The effect of tailings characteristics on cover system success

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ABSTRACT: Mine tailing properties significantly differ from other mine waste (e.g. waste rock and heap leach material) such that cover system design criteria for cover success and post-closure monitoring should require different approaches. Tailings can generally be classified into three material types corresponding to location within the impoundment, with each material type possessing distinct physical and hydraulic properties. Finding from tailings reclamation research and performance monitoring at five tailings facilities in the southwestern United States indicate that: (1) alternative cover system designs based on location within the impoundment can maximize performance (and reduce costs), (2) tailings underlying shallow evapotranspirative cover systems play a significant role in reducing net percolation, whether they are non-acid or acid, and (3) depending on the cover material properties and climate, monolayer covers over acid tailings may show limited acidification and salinization. Consequently, tailings cover system design should consider potential interactions between the tailings, cover material and vegetation.

1 INTRODUCTION

Closure and reclamation of mine tailings facilities are guided by three general goals. The first goal is to develop a sustainable reclaimed land which is stabilized against wind and water erosion, revegetated, and in the long-term the reclaimed surface is a soil material that has structure and nutrients of a typical soil for the area. These components are inherently related such that non-acidic tailings stabilization can be achieved if the tailings material has a nutrient composition and hydraulic properties that will support vegetation. In cases where the tailings material is too acidic or saline to support vegetation, cover material may be utilized which provides a growth medium and protects the tailings material from erosion.

A second goal is to minimize deep percolation and drainage from the tailings material, which can serve as a long-term pollution source to surface and groundwater. In arid and semi-arid environments, deep percolation can be reduced by placing an appropriately designed cover system that acts to store water within the cover material where it is available for evaporation and transpiration (Dwyer, 2003; Albright et al., 2004; Milczarek et al., 2009). An appropriately designed store and release cover system will use cover material with adequate structure and nutrient composition to support vegetation, and with hydraulic properties that allow for sufficient soil-water storage to retain infiltrated water from rainfall or snowmelt events.

The final goal is to develop a closure and reclamation plan that optimizes performance while limiting capital, operation and maintenance expenses. This requires developing site-specific closure and reclamation plans that account for conditions (e.g. climate, tailings properties, borrow material properties, area vegetation) specific to that site. Applying a "one size fits all" closure and reclamation plan may fall short of meeting the needs or may result in unnecessary work, both of which increase either short-term and long-term costs.

This paper presents a general summary of findings from over a decade of copper tailings reclamation research and performance monitoring at five copper tailings facilities in the southwestern United States. These copper tailing facilities are located in the Sonoran or Chihuahuan deserts and are characterized by average annual precipitation that range from 300 to 450 mm and reference evaporation conditions exceeding 1700 mm per year. The findings are presented within the context of the three closure and reclamation goals.

2 IMPORTANT TAILINGS CHARACTERISTICS

Mine tailing properties differ significantly from other types of mine waste, such that reclamation design, the criteria for reclamation success, and post-closure monitoring require different approaches from the standard methods used for waste rock and heap leach material. Tailings lack organic matter, soil microbes, soil structure, and plant nutrients which complicate reclamation activities. In addition, tailings can have a low hydraulic conductivity and high moisture retention such that drainage from saturated tailings material may take decades to centuries.

2.1 *Physical characteristics*

Tailings are poorly graded material primarily made up of mostly silt sized particles and lack soil structure. Due to fluvial deposition processes, significant sorting and layering of the tailings material typically occurs within an impoundment regardless of the deposition method. In general, three textural areas are created: (1) beach sands which represent coarser textured material that settled out first, (2) the slimes which represent finer textured material that settled out last, and (3) a mixed area between the slimes and beach sands. Figure 1 provides an example of particle size distribution for beach sand and slimes material.

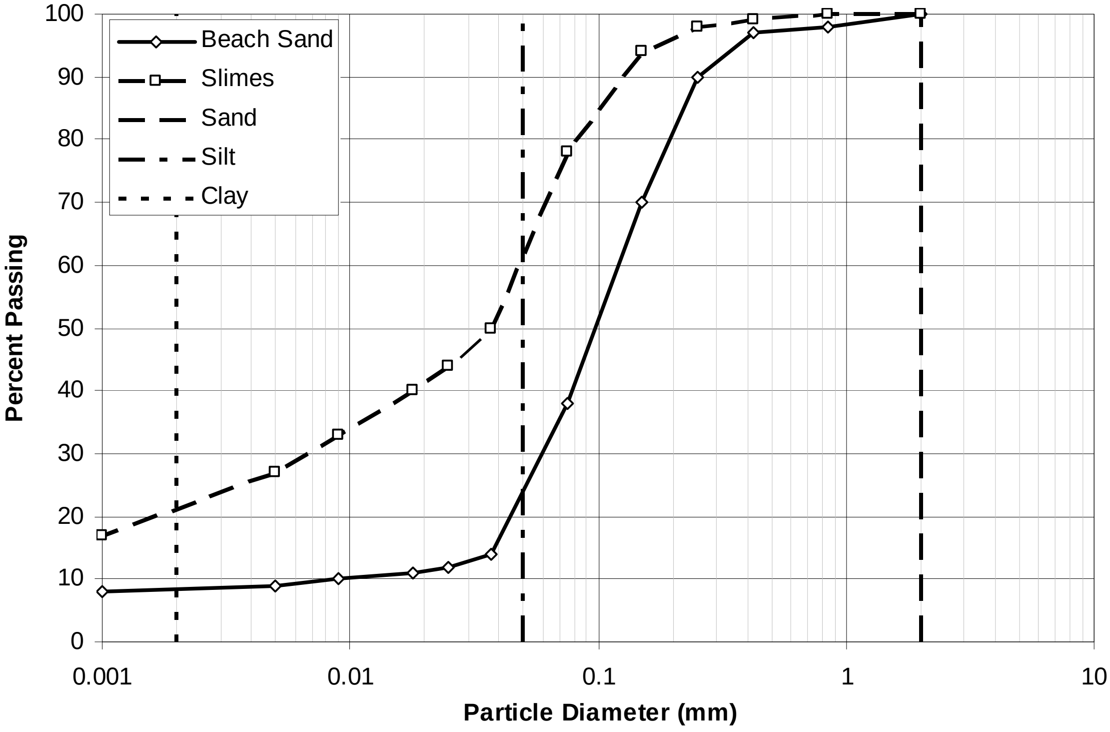


Figure 1. Example particle size distributions for beach sand and slimes tailings material.

2.2 *Hydraulic characteristics*

The soil water characteristic curve (SWCC) which describes the soil-water content versus pressure head, and the hydraulic conductivity function which describes the hydraulic conductivity versus soil-water content or pressure head, varies significantly by the different impoundment textural areas. Figure 2 shows an example SWCC and hydraulic conductivity function for beach sand and slimes material. Slimes material has greater soil water retention capacity and hence greater plant available water than the sand material. However, the slimes material is less conductive than the beach material at wetter (less negative) pressure heads. Under these pressure head conditions (i.e. during and after tailings deposition) the slimes material impede downward flow more than the beach material and will result in significantly increased drainage times of tailings water compared to that from the beach area material. As an example, assuming initial capillary pressures of -10 cm and a tailings impoundment thickness of 100 ft, it would take approximately 500 years for the slimes material to drain free water, whereas the beach material would only take 0.5 years. The result is drain down of the slimes material can take decades to centuries, albeit at very low rates (i.e. 1 gpm/acre of impoundment). Depending on the size and height of the impoundment, variable saturation and drainage conditions can be expected within the different tailing textural areas.

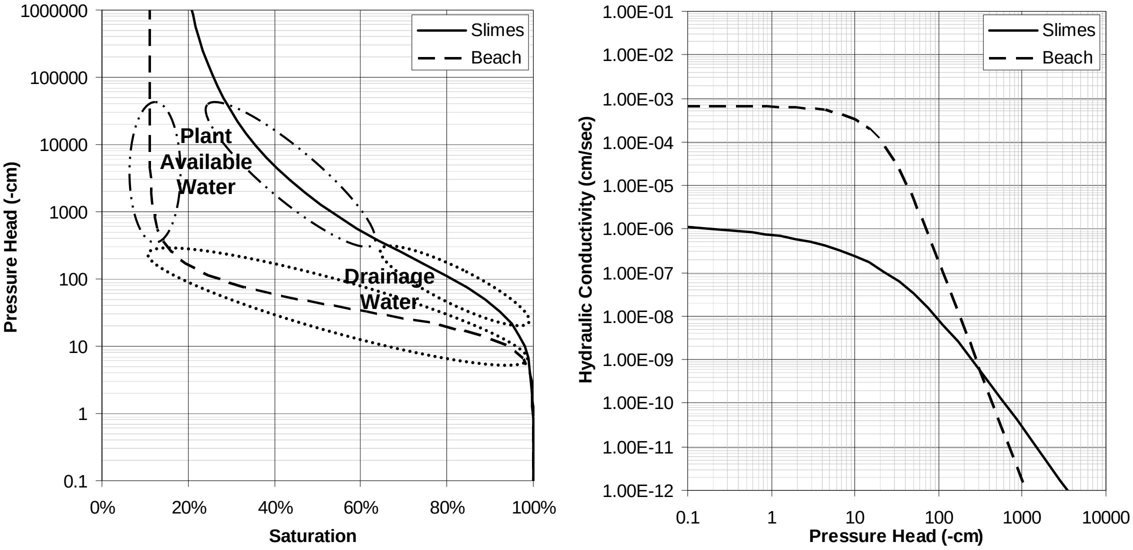
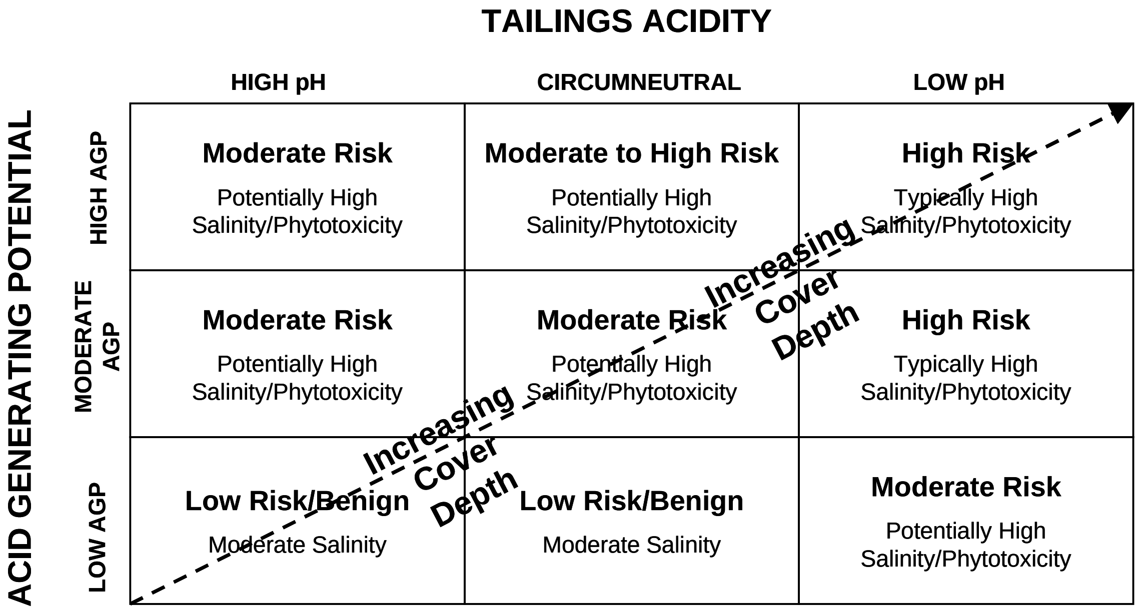


Figure 2. Example moisture retention curve and hydraulic conductivity function for beach sand and slimes tailing material.

2.3 *Geochemical characteristics*

Tailings are typically plant nutrient limited, have minor levels of organic carbon and a functioning microbial community, and can be saline to hyper-saline. All of these factors limit the potential for direct revegetation of tailings material. Additionally, the ore body mineralogy can result in high acid generation potential, acidity and high plant available metals. Nonetheless, circumneutral to moderately acid tailings have been successfully revegetated in a variety of climatic environments using organic matter addition and lime amendments as needed (i.e. Brown et al., 2005; Sauer, et al. 2002; Bengson, 2000; Munshower et al., 1995). In general, the effect of tailing geochemical characteristics on potential revegetation and whether a cover system is needed can be classified as shown in Figure 3.



	HIGH pH	CIRCUMNEUTRAL	LOW pH
HIGH AGP	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**Moderate to High Risk** Potentially High Salinity/Phytotoxicity	**High Risk** Typically High Salinity/Phytotoxicity
MODERATE AGP	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**Moderate Risk** Potentially High Salinity/Phytotoxicity	**High Risk** Typically High Salinity/Phytotoxicity
LOW AGP	**Low Risk/Benign** Moderate Salinity	**Low Risk/Benign** Moderate Salinity	**Moderate Risk** Potentially High Salinity/Phytotoxicity

Figure 3. Tailings geochemical characteristics and influence on relative cover system depth potentially required to support revegetation.

3 REVEGETATION

General observations regarding vegetation success on reclaimed copper tailings in the southwestern United States are as follows. Organic amendments can be successfully used to reclaim circumneutral tailings, however, low to moderate amendment rates should be used to limit high-nutrient conditions that favor for undesirable non-native species. Volunteer revegetation on copper tailings has been observed on circumneutral tailings, though vegetation is generally limited to the slimes area and halophyte species (Milczarek, 2006). Greenhouse and field experiments with raw tailings treated with biosolids and green waste showed significant vegetative cover with native species which outperformed untreated plots over at least eight years (Thompson et al., 2001; Milczarek et al., 2006). These tailings also showed no significant changes in geochemical weathering and nitrate leaching (Pond et al., 2005).

Other long-term experiments with organic amendments added to 30 cm and 60 cm cover depths over acid tailings have shown that significant differences in vegetation density were sustained after 10 years of reseeding (Milczarek et al., 2009). Figure 4 shows that the addition of biosolids at two different levels resulted in significantly greater mean native and non-native vegetation ground cover, grass, and forb and shrub groundcover than in unamended plots. However, unamended plots generally showed greater native species diversity, but lower overall frequency and biomass. The influence of organic amendments on vegetation ground cover was observed to persist over 10 years after application relative to the unamended plots.

In this same study, there were no significant differences over ten years in observed vegetative ground cover between 30 cm and 60 cm cover depth test plots over acid tailings (Figure 5). This effect may be due to the endemic presence of South African grasses in the southwestern United States. In general, the South African grasses did well in all test plots, but, greater native species success was observed on the 60 cm cover depths (Milczarek et al., 2009).

High salinity and/or acid tailings has been shown to restrict vegetation success in shallow covers (e.g. less than 15 cm) most likely due to root contact with high salinity and acidity levels. Virtually all semi-arid plant species are acid intolerant with soil pH levels below 5 considered to adversely affect vegetative growth (i.e. Borden et al., 2005; Barth, 1986; Shafer, 1979). Salt-tolerant plants can withstand higher salinity levels, however, vegetative density and the ability to extract water efficiently may diminish with increasing salinity. Examples of reclaimed copper tailings with a 15 cm cover overlying circumneutral tailings and a neighboring area with 15 cm cover overlying moderately acidic (pH > 5) tailings are shown in Figure 6. Both pictures were taken ten years after seeding and planting of trees and shrubs. Tree and shrub planting was limited to the circumneutral tailings area, otherwise seeding treatments were identical. The greater vegetative success in the circumneutral tailings plot compared to that in the moderately acidic tailings plot can be observed.

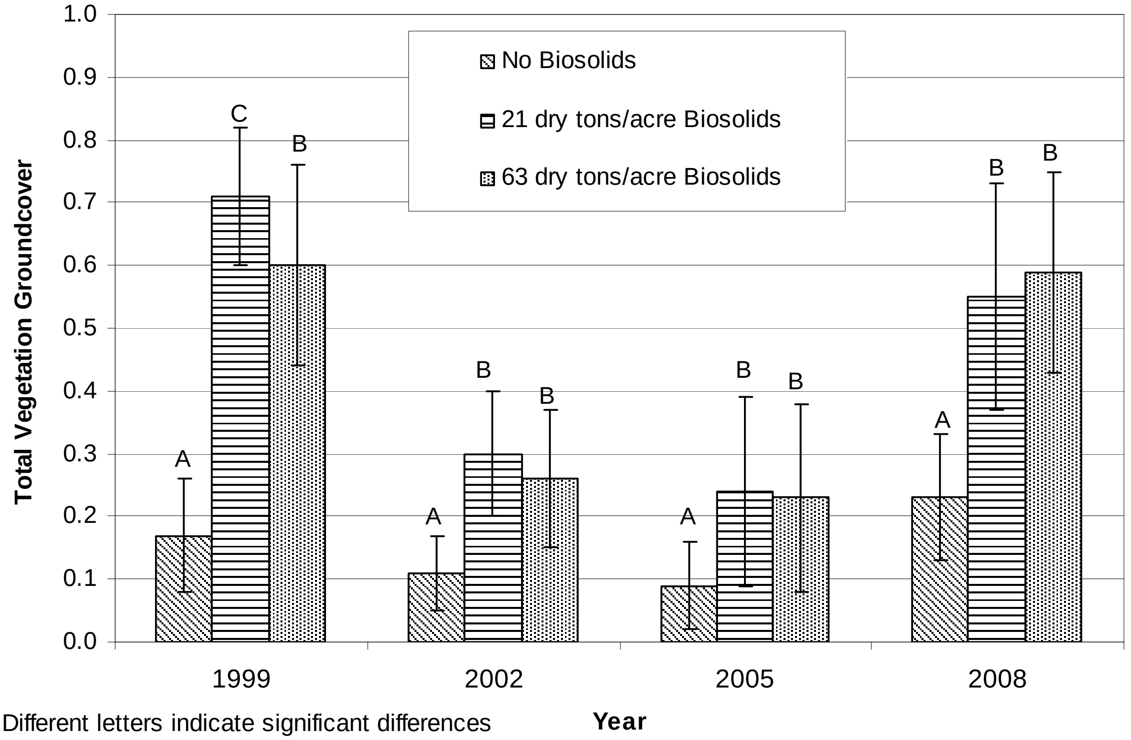


Figure 4. Mean vegetation groundcover for amended and non amended plots.

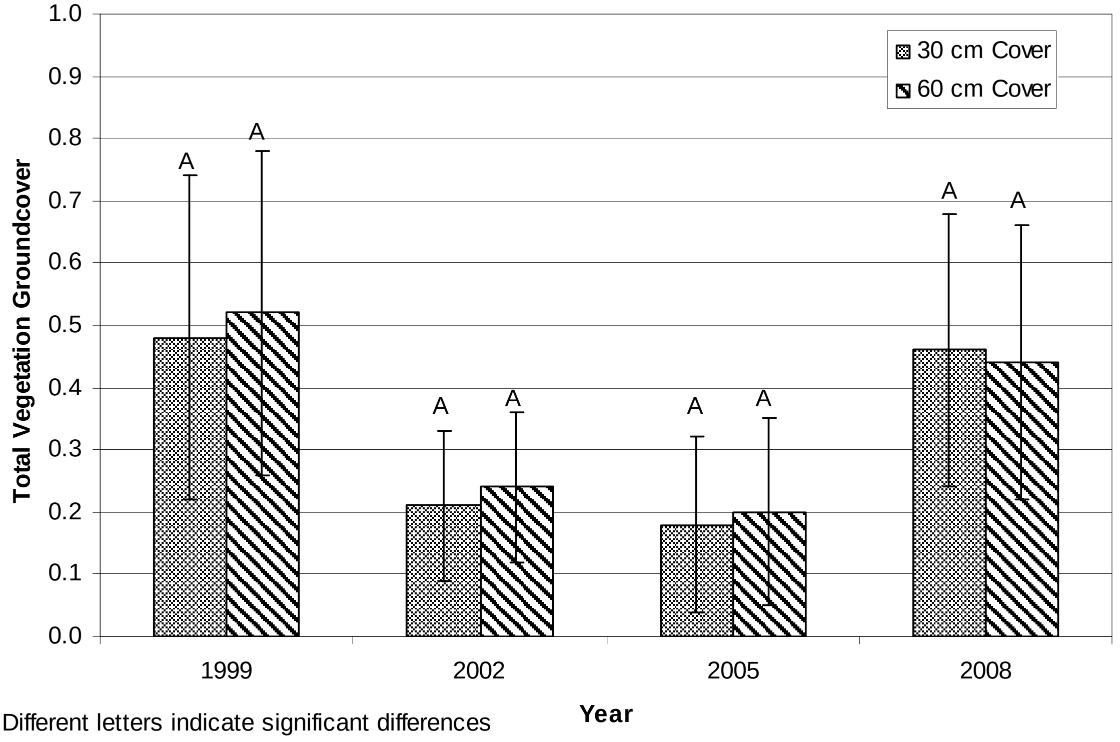


Figure 5. Mean vegetation groundcover for 30 cm and 60 cm cover plots

Figure 6. Vegetation on circumneutral (left) and moderately acidic (right) tailings plot with 15 cm cover material.

The ability of plant roots to propagate into tailings is influenced by many components, including compaction, salinity, and acidity. Frequently, a combination of tailings salinity and the dense nature and generally poor soil structure of deposited and consolidated tailings limits root extension and density. Moreover, the generally low permeability of mixed and tailing slime areas limits the downward infiltration of moisture at depth, resulting in root concentration near the surface. At several reclaimed copper tailings in the southwestern United States, plant roots have been observed to actively root into circumneutral and moderately acidic (pH > 5) tailings (Milczarek et al., 2006). Table 1 presents rooting profile descriptions for several reclaimed tailings areas. Roots were observed down to 20 cm below the tailings and cover material contact, although rooting was at much lower densities than in the soil cover material. The implications for reclamation planning are that rooting into the tailings material extends the depth of plant water extraction and makes the tailings a component of the overall cover system.

Finally, vegetation characteristics vary with location with mesic type vegetation (e.g. creosote and salt cedar) in the slimes and xeric type vegetation (e.g. cattails) in the beach sands. This may change over time as the slimes area dries out and if surface runoff is not available to replenish drained and evaporated moisture.

The vegetation monitoring results indicate that an understanding of the geochemical characteristics (e.g. pH and salinity) and hydraulic characteristics (e.g. slimes or beach area) of the tailings material and their spatial distribution will allow for increased likelihood of long term revegetation success.

Table 1. Rooting profile descriptions for circumneutral and moderately acidic reclaimed tailings plots

Trench ID	Cover Depth (cm)	Soil Cover (above tailings contact)	Root Density[1] 0-10 cm below tailings contact	10-20 cm below tailings contact
P1	13	4	2	0
P2	24	4	1	1
P3	19	4	2	0
P4	12	4	1	0
P5	21	5	4	1
P6	16	4	3	1
P7	21	4	1	0
P8	24	4	3	2
P9	11	4	3	2
P10	19	5	4	3
P11	17	4	3	2
P12	18	3	2	2

[1] Root density descriptions use a modified USDA classification system for root abundance: 0=none, 1=very few/none, 2=few, 3=few/common, 4=common, 5=common/many, 6=many

4 INFILTRATION AND NET PERCOLATION

Infiltration is the process of water entry into the soil (e.g. rain or snowmelt event). Infiltrated water may return to the atmosphere through evaporation or transpiration of plants. Water that remains in the soil profile and continues downward past the evapotranspiration zone is termed net percolation and over the long term can be considered equivalent to aquifer recharge. Cover systems act to increase the evapotranspiration zone, water storage capacity and return of infiltrated water to the atmosphere by evapotranspiration processes.

Monitoring data collected on cover systems in the southwestern United States indicate that shallow cover systems can effectively store and release precipitation, though episodic sequences of above-average precipitation can result in net percolation past the cover system (i.e. Milczarek et al., 2009; Fayer and Gee, 2006; Waugh et al. 2006; Nyhan, 2005; Scanlon et al., 2005; Albright et al., 2004; Dwyer, 2003). In the case of cover systems over tailings, the contrast in hydraulic properties between the tailings and cover material also can significantly affect the cover system performance. For example, Figure 7 presents in-situ soil water pressure head data collected at 180 cm below ground surface under 30 cm and 60 cm coarse-grained cover material and a no (0 cm) cover (Milczarek et al., 2009). Wetting and drying patterns shown at 180 cm below ground surface indicate that under conditions of normal precipitation little to no wetting of the subsurface occurs at depth with either cover system depth. However, when above-average precipitation follows very dry periods, equivalent or greater wetting occurs at depth below the 60 cm cover than the 30 cm cover (i.e. August 2002 and July 2006). These data indicate that after periods of drought, differences in evapotranspiration rates could be diminished and the thicker profile of higher conductivity cover material over low conductivity tailings may actually result in increased net percolation due to more rapid downward percolation of precipitation through the upper 60 cm. Of note, the bare-tailings plots consistently showed drier conditions than did the covered plots at the 180 cm depths. This result is due to higher runoff rates from the bare tailings surface than from the cover material.

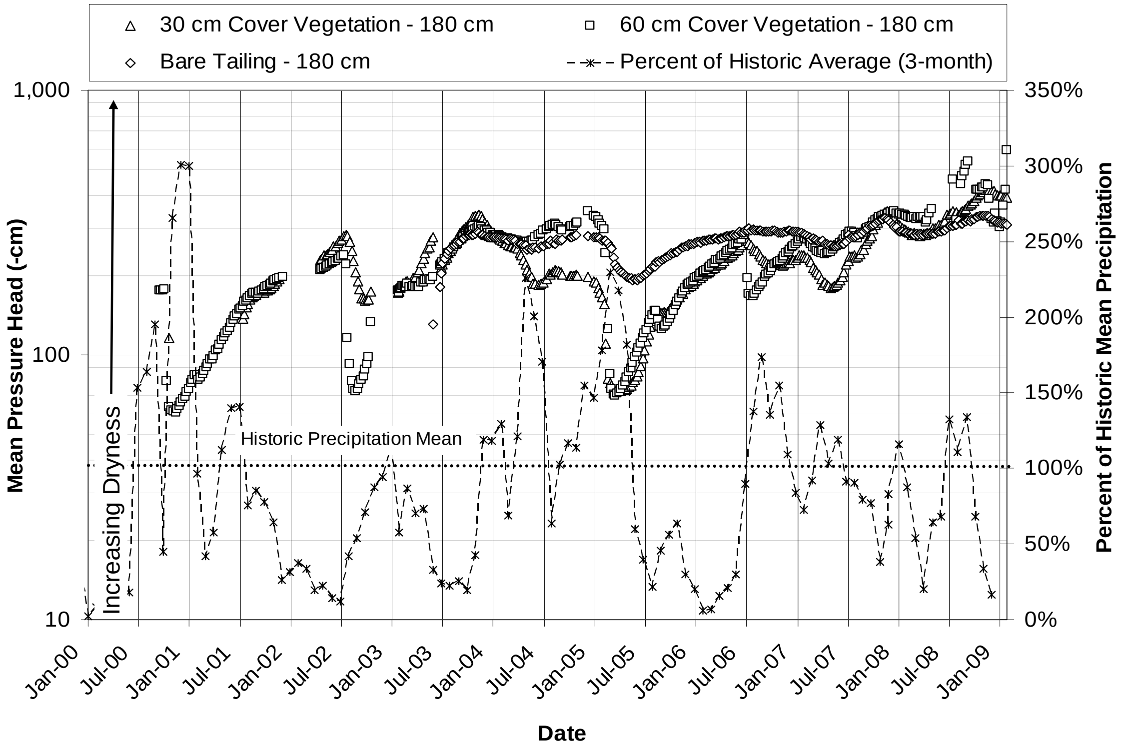


Figure 7. Pressure head measurements for vegetated plots with 30 cm and 60 cm cover and bare tailings.

Table 2 presents estimated total and average downward flux across tailing reclamation treatments using in-situ soil water pressure measurements and the simplified two-layer flux model described in Milczarek et al (2009). Predicted downward fluxes through the 60 cm cover systems were slightly greater than the 30 cm cover systems. The higher estimated flux rates through the deeper covers are due to observed lower-permeability tailings layers below the 30 cm cover plots than the 60 cm cover plots. With the exception of the bare-tailings plot, the average estimated flux rates are not significantly different. These predictions also indicate that the underlying tailings permeability have a significant affect on cover system performance in controlling net percolation.

Table 2. Estimated downward flux rates for different treatments.

Treatment	Flux	
	cm/yr	Percent of precipitation
30 cm cover, low vegetation	0.37	1.3
30 cm cover, high vegetation	0.12	0.3
60 cm cover, low vegetation	0.55	1.7
60 cm cover, high vegetation	0.48	1.5
Bare tailings	0.02	0.1

Finally, Figure 8 presents the predicted net percolation using a calibrated unsaturated flow model (UNSAT-H Fayer, 2000) and applying a 98-year climate record for a coarse-grained cover system located over tailing beach sand and slimes areas. Model predictions indicate that for the tailings beach and sideslope materials the cover system could be expected to limit net infiltration to between approximately 4.5 to 7 mm per year, depending on cover thickness. Increasing the cover thickness from 45 cm to 90 cm was predicted to only nominally decrease the net percolation by 2.5 mm per year. However, decreasing the estimated saturated hydraulic conductivity of the underlying tailings to approximate hydraulic property differences between the slimes and beach areas showed greater predicted reductions due to reduced wetting front depths and subsequently higher available moisture for evapotranspiration. The unsaturated flow model results and estimated flux rates presented in Table 2 indicate that increasing cover thickness can have less influence on net percolation than the underlying tailings characteristics.

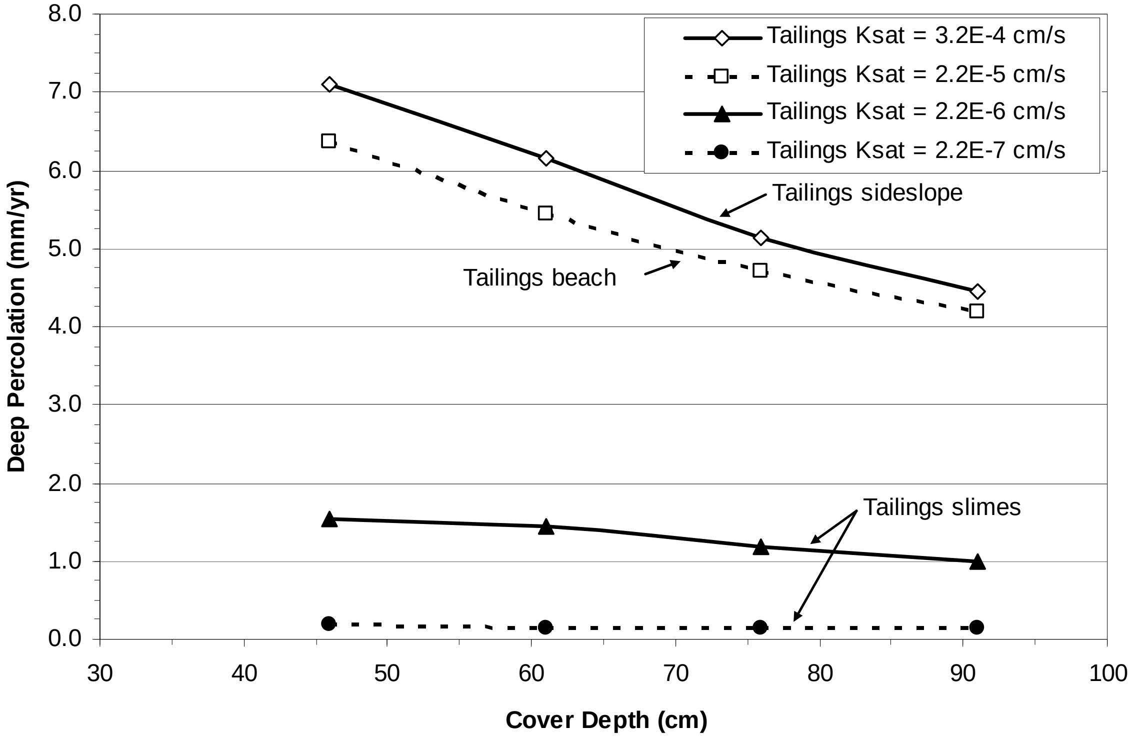


Figure 8. Predicted net percolation with different cover material depths and tailings saturated hydraulic conductivity (Ksat).

5 TAILING SOLUTION MIGRATION INTO COVERS

Low pH and high electrical conductivity (EC) of copper mine tailings in semi-arid and arid environments raise concerns regarding potential upward migration of salinity and acidity into the cover materials. Limited upward salinity migration from acidic tailings into reclaimed minespoil cover soils has been observed on time-scales up to 25 years (i.e. Dollhopf et al., 2001; Dollhopf et al., 2003; Munk et al., 2006). Salinity and acid migration has also been observed to be negligible under moderately acidic conditions and limited to approximately 15 cm above the cover and tailings contact (Milczarek et al., 2009; Milczarek et al., 2010).

Figure 9 displays profiles of pH and EC relative to the tailings-cover material contact (Milczarek et al., 2010). pH and EC results were observed to be highly variable across the test plots, however, samples generally displayed decreased pH and higher EC values within 5 cm to 10 cm above the tailings/cover system contact. EC and pH returned to near background levels within 15 cm above the contact. Similar tests performed five years prior showed that pH and EC values were essentially similar over the five year period. The observed nominal effects in pH and EC migration are believed to be in part affected by cover material neutralization potential due to the cover material being strongly calcareous.

EC and pH effects from acidic tailings have been observed to be greater in shallow (i.e. 30 cm) than in deeper (i.e. 60 cm) cover systems at equivalent depths above the tailings/cover system contact (Milczarek et al., 2010). Because the tailings/cover contact in shallow covers is closer to the surface than in deeper covers, hydraulic gradients which drive upward advective flux may be greater at the tailings/cover contact. Diffusion may also be a secondary cause of decreased pH and increased EC at depths near the tailings/cover contact. However, if diffusion were the primary cause, EC and pH levels would be expected to be generally uniform across depths. Advection of tailings solution into the cover system is likely to be driven by episodic rainfall events that wet the tailings and are limited to a very shallow region above the tailings/cover contact due to rapid decreases in hydraulic conductivity with distance above the contact due to drier conditions nearer the surface. Vegetation monitoring results from several semi-arid reclaimed tailing sites in the southwestern United States (i.e. Milczarek et al., 2009; Milczarek et al., 2010; Munk, 2006) indicate that pH and EC changes above the cover contact has not negatively affected vegetative cover, rooting dynamics, or cover performance for a range of cover system depths and varying tailings chemistries.

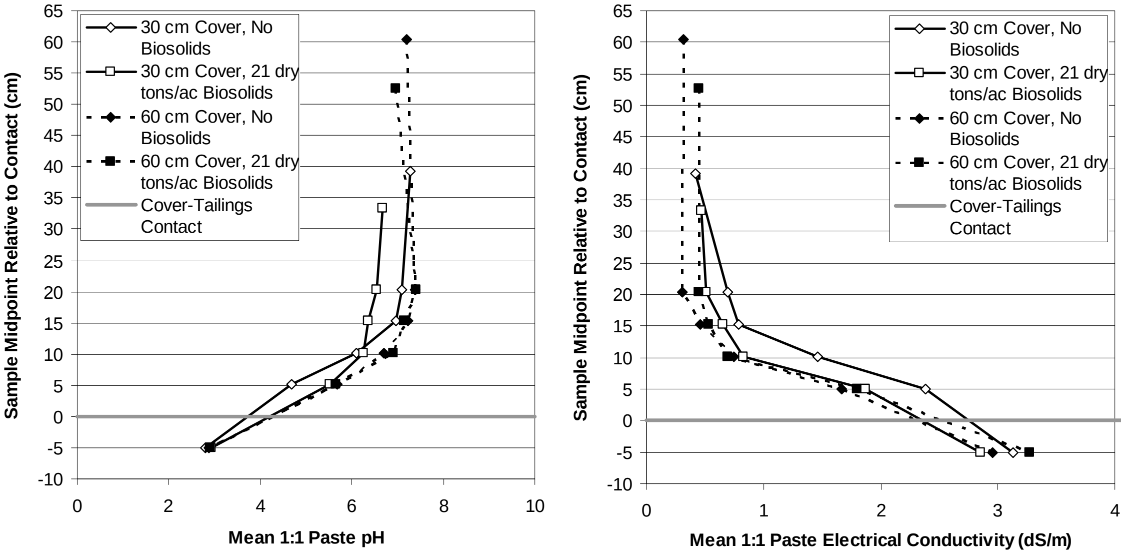


Figure 9. pH and electrical conductivity for different treatments.

6 CONCLUSIONS

General findings from over a decade of tailings reclamation research and performance monitoring at five tailings facilities in the southwestern United States indicate that circumneutral tailings can be directly revegetated with organic amendments or using a shallow cover. The effective depth of a cover system in supporting vegetation and controlling net percolation can range from 15 cm for circumneutral tailings to 60 cm for acidic tailings. Revegetation seed mixes should consider differences between beach sand and slimes areas as well as cover depth, such that mesic species can be used in slimes areas and xeric species will be more successful in beach/mixed areas. Deeper covers also may promote better success of native seed mixes. Plants can actively root into circumneutral and moderately acidic tailings, indicating that water balance modeling of the cover system should allow for evapotranspiration at depths into the tailings. Low permeability tailings also serve to slow down infiltration and retain water in the cover and can have a greater effect on net percolation than does cover depth. Finally, upward acidity and salinity migration into covers appears to be limited to shallow depths above the cover-tailings contact. These finding indicate that tailings affect the performance of store and release covers and their influence and spatial variability should be considered during cover design.

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