MYTHS, MODELS, AND REALITIES

Infiltration and Seepage Control in Mine Reclamation Covers in the U.S. Southwest[1]

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ABSTRACT

In semi-arid climates, acid drainage can be minimized after mine closure by preventing the deep percolation of precipitation into mine waste. A review of mine closure plans from the southwestern U.S. shows a variety of reclamation cover systems that have been proposed, frequently under similar semi-arid conditions. Justifications for the proposed systems range from myth to sophisticated model. Long-term data collected from instrumented sites at hard rock mines and U.S. Department of Energy mixed waste and uranium mill tailings sites reveal that soil cover systems greatly reduce but most likely do not eliminate seepage, and that current numerical models do not accurately predict seepage. This paper presents the hypothesis that recharge through soil cover systems will approach natural site-specific recharge rates, and recommends that reclamation programs use both existing knowledge and field-testing programs to determine site-specific conditions.

INTRODUCTION

Excluding water from acid-generating material is the most feasible way to control acid mine drainage (AMD) in a semi-arid environment. *Similarly, excluding water from mine wastes reduces the rate of pollutant leaching into groundwater*. Consequently, mine closure plans in this environment generally focus on minimizing infiltration and deep percolation (i.e., seepage) resulting from precipitation on waste rock, spent leach ore, or tailings. The amount of long-term steady-state seepage is a function of climatic conditions, plant species rooting depth and water consumption, and waste material and cover system hydrologic properties. A cover system can hypothetically be engineered to eliminate seepage; however, the long-term performance of reclamation cover systems is relatively unknown. Furthermore, quantifying the amount of seepage in semi-arid environments is often difficult due to low unsaturated flow rates and highly variable hydrologic properties.

A review of mine closure/reclamation plans in Arizona, Nevada, and New Mexico reveals a variety of proposed reclamation designs. The key to most design approaches is the use of store-and-release cover systems, where seepage is minimized by storage of infiltrated water in soil or waste until vegetation can transpire the stored water. For this paper, the following three general cover designs are defined, in order of increasing engineering and cost:

Monolayer vegetated cover: a single layer of topsoil or growth media, or direct revegetation into the mine waste.

Layered vegetated cover: the incorporation of a capillary break between the vegetated cover and the waste material. These covers can also incorporate low permeability layers.

Resistive low permeability cover: typically, a layer of geosynthetic and/or compacted natural material overlain with an erosion-resistant vegetated cover.

As shown in Table 1, the majority of proposed closure designs in Arizona and Nevada are monolayer vegetated cover systems. It should be noted that many of the closure designs are conceptual; final closure plans will likely change.

Table 1. Frequency of proposed cover types for mine facilities in Arizona and Nevada (includes conceptual designs[a])

State	Monolayer Vegetated Cover		Layered Vegetated Cover	Resistive Low Permeability Cover
	Revegetation (No Cover)	Single Layer		
Arizona[b]	7	10	2	2
Nevada[c]	7	5	2	0

[a]For simplicity, each mine site was defined as having up to three facility types, waste rock, tailings and leached ore.
[b]Proposed closure plans from 10 mine sites reviewed.
[c]Proposed closure plans from 8 mine sites reviewed.

The appropriateness of a design for a particular reclamation project is determined by the potential for AMD or pollutant leaching, the amount of predicted

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future seepage, and cost. Cover system selection, design, and predicted performance are based on a number of assumptions, including the following:

- Hydrologic properties of cover and waste material can be adequately characterized for engineering and modeling purposes.
- Performance criteria will be met for the duration of the regulated closure period.
- Models can accurately predict the amount of long-term seepage resulting from a particular design.

In addition, closure plans have frequently stated that:

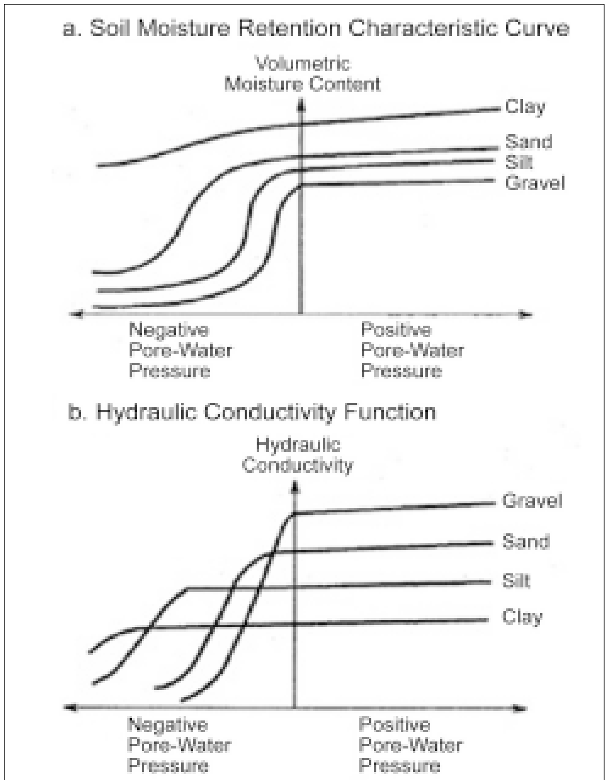
- Seepage will not occur if the field capacity of the soil or waste material is not exceeded.

In the absence of long-term data, these assumptions may or may not be valid. This paper will review these assumptions and propose some general principles for approaching reclamation projects.

BACKGROUND

To date, very little reclamation cover system monitoring has been conducted in the southwestern U.S. Performance monitoring has been conducted at other semi-arid sites, including a waste-rock dry cover system at a site in Montana (Wilson and others, 1995), and a number of cover system test designs for radioactive landfills (Albright, 1999). A significant amount of literature examining the hydrologic properties of soils and waste and the design of store-and-release covers has been published (e.g., Benson and Khire, 1995; Anderson, 1997; Gee and Ward, 1997; and Swanson and O'Kane, 1999). The reader is referred to these studies for more detailed discussions.

Briefly, the rate at which water infiltrates, and seeps from, a cover system is a function of soil moisture retention characteristic (MRC), climate, type of vegetation, and degree of saturation in the soil and waste. Figure 1 shows generalized MRC curves for different soil types (Figure 1a) and the calculated relationship between pore water pressure and hydraulic conductivity (Figure 1b). Figure 1b demonstrates that as pore pressure decreases (i.e., the soil becomes drier), the hydraulic conductivity of coarse-grained material quickly drops below that of fine-grained material. When a fine-grained material is placed over a coarse-grained one, a capillary break is created; flow into the coarse-grained layer is limited and

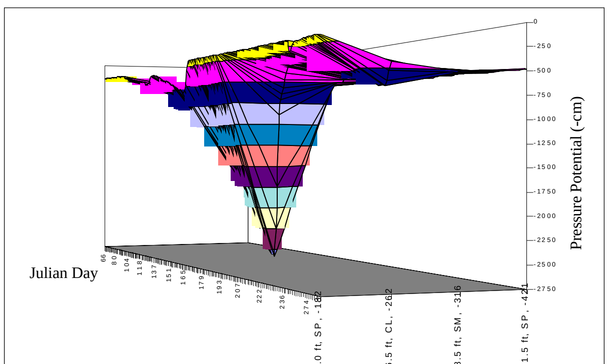


Source: Swanson and O'Kane, 1999

Figure 1. Soil moisture characteristic curves and hydraulic conductivity relationships for different soil types.

the pore pressure must increase for significant flow to occur between the different soil types, which results in increased water storage in the fine-grained material.

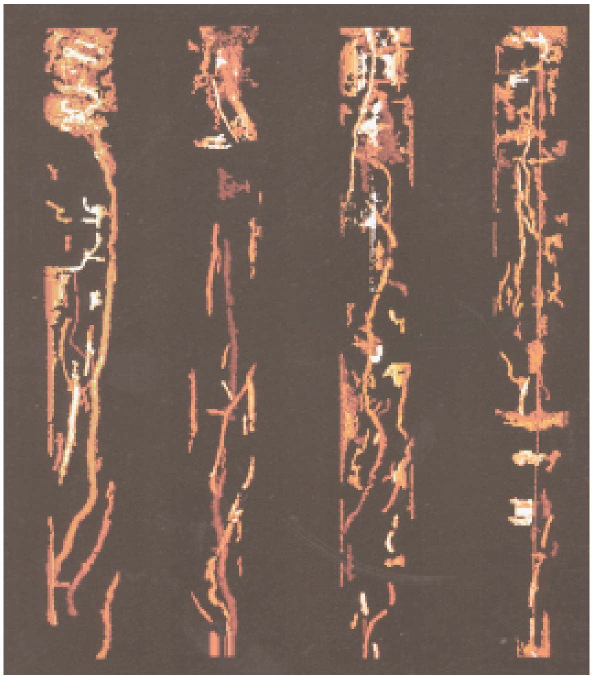
In addition, it is important to note that significant spatial variation in material properties (i.e., texture, density and porosity) and related hydrologic properties will occur in constructed cover systems, as well as in natural undisturbed sediments. These localized variations in material properties can significantly change the MRC curve and resultant hydraulic conductivity functions.



Source: Hammermeister and others, 1999

Figure 2. Trends in pressure potential over time in irrigated salt bush plot.

The ability of a vegetated cover system to transpire stored water is dependent on the plant species present, available rooting depth, and climate. In general, plant species adapted to arid environments are extremely efficient at exploring the subsurface and finding water. Figure 2 shows salt bush (*Atriplex*) removing water at depths greater than 8.5 feet below ground surface (bgs). On the other hand, plant roots will generally not extend into phytotoxic material, such as AMD. Moreover, dead plant roots (and burrowing animals) create macropores and increase the potential for preferential flow paths (Figure 3), which could greatly increase seepage (Jury and Flühler, 1992 and Perret and others, 1999).



Source: Perret and others, 1999

Figure 3. Three-dimensional reconstruction of macropores in intact soil cores.

Overall, the performance of a cover system that relies on measured soil characteristics to control seepage is subject to great uncertainty, due to spatial variability in cover and waste material properties and the effectiveness of the plant species used in reclamation. Consequently, the ability to predict the performance of a cover system is difficult.

COVER SYSTEM ASSUMPTIONS

Assumption

The hydrologic properties of cover and waste material can be adequately characterized for engineering and modeling purposes.

Review

As stated, spatial variability in material properties can significantly affect hydrologic characteristics. As the size of the area to be reclaimed increases, the variability of cover and waste material is likely to increase, with a concomitant increase in cost of material characterization and cover construction. Consequently, a cover system design should define the limits of acceptable variability in cover material properties, assuming strict construction quality assurance, and the resultant variability in seepage should also be assessed in order to estimate cover system performance.

Assumption

Performance criteria will be met for the duration of the regulated closure period.

Review

Whether performance criteria can be met for the duration of closure is a function of site-specific conditions. Over time, the plant community established on the reclamation site will likely approximate nearby site conditions. For example, Waugh (1998) reported that within 10 years, the average saturated hydraulic conductivity of a resistive layer uranium mill tailings cover system increased by over an order of magnitude due to the presence of deep rooting plants. Another study, reported by Anderson (1997), showed that plant roots were able to penetrate, and extract water from, a 0.5-meter gravel layer/capillary break below a 1-meter soil cover. Consequently, cover system designs should address site-specific factors, such as plant rooting depths, and erosion which could change design assumptions.

Assumption

Numerical models can accurately predict the amount of long-term seepage resulting from a cover design.

Review

Numerical models are important tools in assessing cover system design performance; however, the accuracy of unsaturated flow models is limited, primarily by the need for extensive input data. Fayer and Gee (1997) determined that a calibrated UNSAT-H model could simulate only 52 percent of the observed seepage in a lysimeter at a Hanford, Washington site. Furthermore, this value was only achieved after accounting for hysteresis, a soil property not normally measured. Extensive validation and sensitivity analyses performed on five numerical models commonly used for landfill cover evaluation showed variations in both prediction accuracy and the sensitivity of each model to different parameters (Wilson and others, 1999). Other problems included modeling the effect of freeze-thaw conditions and water redistribution in sloped cover systems. At this time, models are most useful for evaluating the potential performance in different cover designs.

Assumption

Seepage will not occur if the field capacity of the soil or waste material is not exceeded.

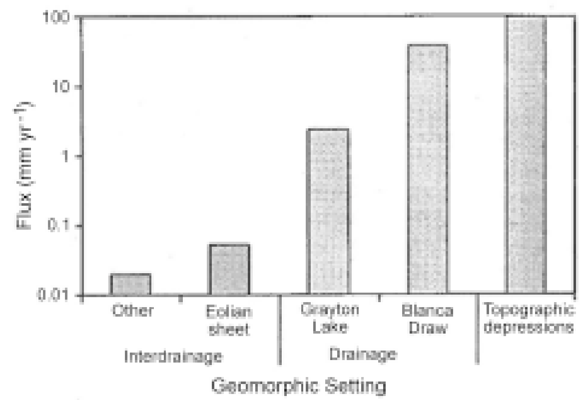
Review

This statement is essentially a myth. Rapid percolation occurs when soil water content is between saturation and field capacity. Unsaturated flow occurs, albeit more slowly, at water contents below field capacity. Unsaturated flow is more accurately described as the movement of water from a high-energy pressure potential (i.e., low negative pore pressure) to a low-energy pressure potential (i.e., high negative pore pressure).

In the case of Figure 2, flow moves upward towards the 8.5-foot-bgs level during most of the year, resulting in zero flux below at least 11.5 feet bgs (i.e., the zero flux plane) during this time period. However, during the remainder of the year, water moves downward throughout the profile, and is lost as seepage. In semi-arid climates, seepage most likely results from successive precipitation events in periods of low evapotranspiration (i.e., winter).

NATURAL SEEPAGE RATES

A variety of studies have been conducted to assess long-term natural recharge (i.e., seepage) rates in arid environments (Gee and others, 1994; Tyler and others, 1996; and Scanlon and others, 1999). These studies have shown that the magnitude of seepage in arid environments is related to soil hydrologic properties, vegetation density, geomorphic setting, and climate.



Source: Scanlon and others, 1999

Figure 4. Mean seepage estimates for various geomorphic settings.

Specifically, Scanlon and others (1999) determined that seepage could increase by several orders of magnitude between interdrainage areas and topographic depressions (Figure 4), whereas Gee and others (1994) found that seepage through unvegetated sandy soils could be as high as 10 to 50 percent of annual precipitation. Tyler and others (1996) found that, in southern Nevada, recharge rates ranged from 0.01 to 2 millimeters per year at depth. Hendrickx (2000) recently determined that localized recharge occurs through extensive caliche deposits (i.e., calcium carbonate) previously thought to limit groundwater recharge in south-central New Mexico.

These studies indicate that cover designs should attempt to minimize site-specific variability and emulate the local conditions under which minimum seepage occurs.

COVER SYSTEM PERFORMANCE

A variety of cover systems have been constructed for mine reclamation and radioactive waste disposal landfills. Table 2 summarizes these cover types and initial results (Wilson and others, 1999).

Almost exclusively, reclamation cover systems in Arizona and Nevada rely on no cover or monolayer cover systems ranging from 6 inches to 4 feet in depth. In several cases, the monolayer covers overlie gravelly leached ore or waste

Table 2. Types of cover designs tested at various facilities.

Site/Laboratory	Average Precipitation (cm/yr)	Cover Type/Depth	Cover Type Example	Seepage	Reported Monitoring Length (years)
Pacific Northwest National Laboratory (Hanford, Washington)	16	Hanford prototype barrier/2 m	Figure 5g	None	5
		1.5 m silt loam w/ surface gravel over sand and gravel	NA	None	3
		1.5 m silt loam over 0.2 m gravel/sand	NA	None	3.5
Hill Air Force Base (Ogden, Utah)	43.6	0.9 m sandy loam monolayer	NA	41 cm	3.8
		1.5 m sandy loam over 0.3 m gravel	NA	24 to 30 cm	
		1.2 m sandy loam over 0.3 m sand and 0.6 m clay	NA	0.01 cm	
Idaho National Energy and Environmental Laboratory (Idaho Falls, Idaho)	22.9	2.0 m monolayer	Figure 5h	Yes	2.5
		Capillary	Figure 5a	Slight	
		Capillary	Figure 5c	Very slight	
Los Alamos National Laboratory (Los Alamos, New Mexico)	47.1	0.2 m topsoil over 1.08 m crushed tuff (monolayer)	NA	17 cm	3
		0.71 m topsoil over 0.46 gravel, 0.91 m cobble, and 0.38 crushed tuff	NA	5.7 cm	
Nevada Test Site (Mercury, Nevada)	10	2 m monolayer	NA	None	5
Sandia National Laboratories (Albuquerque, New Mexico)	22.1	0.15 m topsoil over 0.45 compacted soil	NA	Yes	1
		Restrictive	Figure 5d	Yes	
		Capillary	Figure 5f	Yes	
		Capillary	Figure 5e	Yes	
		Monolayer	Figure 5b	Yes	

rock that acts as a capillary break. Several mines in Nevada are monitoring flow rates from closed heap leach pads; however, short-term (i.e., less than 5-year) flow rates are primarily due to residual drainage. Plans have been made to install soil moisture monitoring equipment at several reclamation sites in Arizona and Nevada, which will result in further data. A more complete data set exists from lysimeters constructed to evaluate seepage from alternative cover systems at U.S. Department of Energy (DOE) sites.

Figure 5 illustrates cover designs that are being tested at DOE laboratories in Washington, New Mexico, and Idaho. Research concerning infiltration and seepage into various cover systems has been ongoing since the early 1990s. In addition, eight monitoring sites in the U.S. Environmental Protection Agency Alternative Cover Assessment Program (ACAP) are located in areas that receive less than 12 inches of rain per year.

It should be noted that the material-type consistency and construction quality assurance of these test covers are tightly controlled. With the exception of the Nevada Test Site and the Hanford site, which receive less than 16 centimeters of precipitation per year, all monolayer covers tested have produced seepage (Albright, 1999). Several of the capillary barriers also produced seepage. Finally, these cover depths are greater than most depths currently proposed for mine closure in both Nevada and Arizona.

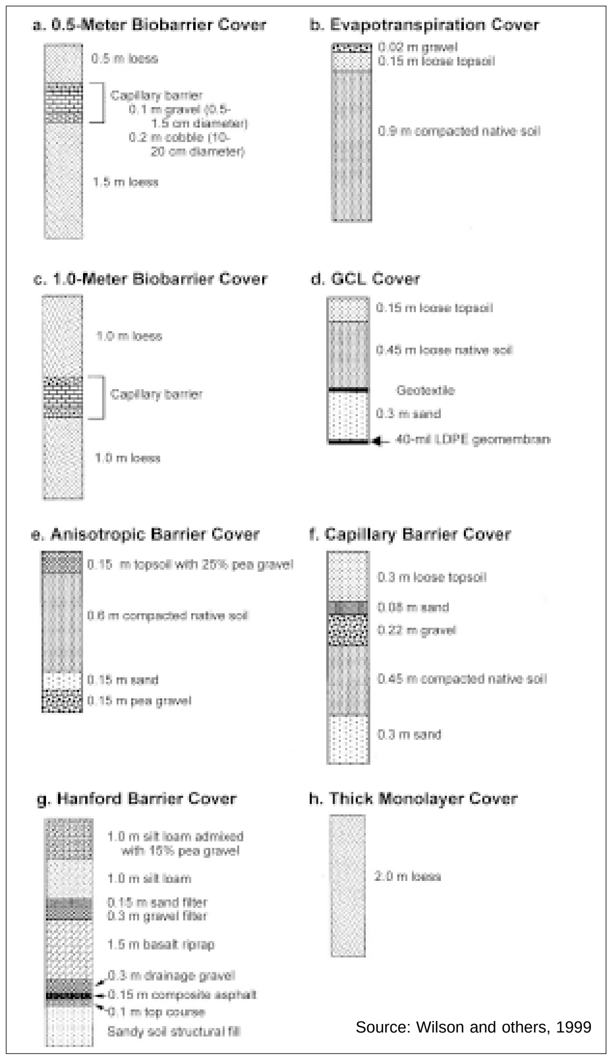


Figure 5. Examples of cover designs.

Data from Sandia National Laboratories and the Idaho National Energy and Environmental Laboratory are most applicable to eastern Arizona and northeastern Nevada, respectively. Nevada Test Site data may be applicable to the more arid regions of southern Nevada and western Arizona. Nonetheless, conditions at individual mine sites vary enough to warrant site-specific field testing to design optimum cover systems for reducing AMD.

Mine reclamation cover systems differ from DOE systems in other respects, including the presence of significant sideslopes and the wide variability in mine waste hydrologic characteristics. In addition, post-operational seepage from heap leach piles and tailings will be far greater than seepage from incident precipitation for an extended period of time.

CONCLUSIONS

- Seepage from precipitation can be greatly reduced through the use of store-and-release covers. However, there are limitations in soil cover efficiency.
- Unsaturated flow occurs below field capacity, albeit slowly. The amount of flow between field capacity and saturation is rapid compared to that below field capacity, which is driven by pressure potential energy differences.
- Variability in vegetation density, material properties, and topographic conditions can result in localized increased seepage.
- Given the size of most reclamation sites, design cost, and the cost of reducing variability, some seepage will likely occur in all soil covers. Nonetheless, seepage from well-designed cover systems should be very low.
- A soil cover system should have sufficient available water storage as determined by climate, cover and waste material MRC curves, and transpirative efficiency of vegetation.
- Site-specific natural recharge is most likely the best analogue for the long-term seepage potential from a soil cover system.
- Field testing prior to full-scale reclamation is highly recommended. “Start small, collect good data.”
- More data are needed to assess the effects of sideslopes on seepage reduction and the effectiveness of local plant communities in maximizing transpiration.

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– *Alligator Ridge, Bald Mountain Mine, Placer Dome, Inc.*
– *ASARCO Mission Complex*
– *ASARCO Ray Complex*
– *ASARCO Silverbell Mining District*
– *Buckhorn Mine, Cominco American*
– *BHP Copper, Pinto Valley Mine*
– *BHP Copper, San Manuel Mine Site*
– *BHP Copper, San Manuel Plant Site*
– *Cyprus Miami Mining Company*
– *Cyprus Sierrita Mining*
– *Cyprus Bagdad*
– *Fondaway Canyon Mine, El Paso Energy Corporation*
– *Bald Mountain Mine, Placer Dome, Inc.*
– *McCabe-Gladstone Mine*
– *Phelps Dodge Copper Queen Branch*
– *Phelps Dodge Morenci, Inc.*
– *White Pine Mine, Western States Minerals Corporation*
– *Wind Mountain Mine, Kinam Gold, Inc.*
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