

Preprint 02-100

HYDROLOGIC ASSESSMENT OF WASTE ROCK STOCKPILES: A CASE STUDY FROM AJO MINE, ARIZONA

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ABSTRACT

Hydrologic assessments of existing and proposed waste rock stockpiles (WRS) are typically required for application of operating and closure permits at mine sites. The results of these assessments can be used to determine the applicability of the state groundwater permit program requirements to the operation and closure of these stockpiles.

The objective of this hydrologic assessment was to ascertain whether or not the WRS at the Ajo Mine have a reasonable probability of discharging potential pollutants to the underlying aquifer under the operational mine conditions. The hydrologic assessment was performed based on an evaluation of climatic data, prediction of the net infiltration rate through the WRS and prediction of additional hydrologic factors such as the time required to deplete available moisture storage in WRS.

The predicted net infiltration rates ranging from 0.13 inches/year (1.1×10^{-9} cm/s) to 0.24 inches/year (1.9×10^{-8} cm/s) are below the threshold value of less than 10^{-7} cm/s recommended by Hutchison and Ellison (1992) as being characteristic of conditions that produce no or negligible quantities of seepage. In addition, the total time required to deplete available moisture storage within the Ajo Mine WRS and for any potential seepage from the WRS to reach the underlying aquifer is estimated to range from 260 years to 1,950 years.

Collectively, the climatological and geotechnical investigations and the hydrologic predictions demonstrate that the WRS at the Ajo Mine hydrologically do not have a reasonable probability of discharging pollutants to the underlying aquifer. As a result of this prediction, the stockpile will not be regulated under the state groundwater permit program and operational and reclamation requirements will be limited to managing surface water runoff.

INTRODUCTION

The Ajo mine is an inactive open-pit copper mine located approximately 100 miles southwest of Phoenix, Arizona. The major facilities at the mine site are tailing impoundments, an open-pit and the WRS. The WRS in Ajo mine cover approximately 1,000 acres and include the deposition of 540 million tons of rock over approximately 50 years. Rock was stockpiled at these WRS from the 1930s to 1984. The WRS are the focus of this case study.

Based on the period of operation of these facilities, the WRS are considered closed facilities under Arizona Revised Statutes (A.R.S.) 49-201.7 and have not been operational since 1984. The operational mine conditions considered in this case study assume that additional waste rock materials would be placed over the existing WRS. This scenario also assumes that

the new waste rock material would have similar and chemical characteristics as the existing WRS.

The objective of this case study was to determine whether or not the WRS at the Ajo Mine are hydrologically non-discharging facilities under the operational mine conditions. As illustrated on Figure 1, the hydrologic assessment included prediction of the following:

- Net Infiltration Rate;
- Time Required to Deplete Available Moisture Storage in the WRS; and
- Migration Time of Potential Seepage to the Underlying Aquifer.

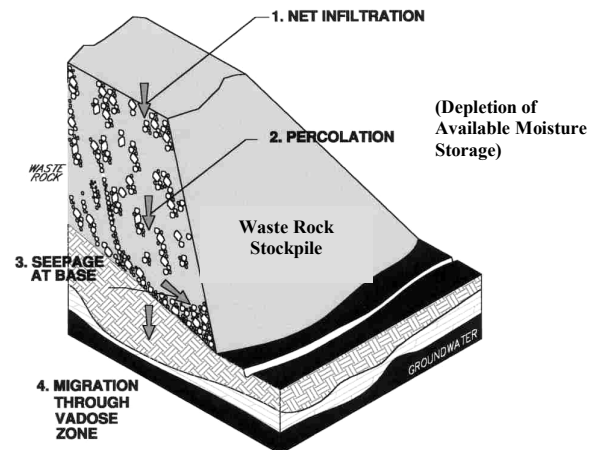


Figure 1. Unsaturated Zone Hydrologic Components of a Waste Rock Stockpile.

HYDROLOGIC PREDICTION METHODS

Net infiltration predictions were made using the HELP (Schroeder et al. 1994) and SOILCOVER (USG 1997) hydrologic models. Predictions of the time required to deplete available moisture storage in the WRS and the average migration time of potential seepage to groundwater were made using calculations based on the unsaturated zone flow theory. These conceptual models and methods used for the predictions are described below.

Net Infiltration

In arid environments (large evaporative zone depth and vapor transport in the WRS) similar to Ajo, Arizona the net infiltration rates can be significantly overestimated if the climate

data and predictive methods are not climate-specific (Hutchison and Ellison 1992). The method used to predict net infiltration through the WRS was sensitive to the arid conditions of the Ajo Mine. A semi-empirical water balance model (U.S. EPA's HELP model; Schroeder et. al. 1994) was used in conjunction with a physically based hydrologic model (SOILCOVER; USG 1997) to accurately predict net infiltration in arid climates. The components of net infiltration are depicted on Figure 2. As shown on Figure 2, precipitation either infiltrates at the soil surface or moves laterally as runoff. Water that infiltrates the soil surface is stored in the soil pores and can be removed from the soil by surface evaporation and plant transpiration (evapotranspiration). The amount of water removed via evapotranspiration is a function of the climate and the soil properties (soil-water characteristics and hydraulic conductivity). Water not extracted via evapotranspiration moves through the active soil zone and infiltrates into the underlying waste rock (commonly referred to as net infiltration).

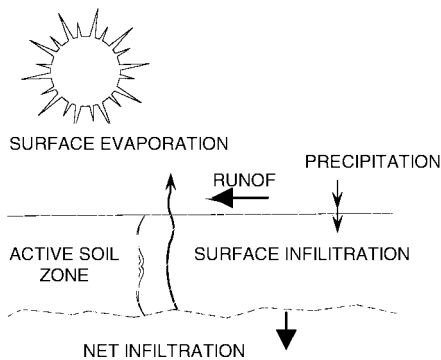


Figure 2. Conceptual Model of the Components of Net Infiltration

The HELP model is a useful tool for rapid analyses of multiple years of data to identify years exhibiting mean and extreme climatic conditions. However, the model does not implicitly account for upward unsaturated flow (a dominant water transport mechanism in arid climates) typically resulting in an overestimation of net infiltration in arid and semi-arid climates (Hutchison and Ellison 1992). The use of a physically based hydrologic model that can accurately simulate upward unsaturated flow is recommended for arid sites (Hutchison and Ellison 1992). The SOILCOVER model has been used in this capacity and has been successfully applied to similar settings for mine sites in the United States, Australia and Canada (S.E.T. 1998, Swanson et.al. 1995; Williams, et.al. 1997; Machibroda, et.al. 1993; and Savci et.al. 2002). In addition, SOILCOVER considers both liquid and vapor transport within the soil profile to provide a more physically-based and accurate quantification of surface evaporation. In dry climates vapor transport near the surface is an important transport mechanism.

The HELP model was used to identify a mean year defined on the basis of annual precipitation and predicted net infiltration. The SOILCOVER model was then used to predict net infiltration for the mean and extreme wet years.

Net infiltration predictions, as described above, were made for surfaces that had the potential to exhibit distinct hydrologic conditions (surfaces with higher density have lower hydraulic conductivity). The potential distinct surface hydrologic types included top areas, both traffic and non-traffic, and side slopes. Hydrologic conditions for these surfaces are likely to be different based on hydraulic conductivity (low hydraulic conductivity for traffic areas, higher hydraulic conductivity for non-traffic top areas and side slopes). In addition, the stockpiles are not graded to shed runoff from the top areas (overall runoff component of the water balance for the top areas was assumed to be zero) and therefore the runoff potential is less than the side slopes.

Depletion of Available Moisture Storage

Waste rocks are typically deposited in a dry state, and as such, has an inherent moisture storage potential that may take many tens to many hundreds of years to deplete. As shown on Figure 3, water that infiltrates through the active soil zone percolates through the WRS, gradually wetting it over time. As shown on Figure 3, percolation within the WRS occurs through an inter-fingered and bedded system of coarse-textured and fine-textured waste rock (waste rock containing appreciable fines that surround the larger particles) that dips at the angle of repose (Herasymuik 1996). Under arid unsaturated conditions, water will flow primarily through fine-textured waste rock, rather than through the coarse waste rock (Newman et.al. 1997).

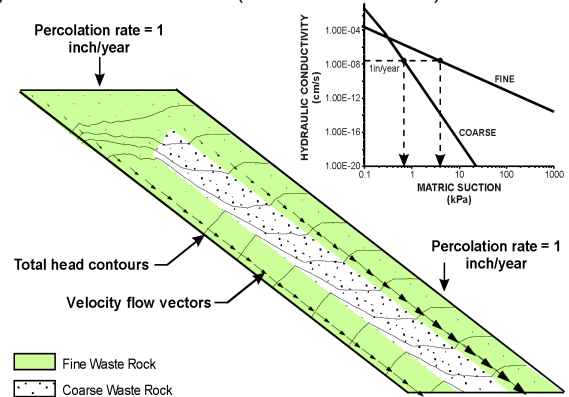


Figure 3. Preferred Flow through Layered Waste Rock (after Swanson et.al. (2000)).

A calculation presented by Guymon (1994) was used to predict the time required to deplete the moisture storage of the WRS. As shown in the calculation presented below, the time required to deplete the available moisture storage was estimated based on the following:

- Available moisture storage (wetted moisture content less the placement moisture content);
- Predicted net infiltration rate;
- Thickness of the WRS; and
- The fraction of the WRS that consists of coarse-textured layers lacking sufficient fine matrix.

$$\Delta t = Z \times \left(\frac{\theta_w - \theta_p}{I} \right) \times (1 - CM) \quad (1)$$

where:

- Δt = time required to deplete available moisture storage;
- Z = Depth of wetting (thickness of the WRS);
- θp = Placement moisture content;
- θw = Wetted moisture content; and
- I = Net infiltration rate; and
- CM = Fraction of development rock lacking fine matrix material capable of transmitting and storing moisture under unsaturated conditions.

Migration of Potential Seepage to Groundwater

In arid and semi-arid climates, the time required for seepage emanating from WRS to migrate to groundwater can be large. The timeframe for this migration depends on the vertical seepage rate from beneath the stockpile, the moisture storage potential of the underlying native foundation material and the depth to the water table. Moisture storage in the vadose zone may have been made available in response to the placement of the existing WRS (infiltration at the native ground surface is shut off when stockpile is placed, allowing moisture contents in the vadose zone to decrease and make available additional moisture storage).

The average time required for seepage emanating from the base of the stockpiles to reach groundwater was estimated using

a simple calculation described by Guymon (1994) and Maidment (1993). As shown below, this method uses the predicted net infiltration rate and the field moisture content of the vadose zone to predict the average velocity of the migrating water.

$$v = \frac{q}{\theta_v} \quad (2)$$

where:

- q = Seepage rate from the base of the WRS (Equal to the net infiltration rate after the available moisture storage has been depleted);
- θ_v = Moisture content of the vadose zone; and
- v = Average velocity of the migrating water.

The average velocity of the migrating water was used to estimate the average time required for the migrating water provides a conservative prediction as the moisture storage of the vadose zone is assumed to be negligible.

Average migration times for potential seepage to the aquifer were calculated for bedrock and alluvium foundations that underlie the WRS. The WRS at Ajo Mine are underlain by Quaternary alluvium and two bedrock types (volcanics and fanglomerate). In addition, the calculations were performed for

the representative vadose zone thickness based on the groundwater elevation for the mine site.

HYDROLOGIC CHARACTERIZATION

The hydrologic characterization was designed to collect the data required to define the input parameters for the hydrologic predictions and included a climate and a geotechnical investigation.

Climate Investigation

Climate parameters required for HELP and SOILCOVER modeling include precipitation, evaporation, temperature, relative humidity, wind speed and solar radiation. Evaporation data is used to evaluate the evaporation predictions made by the SOILCOVER model.

The climate for the Ajo Mine is arid with lake evaporation approximately eight times greater than the annual precipitation. The average annual and monthly precipitation for Ajo, Arizona for the period from 1913 to 1989 is presented on Figure 4. Figure 4 shows an average annual precipitation of 8.9 inches, with 37 percent of this amount occurring during July and August as the result of brief, intense thunderstorms. The driest months of the year are May and June, with an average monthly precipitation of 0.10 inches and 0.08 inches, respectively.

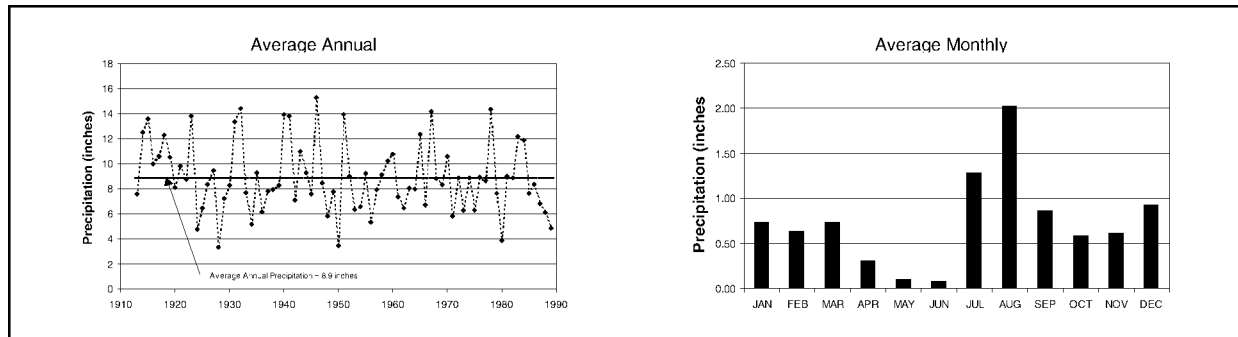


Figure 4. Average Annual and Monthly Precipitation for Ajo, Arizona (1913 to 1989) (Source: Western Regional Climate Center)

The average annual pan evaporation at the Ajo Mine is 110.0 inches while the average annual calculated lake evaporation is 73.7 inches. The data are based on a pan evaporation coefficient of 0.67 (U.S. Weather Bureau 1959). Figure 5 presents the average monthly lake evaporation.

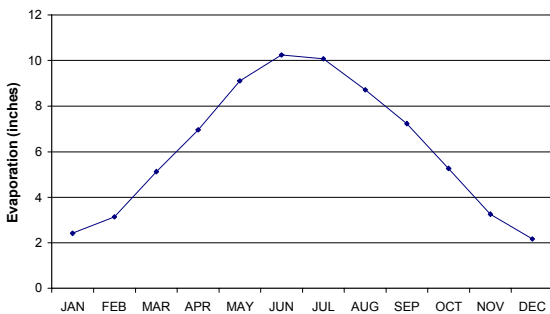


Figure 5. Average Monthly Evaporation for Ajo, Arizona (Source: National Oceanic and Atmospheric Administration; Average monthly evaporation estimates based on data from Yuma and Tucson stations).

Average monthly temperatures for the Ajo Mine range from 53 degrees Fahrenheit in January to 90 degrees Fahrenheit in July. The average relative humidity ranges from a high of 49 percent in December to a low of 22 percent in June. Average wind speed ranges from 6.6 miles per hour (mph) in October to 8.3 mph in July.

Geotechnical Investigation

The geotechnical investigation includes the following programs:

- In-Situ Testing Program;
- Shallow Test Pit and Surface Sampling Program;
- Drilling Program; and
- Visual Profiling Program

In-Situ Testing Program: The in-situ testing program included hydraulic conductivity and density testing. The testing characterized conditions for the three primary surface hydrologic types, namely: non-traffic surfaces, traffic surfaces and side slopes.

HYDRAULIC CONDUCTIVITY: Saturated hydraulic conductivity was measured in-situ at nine locations (three on each of the different surface hydrologic types, namely: non-traffic surfaces, traffic surfaces and side slopes) using a tension infiltrometer (Soil Measurement Systems 1997, Hussein and Warrick 1995).

The testing results are presented in Table I and are categorized according to the surface hydrologic type. As shown in Table I, the hydraulic conductivity for traffic and non-traffic areas did not vary significantly, and therefore, a mean value was calculated to represent both traffic and non-traffic surfaces (i.e., 1.0×10^{-4} cm/s). The mean hydraulic conductivity for side slopes was higher than the traffic and non-traffic areas on the top of the stockpiles at 5.4×10^{-4} cm/s.

Table I. In-situ Saturated Hydraulic Conductivity

Surface Type	Saturated Hydraulic Conductivity (cm/s)	Mean Values (cm/s)
Non-Traffic	1.35E-04	1.00E-04
	1.04E-04	
	1.22E-05	
Traffic	3.87E-05	
	1.46E-03	
	1.06E-04	
Slope	4.33E-03	5.43E-04
	3.46E-04	
	1.07E-04	

DENSITY: Density was measured in-situ at each hydraulic conductivity test location to aid in interpretation of the hydraulic conductivity data. Tests were conducted using a Troxler nuclear density gage (Troxler 1970).

The results of the density tests are shown in Table II and are categorized according to the surface hydrologic type. Consistent with the hydraulic conductivity test results, the density of traffic and non-traffic areas did not vary significantly. As shown in Table II, the average density for traffic and non-traffic surfaces was 121 pounds per cubic foot (pcf) and the average density of the side slopes was 109 pcf. These density values are consistent with the trend revealed in the hydraulic conductivity testing where the higher hydraulic conductivity corresponds to lower density.

Table II. In-situ Density Test Data

Surface Type	Dry Density (lb/ft ³)	Average Dry Density (lb/ft ³)
Non-Traffic	120.1	121.3
	119.9	
	116.5	
Traffic	128.0	
	128.4	
	113.1	
	119.3	
	125.0	
Slope	112.3	108.7
	112.7	
	100.8	
	108.9	

Shallow Test Pit and Surface Sampling Program: The shallow test pit and surface sampling program was designed to collect particle size data for estimating the soil-water characteristic curve and moisture content distribution for estimating the evaporative zone depth.

PARTICLE SIZE DISTRIBUTION: Samples of approximately 5 gallons were collected for laboratory measurement of particle size distribution at 20 locations (six shallow test pits and 14 surface sample sites). In addition, three samples of larger size (55 gallons) were collected from three of the six shallow test pits to characterize the particle sizes that could not be accounted for in the 5-gallon samples.

The results of the particle size testing (5-gallon samples) are presented in Figure 6. The average texture consists of 5% cobbles, 67% gravel, 20% sand, 7% silt and 1% clay.

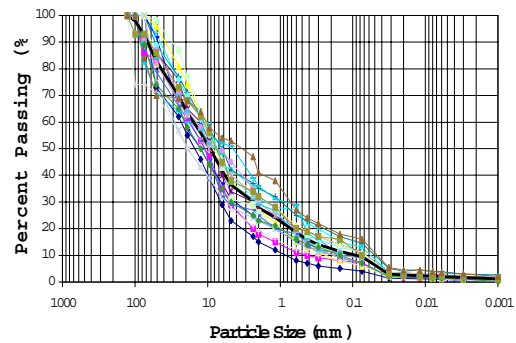


Figure 6. Particle Size Distribution

PREDICTED SOIL-WATER CHARACTERISTIC CURVES: The average particle size distribution measured for the Ajo samples was used in the SOILVISION program (SoilVision Systems, Ltd. 1997) to predict the average soil-water characteristic curve (SWCC) for the Ajo WRS. SOILVISION is a database knowledge-based system assists in the estimation of saturated and unsaturated soil properties for geotechnical engineering problems such as slope stability analyses and soil cover design. The database contains over 5,000 experimentally measured SWCC and an algorithm that predicts the SWCC from the particle size distribution.

The SWCC for the Ajo Mine WRS was predicted in accordance with the procedures presented in Swanson et al. (1999). The predicted SWCC is shown on Figure 7.

SHALLOW MOISTURE CONTENT PROFILING: The shallow moisture content profile data was used to estimate the evaporative zone depth for HELP modeling and to provide a basis for evaluating SOILCOVER model results.

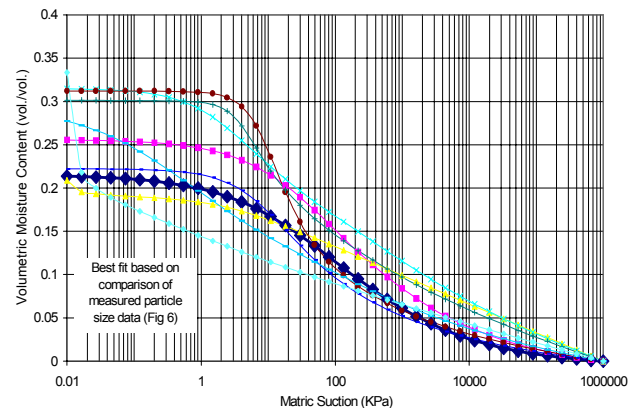


Figure 7. Soil-Water Characteristic Curves.

The results of the shallow moisture content profiling are presented graphically on Figure 8. As shown on Figure 8, the profiles are grouped according to the surface hydrologic type (traffic and non-traffic). The average evaporative zone depth for non-traffic areas is two feet and ranges from three feet to one foot. The evaporative zone depth for traffic areas was generally less than for non-traffic areas and averaged approximately one foot.

Drilling Program: A drilling program was conducted to collect samples to determine the placement and wetted moisture content of the DRS and the moisture content of strata in the underlying vadose zone. The placement and wetted moisture content is required for calculating the time required to deplete available moisture storage and the moisture content of the vadose zone is required to predict potential seepage migration times to

groundwater. Moisture contents obtained from mill feed records at the mine for the period 1961 to 1980 were used to supplement the field data for placement moisture contents.

content in equilibrium with the climate) for drill hole A is approximately 50 feet. The length of time the ground surface was exposed to precipitation at this location was estimated at 30 to 40 years. The moisture contents beneath the wetted zone (average of 1.9 percent) represent the placement moisture content of the WRS. This data corresponds well with placement moisture contents estimated from mill feed records obtained from the mine for the period 1960 to 1981.

The moisture profile for drill hole B reflects two separate construction lifts in the WRS. As shown on Figure 9, the wetted zone in the upper and lower lifts is approximately 40 feet. The surface exposure time for the upper and lower lifts was estimated at approximately 20 years each.

The depth of the wetted zone for drill hole C is more difficult to interpret. The moisture contents in this profile range from approximately one percent to two percent with the exception of a moisture content of approximately 3.5 percent at a depth corresponding to 60 feet. The low moisture contents are likely due to the cobble nature of the development rock at this location. The length of time the ground surface was exposed at this location was estimated at 30 years

NON-TRAFFIC AREAS

TRAFFIC AREAS

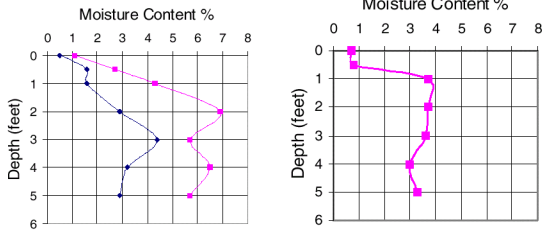


Figure 8. Moisture Content Profiles from a Shallow Test Pit Program

DEEP MOISTURE CONTENT PROFILING: The results of the deep moisture content profiles for the development rock stockpiles are shown graphically on Figure 9. The depth of the wetted, or equilibrated zone ("equilibrated" refers to moisture

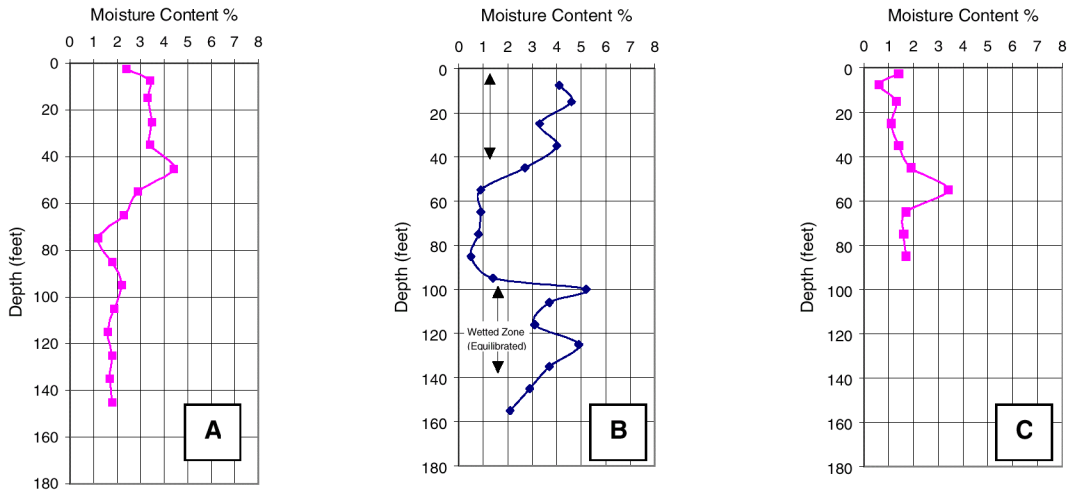
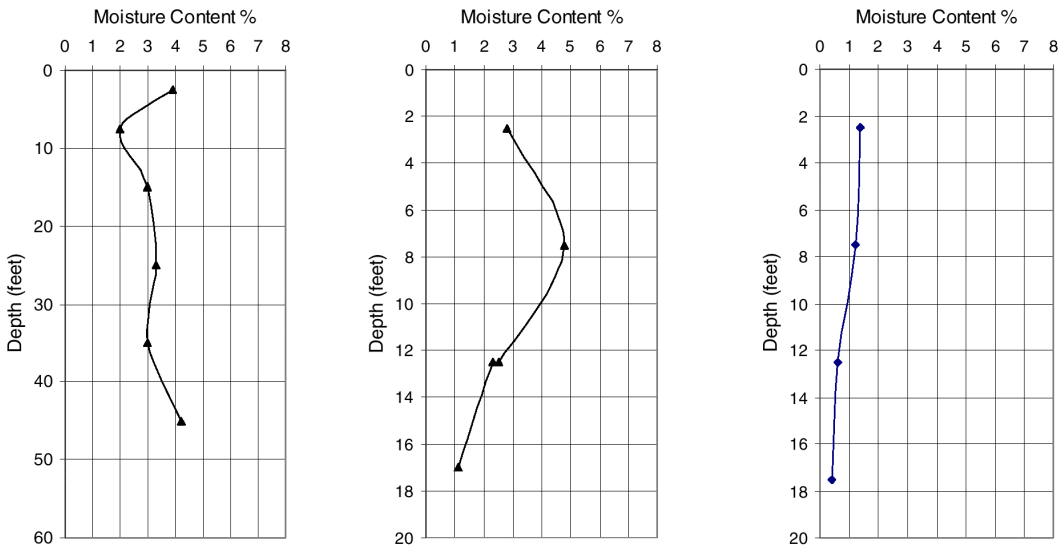


Figure 9. Deep Moisture Content Profiles in the WRS.



Quaternary Alluvium

Fonglomerate

Volcanics

Figure 10. Moisture Content Profiles in the Native Foundation

The results of the deep moisture content profiles for the native foundation are presented on Figure 10. The geology encountered at drill holes included Quaternary Alluvium, Fanglomerate, and the Volcanics. As shown on Figure 10, the moisture content profile for the alluvium averaged approximately 3.2 percent. This material was of similar texture to the material encountered in the waste rock stockpiles (WRS). Based on this similarity in texture, it is useful to note the similarity in moisture content between the wetted (equilibrated) zone of the waste rock stockpiles (average of 3.4) and the average moisture content of the alluvium (average of 3.2 percent). With similar texture, the two profiles should, in fact, wet (equilibrate) to the same moisture content. This comparison supports the wetted moisture content observed in the WRS.

The moisture content profile for fanglomerate and the volcanics averaged 1.7 percent. This moisture is consistent with the placement moisture contents observed beneath the wetted zone in the WRS (average of 1.7 percent) and in the mill feed moisture contents (average of 2.2 percent). Visual Profiling Program: A unique opportunity existed to observe a 50-foot thick, 1,200-foot long exposed section of the WRS. The exposed section was photographed along a transect parallel to the face at 50-foot intervals as illustrated on Figure 11. The exposed section was visually inspected to assess the relative amounts of coarse and fine development rock layers within the stockpile. This assessment was used to verify the percentage of coarse material in the stockpile. This percentage was input to the moisture storage calculation and represents the portion of the stockpile not capable of storing and transmitting moisture under unsaturated conditions.

As shown on the panoramic view on Figure 11, the exposed cut consists of an upper and lower lift. The angle-of-repose dipping is evident in the panoramic view of the lower lift (dipping from left to right) and is also slightly visible in the upper (from right to left). The dipping and random and interspersed coarse and fine-textured layers are evident. The cobbles occasionally visible on top of the lower lift represent the cobble zone that typically is present at the base of end-dumped stockpiles (the larger particles such as cobbles roll to the bottom of the pile). An inter-bedded system of coarse and fine-textured waste rock that appears to be randomly interspersed is also observed.

CONCLUSIONS

The objective of this case study was to assess the hydrologic discharge potential of the potential future expansion of the WRS at the Ajo mine. A hydrologic assessment was performed which included a site-specific hydrologic characterization (climate and geotechnical investigation) and hydrologic predictions. The assessment of the hydrologic discharge potential is based on conclusions from the following:

- Climatic data;
- Predicted net infiltration; and
- Additional hydrologic factors.

Collectively, the conclusions presented herein demonstrate that the combination of existing and potential future WRS at the

Ajo mine hydrologically do not have a reasonable probability of discharging pollutants to the underlying aquifer.

Climatic Data

The climate data at the Ajo mine is arid, characterized by an annual precipitation of 8.9 inches and an annual lake evaporation of 74 inches. Annual precipitation of 10 inches per year is regarded as a threshold value below which, no or negligible, quantities of leachate are expected to be experienced (Hutchison and Ellison 1992).

Based on this threshold value, it is unlikely that the potential future or existing WRS at the Ajo mine will have a reasonable probability of discharging potential pollutants to the underlying aquifer.

Predicted Net Infiltration

The net infiltration rate at the Ajo mine was predicted to be between 0.13 inches/year and 0.24 inches/year and 1.1×10^{-8} cm/s and 1.9×10^{-8} cm/s, respectively. A net infiltration rate of 10^{-7} cm/s is regarded as a threshold value, below which exist conditions that produce no or negligible quantities of leachate (seepage; Hutchison and Ellison 1992). Based on this net infiltration threshold value, it is unlikely that the potential future or existing WRS at the Ajo mine will have a reasonable probability of discharging potential pollutants to the underlying aquifer.

The net infiltration rate for the Ajo mine may also be assessed by comparison to potential seepage rates for lined surface water impoundments. The estimated leakage from a surface impoundment lined with a 1-foot thick clay liner having a saturated hydraulic conductivity of 10^{-7} cm/s is on the order of 2×10^{-7} cm/s assuming one foot of hydraulic head (Hutchison and Ellison 1992). Similarly, the estimated leakage for a geomembrane liner for a hydraulic head of one foot and overlying alluvial type material is on the order of 2×10^{-8} cm/s.

The predicted net infiltration rate (i.e., 1.1×10^{-8} cm/s to 1.9×10^{-8} cm/s) into the WRS at the Ajo mine is an order of magnitude less than the seepage rate through a compacted clay liner and the same as the seepage rate through a geomembrane liner. Therefore, based on this comparison, it would be impractical to design a facility that could limit seepage to rates as low as that dictated by the natural hydrologic system (climate and geotechnical properties) represented by the WRS at the Ajo mine.

Additional Hydrologic Factors

The discharge potential was also assessed based on hydrologic factors such as the time required to deplete available moisture storage in the stockpiles and the migration time of potential seepage to the underlying aquifer.

To assess these factors, two the hydrologic scenarios were considered. Both scenarios (Scenario 1 and Scenario 2) include potential future WRS rock overlying existing WRS and the underlying aquifer. Scenario 1 represents the minimum timeframe where the thickness of the potential future WRS and the existing WRS, and the depth to the underlying aquifer are anticipated minimums (values of 100 feet, 150 feet and 50 feet, respectively). Scenario 2 represents the maximum timeframe in which the thickness mentioned are anticipated maximums (values of 150 feet, 200 feet and 600 feet, respectively).

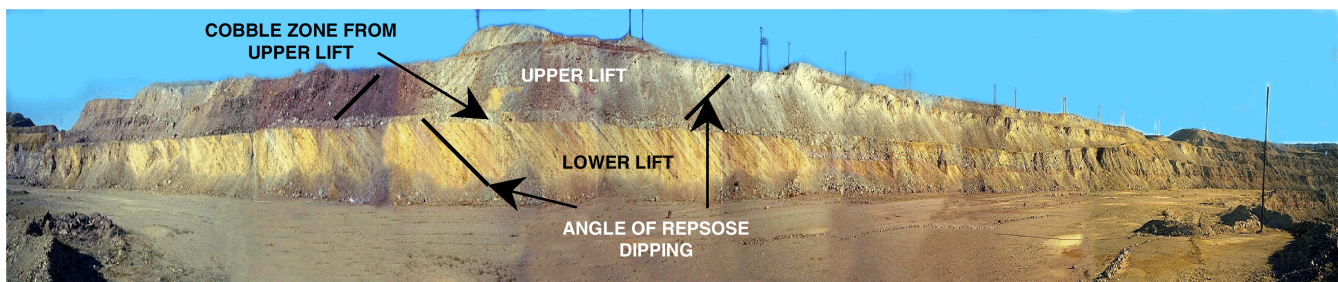


Figure 11. Results of a Visual Profiling Program.

Based on the results of the hydrologic predictions and the physical conditions of the site (thickness and depths to groundwater), the total time required for potential seepage from the WRS to reach groundwater would range from 260 years to 1,950 years.

Collectively, the climatological and geotechnical investigations and the hydrologic predictions demonstrate that the combination of existing and proposed WRS at the Ajo mine hydrologically do not have a reasonable probability of discharging pollutants to the underlying aquifer.

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