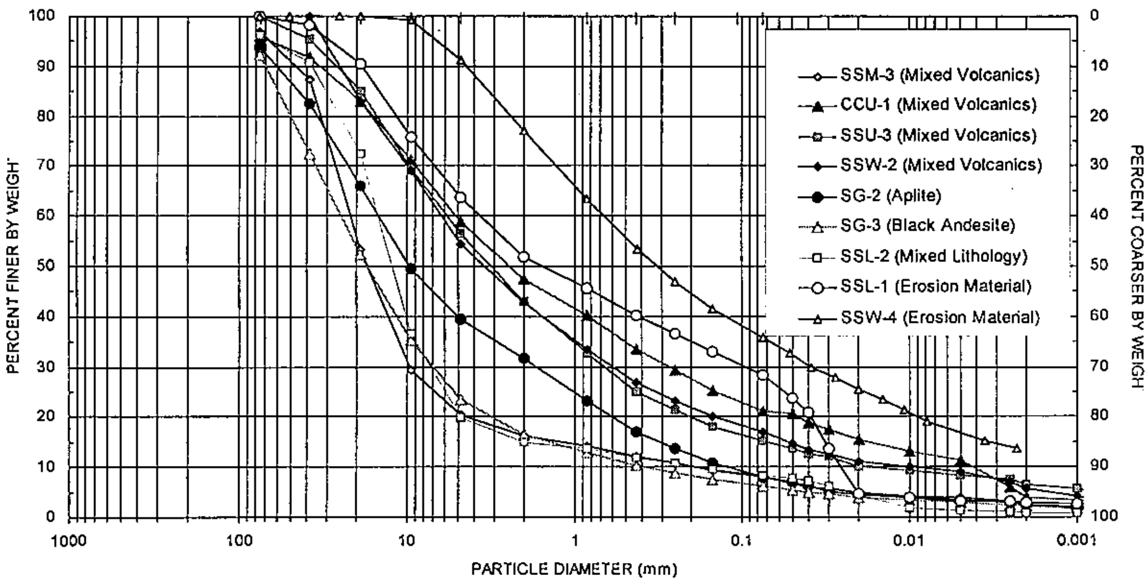

Figure 2. Particle Size Distributions of selected mine rock samples from Questa Mine, New Mexico.

events. This erosion material typically forms a very thin "crust" (~30-60cm) in the up- and midslope 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.

Figure 2 shows particle size distributions for selected mine rock samples from the Questa mine site (taken from RGC, 2000b). Detailed hydraulic testing (soil water characteristic curves (SWCC) and hydraulic conductivity functions) was completed on a subset of these samples (Figure 3). The results demonstrate the large variability in hydraulic characteristics that can be expected across the mine site. Note that the finer-grained material (in particular the erosion material) has a much higher water holding capacity than the coarser-grained mine rock. Although the coarse-grained mine rock shows a higher saturated hydraulic conductivity (Ksat), the finer-grained mine rock generally has a higher hydraulic conductivity under unsaturated conditions (i.e. at high suction).

The climate at the mine site 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) and the long-term average monthly temperature is approximately 4.2°C. The mine is located in an area of high relief and the distribution pattern of mean annual precipitation is complex. Mean annual precipitation data from weather stations in the study region suggest a general trend of increasing precipitation with increasing elevation (approximately 13cm for every 300m increase in elevation, as shown in Figure 4). The long-term average annual precipitation at the mill site located at the base of the mine site is approximately 40cm. Precipitation is common throughout the year with the driest month typically being January and the wettest being August. Precipitation recorded during the summer months of July and August tends to be twice as much as compared to the remaining months. Estimates of lake evaporation (large free-water surface) and actual evapotranspiration (land surface including transpiration from vegetation) on site are 1000mm and 400mm, respectively (RGC, 2000c).

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). 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 Figures 2 and 3). Hence, the rate of net infiltration can be expected to vary significantly among those material types.

However, local climate conditions may also have a strong influence on the amount of net infiltration. At a high-relief site such as the Questa mine, the key climate

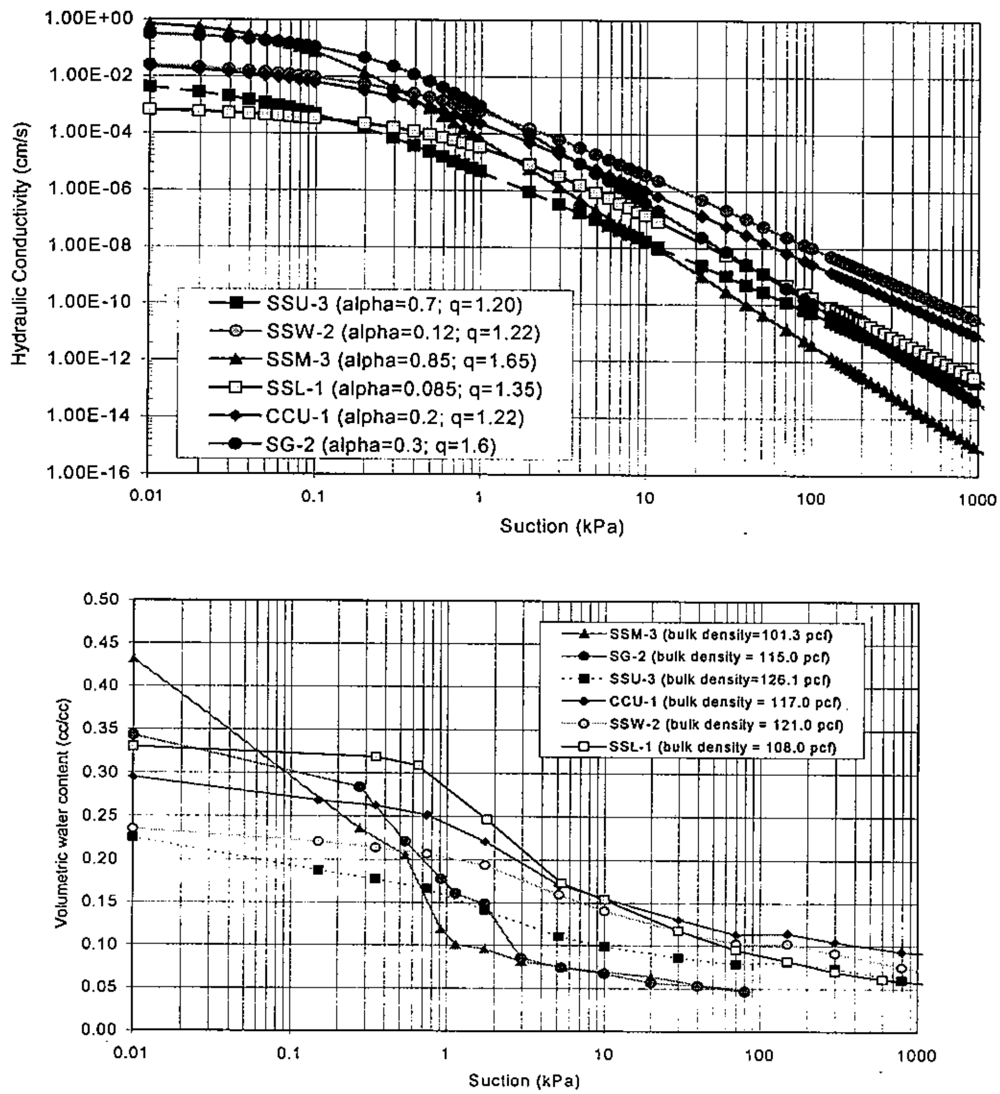

Figure 3. Hydraulic properties of selected mine rock samples from Questa Mine, New Mexico.

parameters influencing net infiltration (i.e. precipitation and potential evaporation) can vary significantly, thus increasing the variability in net infiltration across the site. The general increase in precipitation with higher elevation has already been discussed (see Figure 4). In addition, the duration of snow cover and the depth of snowpack generally increases with higher elevations, which may also significantly increase the amount net infiltration (RGC, 2001). 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 on slope).

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. Both of those effects tend to reduce net infiltration. Clearly, the majority of the mine rock piles at Questa are sloped with slope angles near or at the angle of repose. However, it is presently uncertain to what extent surface runoff and capillary break effects influence the water balance of these sloped mine rock piles. Visual observations suggest that surface runoff occurs only during intense summer thundershower events, and then only on the rock piles with finer-grained mine rock at surface. The capillary break effect arises when a finer-

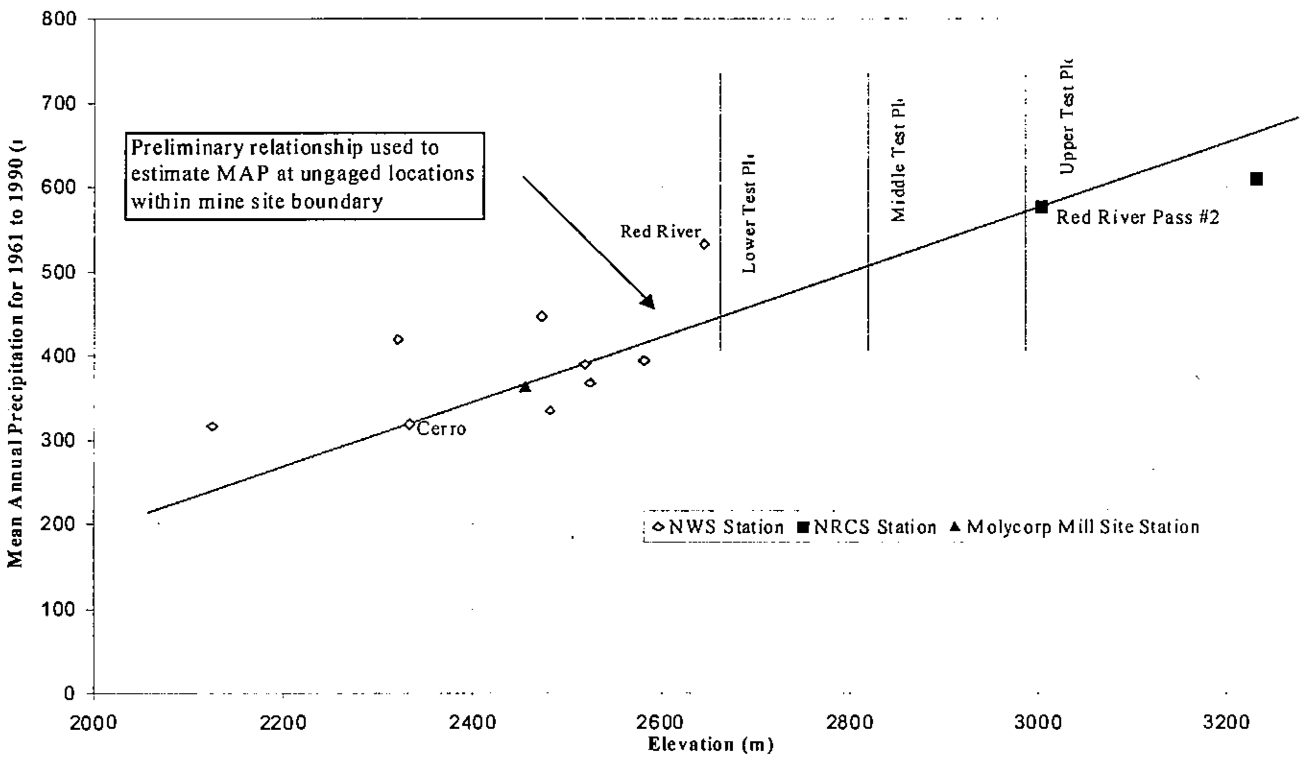

Figure 4. Mean annual precipitation as a function of elevation in the study region (elevation of the primary station infiltration test plots shown for comparison.

grained material (e.g. a surface layer of erosion material) overlies a coarser-grained mine rock. Soil moisture will preferentially move within the finer-grained layer (parallel to the slope) except for the days with high precipitation, when the moisture content of the finer-grained surface layer approaches saturation (e.g. Stormont, 1996). It is unlikely that such a capillary break effect remains effective for the entire slope length (or even large segments between slope benches) due to the heterogeneity of the mine rock. Although the capillary break effect may not prevent infiltration of pore water into the deeper mine rock profile at a down-slope location, it may nevertheless reduce net infiltration because this near-surface flow provides more potential for evaporation.

The test plot study was designed to evaluate all three factors controlling net infiltration, i.e. physical material properties, climate conditions 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 of the primary and secondary stations with respect to lysimeter, *in situ* monitoring and climate monitoring. An instrumented lysimeter (filled with mine rock material from that location) and a detailed weather station were set up at each primary station. The lysimeters provide a direct measurement of net infiltration but limits monitoring of true field conditions (i.e. a deep profile; influence of inclined surfaces and airflow). The net infiltration for true field conditions (in particular for sloped surfaces) will have to be modeled using a soil-atmosphere model calibrated using the monitoring data from these test plots.

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

- well-graded (finer) mine rock material at mid-elevation (El. 2820m) (i.e. TP-4 at upper bench of Sugar Shack South rock pile);
- well-graded (finer) mine rock material at high-elevation (El. 2990m) (i.e. TP-5 on top of Capulin rock pile);
- poorly-graded (coarse) mine rock material at low elevation (El. 2660m) (i.e. TP-6 at lower bench of Sugar Shack South); and
- poorly-graded (coarse) mine rock covered with 30cm (1ft) of fine-grained sediment material at low elevation (TP-7 at lower bench of Sugar Shack South).

A comparison of TP-4 and TP-5 will allow an assessment of the importance of elevation on net infiltration (both sites feature similar materials but are

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 adapto
RH & T = Relative humidity and temperature (RH/T sens
W Sp = Wind Speed (Wind Monitor)
NET R = Net Radiation (net radiometer)

expected to differ in micro-climate). A comparison of test plots TP-4 and TP-6 will allow an assessment of the influence of PSD (texture) of the mine rock material on net infiltration (the sites feature different material types but may not differ significantly in micro-climates). Finally, a comparison of test plots TP-6 and TP-7 will allow an assessment of the importance of a fine-grained sediment layer covering coarse mine rock (observed on most steep rock slopes) on net infiltration.

The secondary stations focus on sloped surfaces to address the need to extrapolate the lysimeter data (which by their nature represent horizontal layers) to the steeply inclined surfaces found in many rock piles at Questa. At the three secondary stations *in situ* monitoring (of soil moisture) combined with precipitation gauging will be performed. This paper focuses on installation and data collection at the primary stations only. For more details on the secondary stations the reader is referred to RGC (2000d).

Table 1 summarizes the instrumentation of the test plot lysimeters. All lysimeters are free-draining and allow drainage to a manhole where the seepage rate is monitored directly and leachate can be collected for water quality analysis. In addition, the volumetric water content is measured in all four test plots (and all access tubes installed at the secondary stations) using the Diviner 2000 system distributed by SENTEK Sensor Technologies, Adelaide, Australia. The Diviner product is a portable probe with a single capacitor-type sensor. The capacitance of a soil increases considerably with an increase in the number of soil water molecules, which are free to relax as their electric dipoles respond to the capacitor sensors field reversal. Finally, *in situ* soil temperature and matric suction are measured in the lysimeter test plots with finer-grained mine rock (i.e. TP-4 and TP-5) using a thermal conductivity type sensor (Campbell Scientific Inc. model 229). The 229 sensor consists of a probe inserted axially in a porous ceramic cylinder (length of 30 mm and diameter of 15 mm). Heating the sensor for a specified time frame and measuring the temperature of the sensor before and after heating indirectly provided suction measurements. The delta T value calculated is a function of the porous ceramic material's ability to dissipate the heat applied. The faster the heat is dissipated, the lower the delta T value that is calculated and the higher the moisture content of the ceramic. The response of the sensor (i.e. the calculated delta T values) is calibrated in the laboratory against known levels of applied suction. The initial temperature obtained before heating the sensor provides a direct measurement of *in situ* temperature.

Instrumentation Of Test Plots

Construction of Lysimeters

Figure 5 shows the as-built drawings for test plots TP-4 and TP-5 illustrating lysimeter dimensions, *in situ* testing results and instrumentation. Figure 6 shows details of the drain discharge system from the lysimeter to the manhole (for TP-4). As-built drawings of test plots TP-6 and TP-7 are shown in RGC (2000d). At each test plot site, a foot print area of approximately 4.6mx4.6m was staked out and the mine rock excavated to a total depth of about 2.4m. The excavated material was then stockpiled for later backfilling (for test plots TP-4 and TP-5 only). The mine rock profile

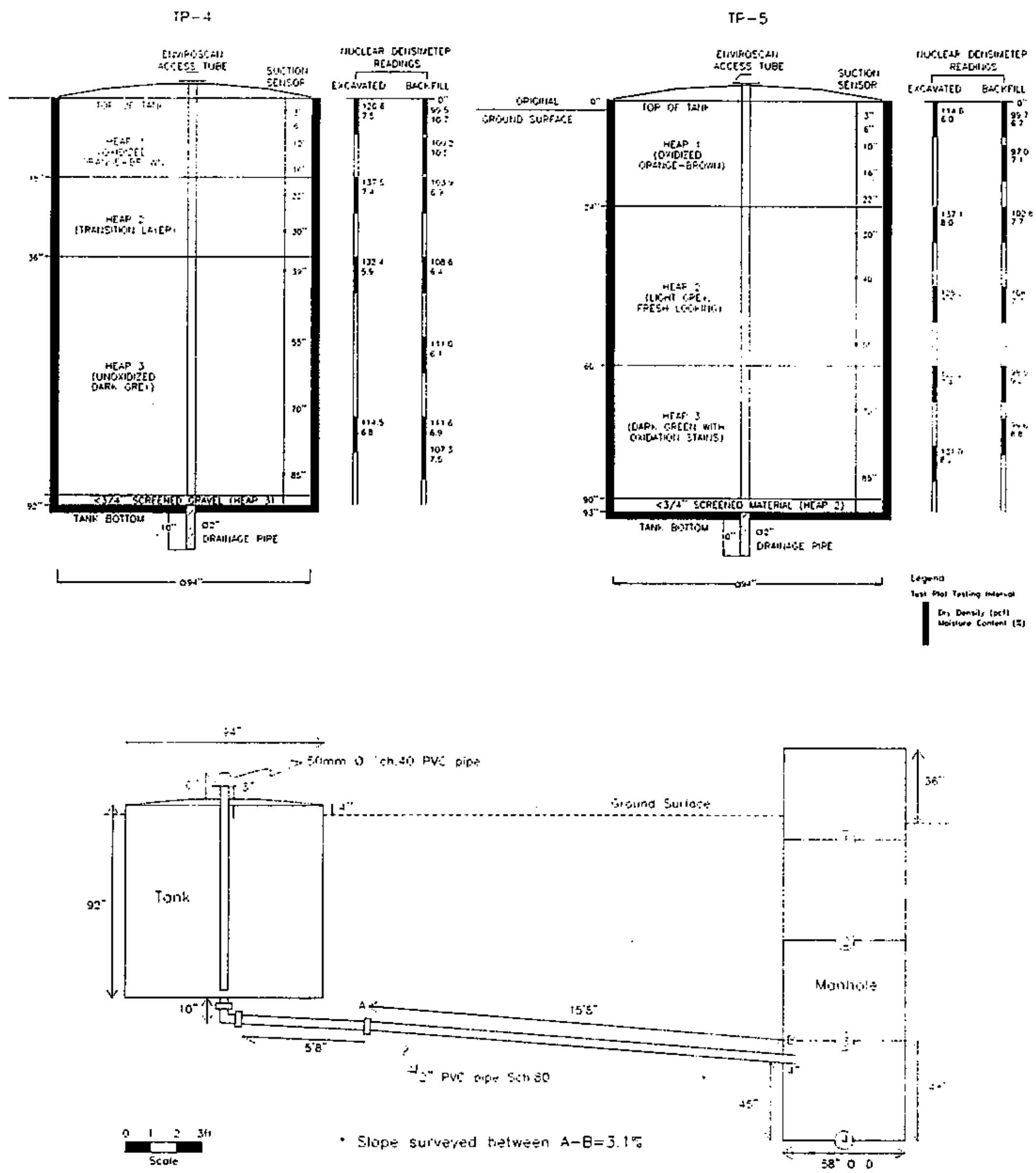

Figure 5. As-built drawings for test plot lysimeters TP-4 and TP-5. The lower panel shows the drain discharge system (for TP-4).

encountered in the excavation was photographed and logged with respect to material type, texture, color, and moisture content. Paste pH and electrical conductivity measurements were taken at representative depths of the soil profile. In addition, representative samples were collected for calibration of the SENTEK moisture content sensors and for further physical and geochemical testing. *In situ* density and moisture contents were measured at representative depths during excavation (Figure 5).

A 20mm thick-walled HDPE tank was used for the lysimeter tanks of the test plots. The lysimeter tank has a diameter of 2.4m and a height of 2.3m representing a total volume of approximately 10,600L (Figure 5). 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 Ø drain in the center of the tank. A filter cloth was laid out inside the tank (across the drain) to prevent future migration of fines into the discharge pipe.

Figure 6 shows the particle size distribution of the mine rock material used for backfill into the lysimeters. For test plots TP-4 and TP-5, an attempt was made to re-create the *in situ* profile by backfilling the stockpiled

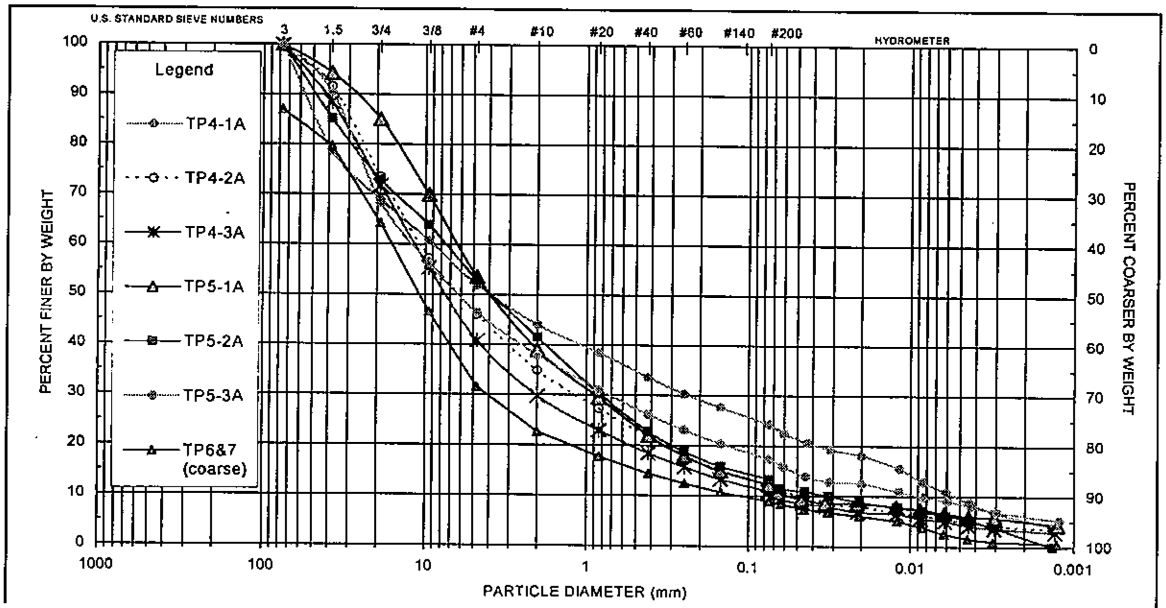

Figure 6. Particle size distributions for mine rock samples used for backfill in test plots.

mine rock in the same sequence (Figure 5). In contrast, test plots TP-6 and TP-7 were backfilled with poorly-graded, coarse mine rock taken from the toe of the rock pile just upslope of these test plots. In test plot TP-6, the entire depth of the lysimeter was backfilled with the coarse mine rock (sample "TP6&7" in Figure 6). In test plot TP-7, however, the top 30cm of the lysimeter were backfilled with a finer-grained erosion material (sample "SSL-1" in Figure 2).

In test plots TP4 and TP5 the backfill material was placed with the bucket of a backhoe and compacted by foot in thin layers. This backfill method resulted in compaction values (e.g. 1586-1788 kg/m^3 or 99.0-111.6 pcf in TP-4) much more similar to those observed in the non-compacted slopes than in the compacted benches. The low state of compaction on the sloped areas was considered more representative of the mine rock piles as a whole. In test plots TP-6 and TP-7 the coarse mine rock was backfilled as loose as possible (i.e. without any compaction by foot) to represent the very low compaction observed in the coarse material on the side slopes, i.e. the original source of the material (1438-1679 kg/m^3 or 89.8-104.8 pcf).

The moisture content of the backfilled mine rock material was generally similar (typically within one percentage point) of the moisture content measured in the excavated mine rock profile (test plots TP4 and TP-5), or in the respective borrow area (test plots TP-6 and TP-7).

In all test plots the first lift of backfilled mine rock was pre-screened to remove the material >19mm (¾ inch) (Figure 5). This screening was done to protect the drain hole and the filter fabric from damage and to act as a uniform drain layer. After placement of this basal layer the 50mm diameter PVC tube (for access of the SENTEK Diviner probe) was placed in the center of the lysimeter. Backfilling of the lysimeter then proceeded in layers of 30-60cm with geotechnical *in situ* testing at designated depths. The suction-temperature sensors were laid out at the appropriate depths and carefully buried in the backfilled mine rock (test plots TP4 and TP-5 only). The area immediately around the PVC access tube was compacted by hand to achieve a good seal. In addition, an annulus bypass ring was installed around the PVC access tube near the surface to prevent preferential channeling into the lysimeter.

After complete backfill the mine rock material at surface was graded to form a slight dome shape (~15cm higher at center) to avoid ponding on the test plots (Figure 5). The potential for run-on was minimized by protecting the test plots with small berms and by regrading the surrounding area to fall about 25-50mm below the rim of the HDPE lysimeter tank.

The general design of the discharge system was the same for all four test plots. A lateral drain pipe (5cm diameter PVC) was glued to the discharge pipe in the center of the lysimeter hole (Figure 5). The drain pipe was constructed with about 3% fall towards the discharge point (to allow easy drainage from the

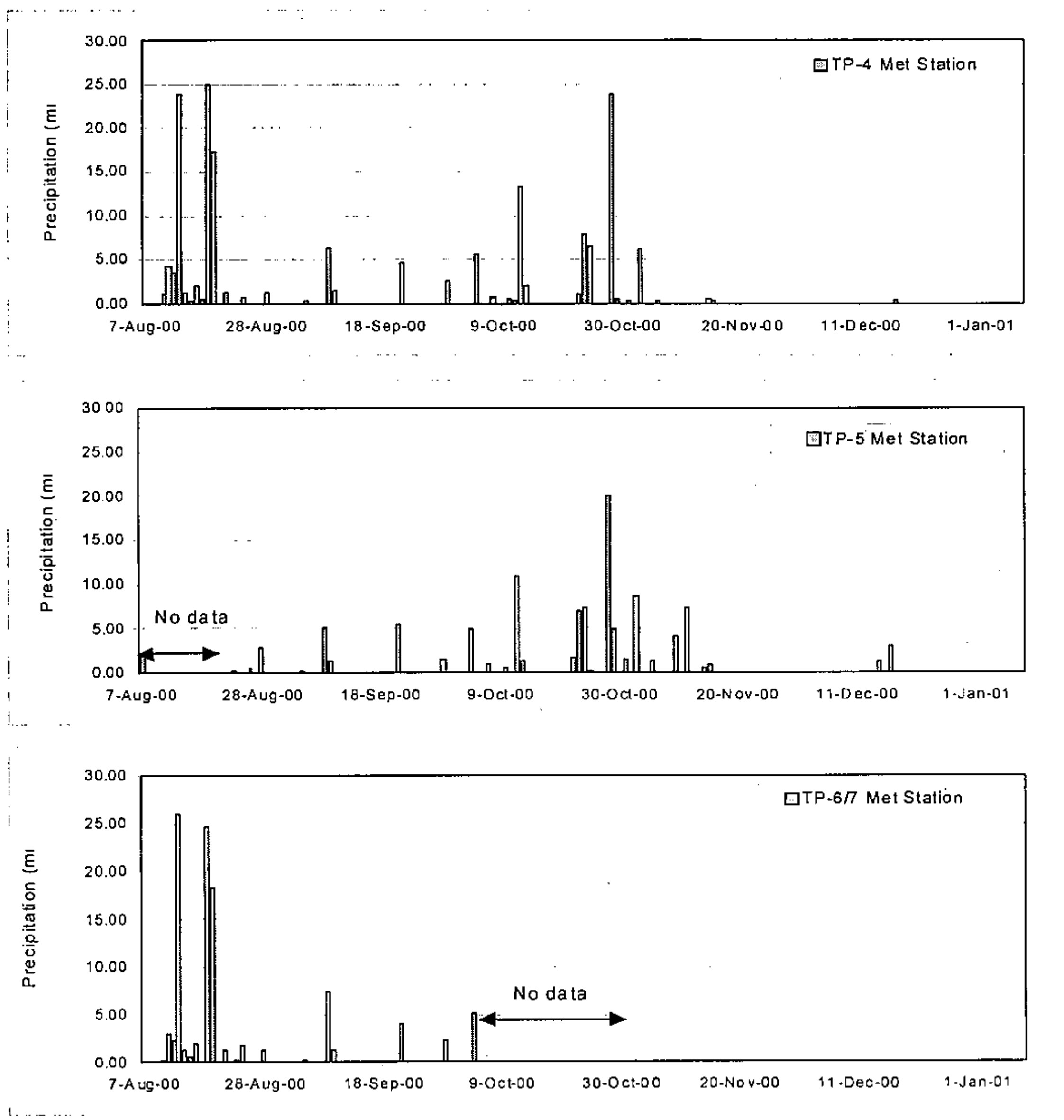

Figure 7. Daily precipitation at three primary stations (August 8, 2000 – January 8, 2001).

lysimeter). The discharge point is located in a manhole at a horizontal distance of about 4.6-6.1m from the lysimeter. A tipping bucket rain gauge was placed under the end of the discharge pipe (in the manhole) to record the amount and timing of discharge from the lysimeter.

Set-up of Meteorological Stations

A fully automated meteorological station was constructed at each of the primary stations to properly evaluate atmospheric boundary conditions for future numerical model calibration. Each climate station was located within ~9m of the respective test plot lysimeter. The weather station consists of a tipping bucket rain gauge (with snowfall adaptor), relative humidity/temperature sensor, wind speed sensor, and net radiometer. All sensors were mounted on a 3m tripod anchored to the surface using pegs and guy wires. The sensors were arranged to measure climate parameters at a nominal height of 1.8m above ground surface. The meteorological station has a stand-alone automated data acquisition system (used jointly with the suction sensors) and is powered by a battery/solar panel/regulator system. The three weather stations were commissioned during construction of the test plots at the primary stations (August 2000).

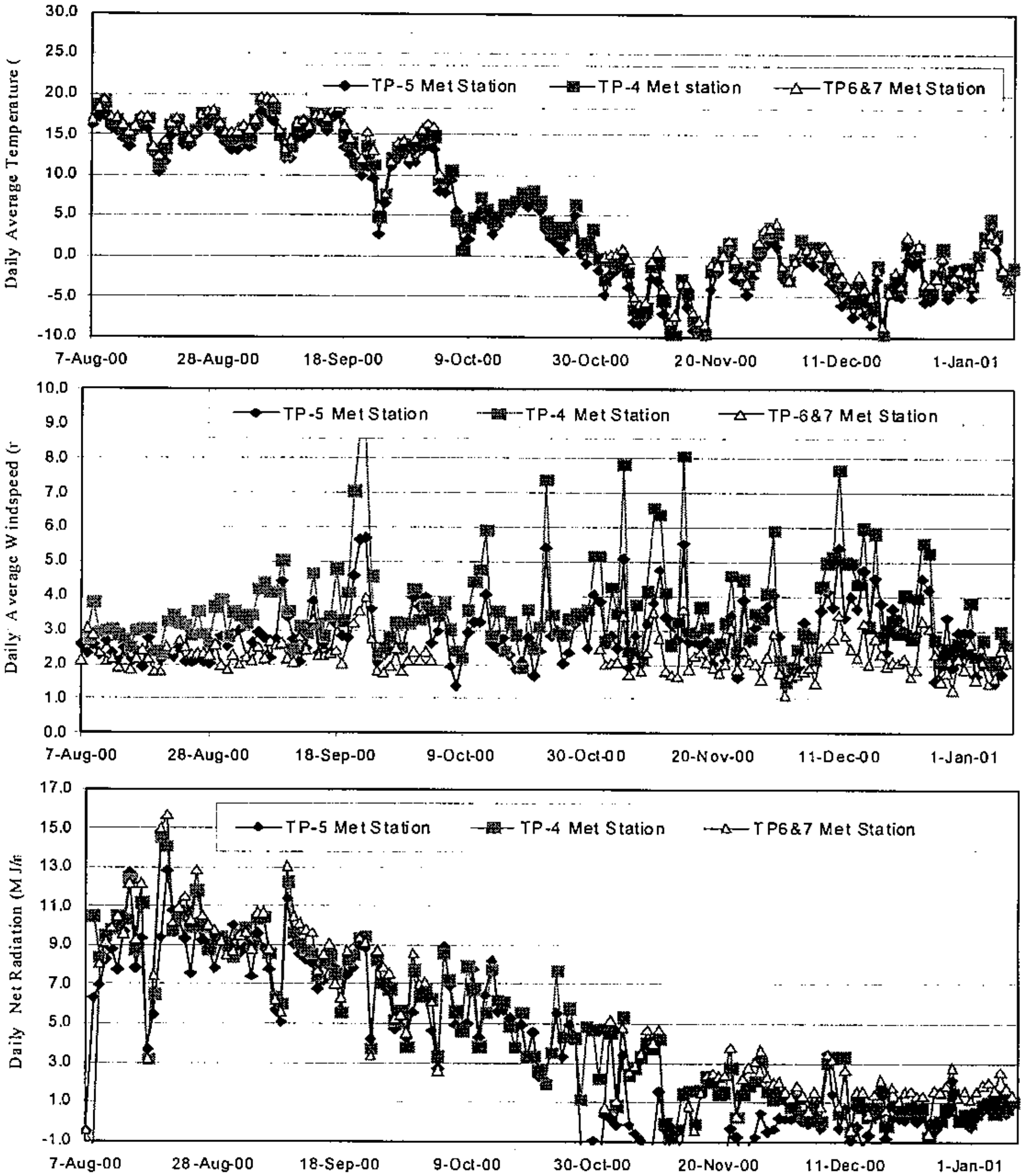

Figure 8. Comparison of climate time trends at the three primary stations.

Initial Monitoring Results

Climate Data

Figure 7 compares the daily precipitation recorded at the three primary stations for the first five months of monitoring, i.e. August 8, 2000 to January 8, 2001. The precipitation recorded at the three stations was very similar for the period of observation, both with respect to total precipitation as well as time trends. The major periods of precipitation occurred in August and October-November. Note that the tipping bucket rain gauges at test plots TP-5 and TP-6 was malfunctioning during August and October, respectively. However, a comparison with other stations (including secondary stations) suggests that the rainfall throughout these observation periods was very uniform across the Questa mine site. After accounting for missing data (using precipitation data from the nearest meteorological station), the total precipitation at the three meteorological stations was very similar (~190mm). In other words, this preliminary data does not support the general trend of increasing precipitation with higher elevation observed for the regional climate stations (Figure 4). However, the expected positive correlation of precipitation with elevation may not have been

Table 2. Summary climate statistics for three Primary Stations (based on daily average values).

Met Station		Average Daily Air Temperature (°C)	Average Daily RH (%)	Average Daily Windspeed (m/s)	Total Daily Net Radiation (MJ/m2)	Cumulative Precipitation (mm)	Cumulative Potential Evaporation (mm)
TP-5 (El. 2987 m)	Average	4.3	53.1%	2.9	3.5	188.0*	317.5
	Min	-12.2	17.6%	1.4	-4.8		
	Max	17.9	97.1%	5.7	12.9		
TP-4 (El. 2819 m)	Average	5.5	50.7%	3.6	4.7	195.6*	401.3
	Min	-9.9	16.9%	1.5	-0.8		
	Max	19.3	93.1%	8.8	14.6		
TP-6/7 (El. 2662 m)	Average	6.2	48.9%	2.3	4.9	188.0*	356.8*
	Min	-8.6	21.0%	1.1	-1.7		
	Max	19.6	85.0%	4.0	15.7		

Notes:
(1) no data available for TP6/7 from Oct-4 to Nov-1, 2000
(2) precipitation gauge at TP-5 did not record from Aug 9 to Aug 25, 2000
(3) values with * are estimated totals using interpolation for period w/ missing data
(4) Potential Evaporation is estimated using the Penman method (1948)

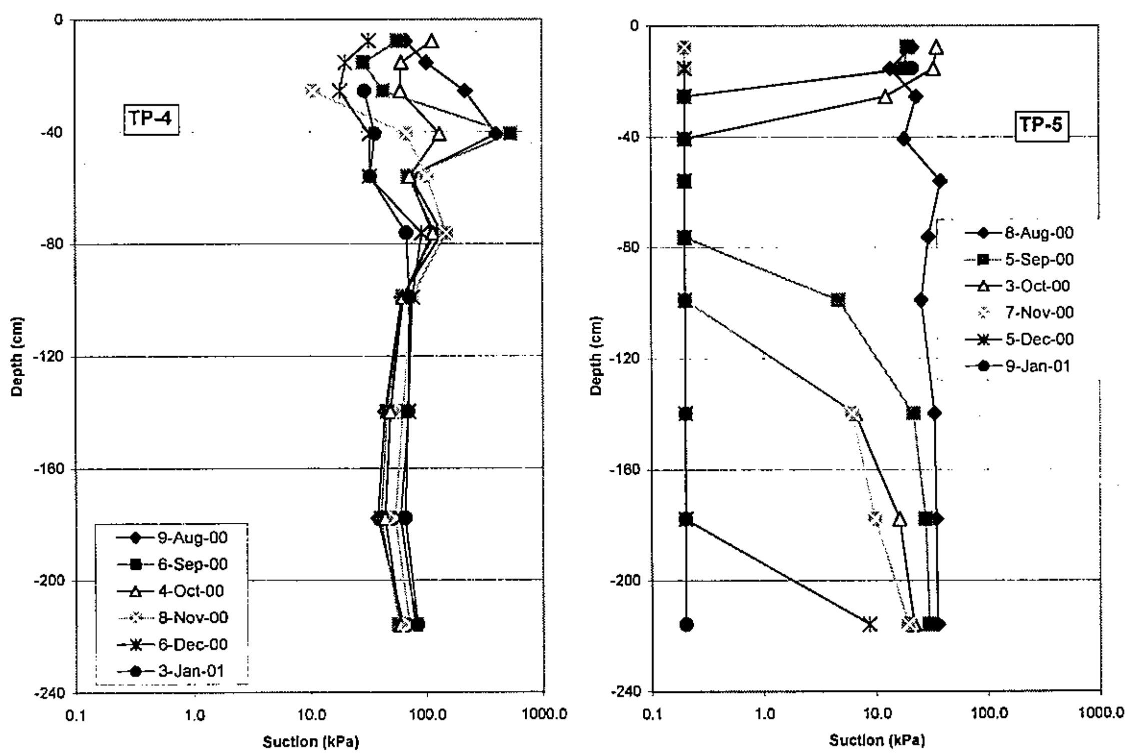

Figure 9. Observed suction profiles in test plot lysimeters TP-4 and TP-5.

observed thus far because of an unusually dry winter (Figure 7). Long-term statistics suggest that high elevation sites receive more precipitation predominantly in the winter months (RGC, 2001). Longer-term monitoring is required to determine to what extent elevation influences precipitation at the Questa mine.

Figure 8 shows time trends of daily average air temperature, relative humidity, wind speed, and net radiation at the three test plot locations for the same observation period. Table 2 provides summary statistics (average, min/max) for these climate parameters (based on daily average values). As expected, air temperature

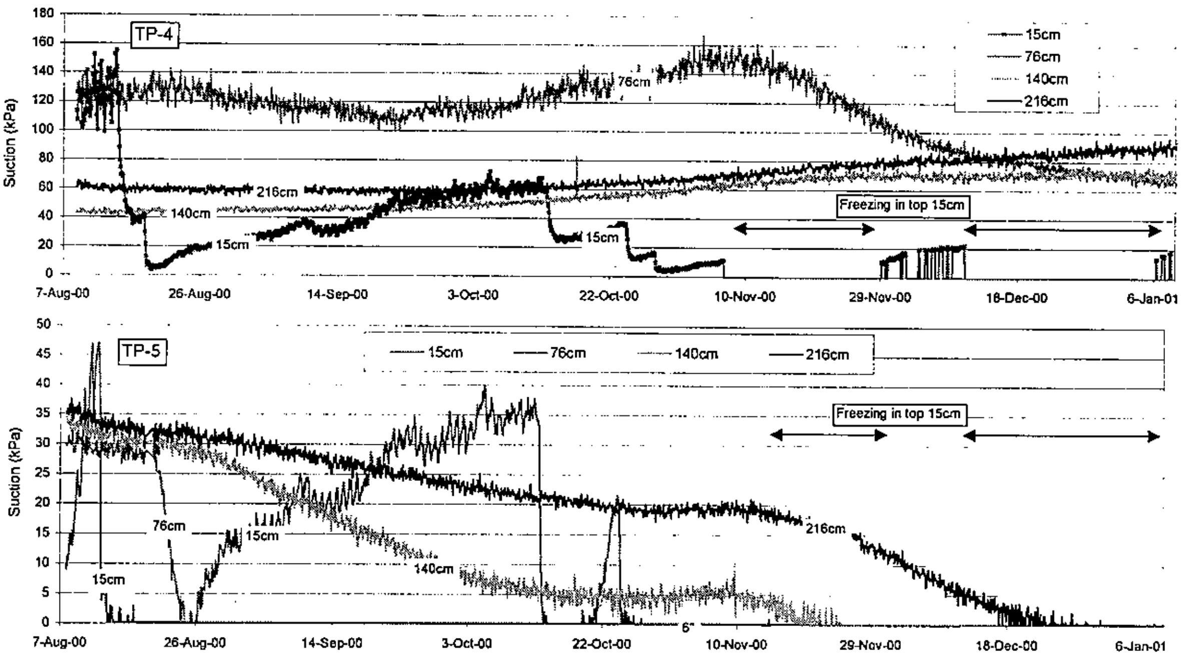

Figure 10. Time trends of suction at selected depths in test plot lysimeters TP-4 and TP-5.

generally decreases with higher elevation. Relative humidity did not show a significant trend with elevation. Average daily wind speed was significantly greater at TP-4 than either at TP-5 and TP-6/7 (Figure 8). The significantly higher winds observed at TP-4 are likely a result of the local site conditions (aspect, location on slope versus bench, distance from Red River valley). The higher winds at this location may be a result of a combination of upslope drafts and strong air movement up and down the Red River valley. The first mechanism is likely less pronounced at TP-6/7 and the latter mechanism is likely not a factor at TP-5. Net radiation appears positively correlated with elevation, i.e. net radiation is reduced at higher elevations. This pattern may be attributed to more cloud cover (fog) and more snow cover (higher albedo) at the higher elevations.

Table 2 also summarizes the cumulative precipitation and potential evaporation (calculated from the meteorological data using the Penman method) for the three meteorological stations. As expected for this climate, the rate of potential evaporation is much greater than cumulative precipitation. The highest potential evaporation (~400mm) was computed for TP-4. Note that potential evaporation is influenced by a series of climate parameters including air temperature, relative humidity, net radiation and wind speed. The significantly higher potential evaporation at TP-4 is likely a result of the very windy conditions observed at this site. The lowest potential evaporation was computed for the high-elevation site on top of Capulin (TP-5) due to the reduced net radiation and lower air temperatures.

Test Plot Response

Figure 9 shows observed suction profiles in lysimeter test plots TP-4 and TP-5 at monthly intervals for the period August 2000 to January 2001. Note that higher suction values indicate drier conditions and lower suction readings indicate wetter conditions. The observed soil suction response differed greatly between these two test plots. In test plot TP-5, the heavy precipitation of August and October-November resulted in the development of a clear wetting front, which migrated steadily downward until the entire mine rock profile in the lysimeter was wetted (see Figure 9). In contrast, no clear wetting front was observed in test plot TP-4. Here, the decrease in suction was limited to the top ~75cm of the mine rock profile and did not reach very low suction values (<1 kPa) indicative of near or full saturation. At depths greater than ~75cm soil suction actually increased over time suggesting a small drying trend.

Figure 10 shows the detailed time trends of suction at selected depths in both test plots. These time trends illustrate the difference in the wetting of the two mine rock profiles. In test plot TP-5, the heavy rains in

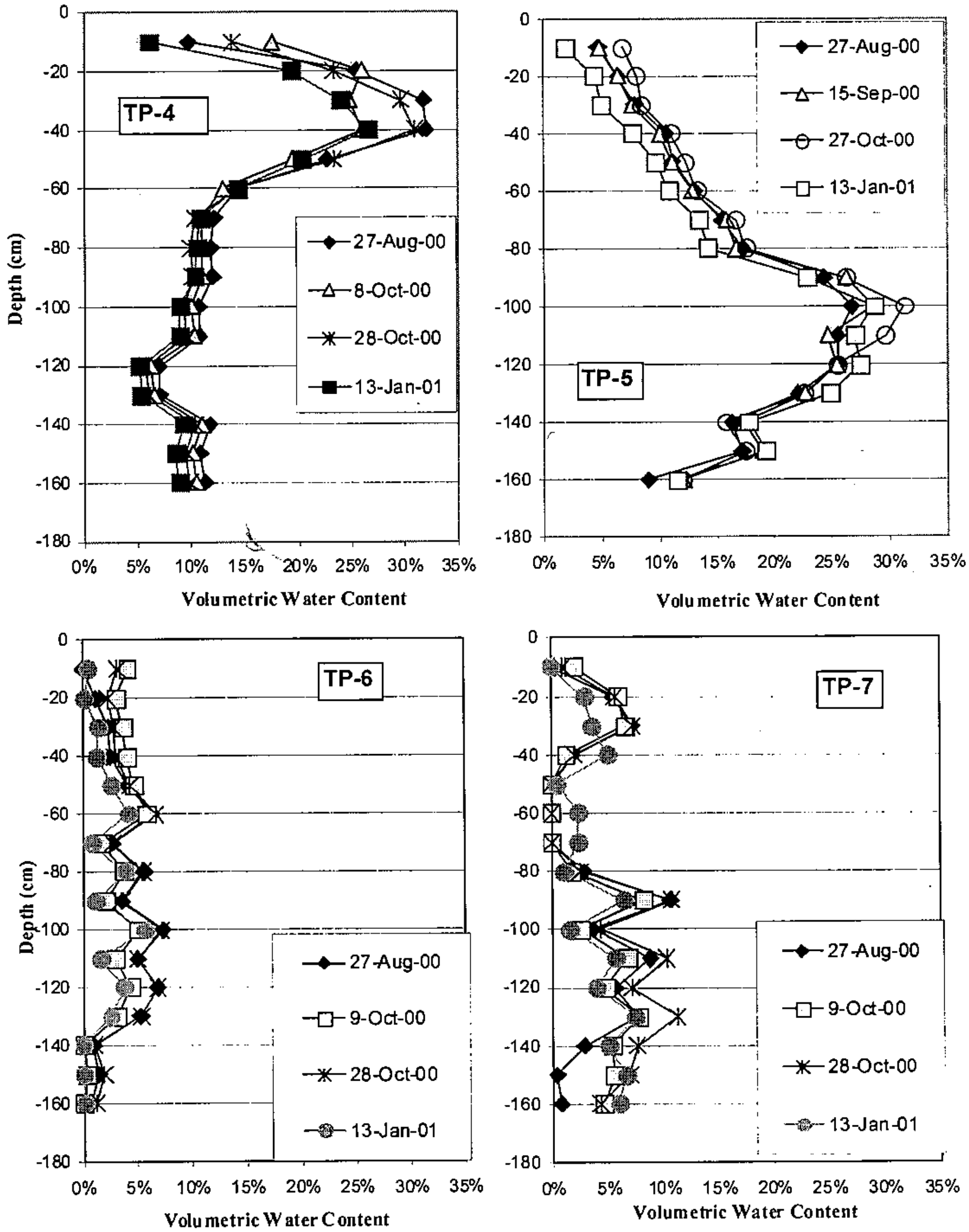

Figure 11. Depth profiles of volumetric moisture content in all four test plots.

August (78.7mm fell between August 13-29) resulted in a rapid wetting of the top 75cm (note steep decline in soil suction at 76cm depth around late August). The wetting of the deeper mine rock profile of TP-5 occurred much more gradual. For example, near-saturation suction values (< 1 kPa) at a depth of 140cm and 216cm were only reached in mid-November and mid-December, respectively (Figure 9).

In test plot TP-4, the heavy precipitation in August and October-November also resulted in a significant reduction in soil suction (i.e. wetting) in the near-surface (e.g. at a depth of 15cm, Figure 10). 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 76cm depth a significant decrease in soil suction was only observed in mid-November. In the deeper mine rock profile (>140cm below surface) the suction actually increased gradually over time suggesting a slight drying trend.

Figure 11 shows results of the volumetric water content measurements carried out using the Diviner 2000 in all four test plots. The observed moisture content profiles in the test plots with the coarse mine rock (TP-6 and TP-7) were consistently lower than in the test plots with the finer-grained mine rock (TP-4 and TP-5). Furthermore, the volumetric moisture content readings did not vary as much in time as would have been expected based on the soil suction readings. Calibration of the Diviner 2000 sensor in the laboratory suggested that the moisture content readings are very sensitive to the material properties (particle size distribution, degree of compaction etc.). In other words there is significant uncertainty in how to reduce the raw field reading into a volumetric water content. Note that soil suction is a stress variable, hence the soil suction sensors do not require field calibration as do the volumetric moisture content sensors. As a result the soil suction readings are generally considered more reliable.

The total discharge observed at the base of test plots TP-4 and TP-5 is consistent with the soil suction trends shown in Figures 9 and 10. At test plot TP-4 no discharge was observed in the first five months of monitoring. In contrast, the total (cumulative) discharge collected from test plot TP-5 was 3.1L. Unfortunately, the time of discharge was not recorded (due to an error in the data logging program). However, the response of the soil suction sensor near the base of TP-5 (at a depth of 216cm) suggests that discharge from the lysimeter started around mid-December. Note that the observed outflow in TP-5 only represents about 0.8mm of net infiltration, i.e. only about 0.4 % of the total precipitation for this five month period. Future monitoring will be required to determine to what extent this low rate of net infiltration is influenced by initial equilibration effects after construction (e.g. storage requirements etc.) and the unusually dry winter precipitation (thus far in water year 2001).

Conclusions

This paper describes the design and installation/instrumentation of infiltration test plots designed to study the net infiltration into mine rock piles at the Questa mine. Initial test plot data collected during the first five months of monitoring illustrate the large variability in infiltration that might be expected under field conditions on the mine rock piles. A preliminary review of the data suggests that the lack of a prominent wetting front in TP-4 may be a result of material properties. The upper 45cm of backfilled mine rock in TP-4 was found to be significantly finer than the mine rock material back-filled into TP-5 (see Figure 6). This difference in particle size distribution of the near-surface layer might explain the very different soil moisture behaviour observed between TP-4 and TP-5. However, the much lower rate of net infiltration may also be influenced by the local climate conditions. Detailed climate monitoring suggests that the local weather conditions at test plot TP-4 are more conducive to evaporation than at test plot TP-5. Soil-atmosphere modeling will be required to evaluate the relative importance of climate conditions, as compared to material properties, in determining the rate of net infiltration.

Modeling work is currently in progress to calibrate the soil-atmosphere model SoilCover using the observed test plot data (RGC 2001b). The detailed climate monitoring at each test plot site allows the use of the "detailed weather option" of SoilCover where potential evaporation is calculated internally based on daily precipitation, daily min/max air temperature and relative humidity, average daily wind speed, and daily net radiation (Geo-Analysis 2000 Ltd., 2000). The hydraulic properties of the mine rock profile (porosity, soil water characteristic curve, Ksat) will be modified during calibration until a good fit with the temporal trends of soil suction, volumetric moisture contents and measured outflow from the lysimeter is obtained. 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.

The results of this infiltration study will be used to assess the effectiveness of alternative closure measures.

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Literature Cited

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

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.

Stormont, J.C. (1996). The Effectiveness of Two Capillary Barriers on a 10% Slope, Geotechnical and Geological Engineering, (14): pp. 243-267, 1996.

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