Monitoring the Performance of Monolayer Evapotranspirative Cover Systems in the Southwestern United States

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ABSTRACT

In arid and semi-arid environments, infrequent precipitation, low subsurface fluxes, and evapotranspiration from below evapotranspirative cover systems create challenges to monitoring moisture flux. Furthermore, in contrast to landfill closures, mine waste closures are frequently an order of magnitude larger (thousands of acres). The large scale of these systems results in increased variability in waste and cover materials, and slope and aspect. Consequently, the use of highly controlled large-scale lysimeters is impractical for both cost and applicability considerations. Instead, simplified, inexpensive monitoring using in-situ soil water pressure potential sensors may be adequate to evaluate the efficiency of different cover systems in the semi-arid southwestern USA.

We have instrumented monolayer ET cover systems at several mine site locations in Arizona and Nevada with soil water pressure potential sensors. The most complete data set, and the focus of this paper, is from ET cover test plots constructed over copper mine tailings at Morenci, Arizona. Four different test plots consisting of two different ET cover depths and two different vegetation cover densities have been instrumented with heat dissipation sensor nests. The sensors measure the soil water pressure potential and allow hydraulic gradients to be determined within and below the cover systems to depths of 180 cm. Three replicate sensor nests were installed in each test plot to account for variability in materials and test plot treatments.

Weather from August 2000 to date was characterized by two months of abnormally high precipitation, followed by sequences of normal and abnormally dry precipitation patterns. Monitoring data indicate that deep percolation occurs in response to periods of extended precipitation. However, subsequent drying was observed to depths of 180 cm below the surface in all test plots. Using conservative assumptions regarding tailing hydraulic properties, one-dimensional downward flux predictions based on the monitoring data indicate very low average annual deep percolation rates (< 1.6 mm per year). Prior to the abnormally dry period, greater cover depth and higher vegetation density reduced the amount of moisture reaching the deeper sensors. Subsequently, observed wetting and predicted deep percolation in the high vegetation density test plots was slightly greater than in the low vegetation density test plots for both cover thicknesses. Although these data indicate the ET cover system performance is dynamic, predicted deep percolation fluxes remain low. Data from other sites also confirm this observation. Monitoring is ongoing to develop a better understanding of ET cover system performance.

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INTRODUCTION

Several authors have noted that the performance of ET cover systems can vary quite differently from predicted performance and also change over time (Durham et al 2000, Milczarek et al 2000, Wels et al 2001a). The former can be attributed to our limited ability to adequately characterise variability in the field and to measure and model physical properties such as preferential flow, partial flow, vapor flow and hysterisis (Fayer and Gee 1997, Simms and Yanful 2000). The latter is most likely due to material settling, consolidation and erosion, and changes in material properties due to the presence of vegetation.

Performance monitoring of ET cover systems in arid and semi-arid environments presents a number of challenges. One approach to monitoring ET cover system performance is to determine moisture flux (deep percolation) through the use of instrumented tank lysimeters (O'Kane et al 2000, and Wels et al 2001a, 2001b) or the construction of lysimeter test facilities (Wilson et al 1999). Lysimeter design requires great care to ensure that the boundary conditions for flow are not changed by the confines of the lysimeter. Specifically, lysimeters may be subject to divergence or convergence of flow, influences from saturation at the bottom of the lysimeter, and wall effects on fluid and gas flow. Convergence into, or divergence of flow away from the lysimeter can result in over- or under-estimation of deep percolation, respectively. The presence of fine-grained material in a lysimeter can also impede infiltration and deep percolation from precipitation, due to air entrapment between the wetting front and the tank bottom.

For lysimeters without a suction device at the bottom, saturation has to be reached before the water can drain from the lysimeters. In the absence of deep rooting vegetation, the presence of saturated material at the lysimeter bottom can increase the moisture content and unsaturated hydraulic conductivity through the profile, resulting in overestimation of deep percolation. After plant specie establishment, deep percolation may be underestimated due to extraction of water at the lysimeter bottom by wicking and deep rooting plant species. Rooting depths of arid plant species are not well documented and are a function of available water. In the southwestern United States of America (USA) evapotranspiration resulting from deep rooted species (*Prosopis v.*) has been observed to depths of greater than 10 meters (Stromberg et al 1992), and evapotranspiration from the common shrub 4-wing saltbush (*Atriplex, c.*) has been observed to depths greater than 3 meters (Hammermeister et al 1999).

Other sources of error can result from the effect of lysimeter walls on fluid flow dynamics. In rocky material with large voids (waste rock) a confined environment will tend to reduce the natural convection of air through the waste and result in overestimation of deep percolation.

Conversely, in tailing environments, lysimeter walls may mask the influence of tailings drainage and consolidation. Finally, excavating and backfilling a lysimeter disrupts material layering and compaction and does not represent the original or natural material conditions. Large-scale lysimeter test facilities reduce many of the boundary effects, although they still require saturation at the bottom and may enhance plant evapotranspiration, and gas phase flow and drying, due to their relative small scale in comparison to the actual waste facility.

Direct estimates of soil water pressure gradients can be made by measuring soil water pressure (matric) potentials and are an alternative or supplement to the use of lysimeters. Their use also allows indirect estimates of flux and deep percolation to be made if the Moisture Retention Characteristic (MRC) curves are known for the subsurface material properties. Unfortunately, due to variability of unsaturated flow properties, flux predictions based on this method are rarely constrained. Nonetheless, the subsurface matric potentials in (inter-drainage) semi-arid environments are generally so dry, that one-dimensional modeling based on pressure potential data and material properties can provide reasonable deep percolation estimates.

APPROACH

Tailings at the Phelps Dodge Morenci Inc. (PDMI) mine in Morenci, Arizona, USA are acidic and areally extensive (approximately 7,000 acres). In order to develop environmentally sound and cost-effective reclamation strategies, a series of tailings reclamation experiments were initiated on an east facing side-slope (4:1) between 1997 and 1999. Sixty-six test plots have been established to conduct eight experiments (in triplicate). A detailed description of the various reclamation experiments was previously presented by Vinson et al (1999).

Figure 1. View of PDMI Test Plots Looking West

Monolayer cover depths of 30 cm and 60 cm are being investigated. In September 2000, heat dissipation sensor (HDS) nests were placed at depths of 15, 45, 90 and 180 cm below ground surface (bgs), in triplicate (three nests per plot) into each of the following test plots:

Test Plot D = 30 cm cover with low vegetative cover.
Test Plot E = 30 cm cover with high vegetative cover.
Test Plot J = 60 cm cover with low vegetative.
Test Plot K = 60 cm cover with high vegetative cover.

This in-situ soil water potential monitoring scheme gives us the opportunity to observe major wetting and drying events and variability between sites, and the ability to estimate deep percolation fluxes.

Climatic Regime

Average annual precipitation is approximately 328 mm. Precipitation is bimodal, with approximately 55 percent of precipitation occurring from short, intense thunderstorms from July through September, and the remainder occurring as low-intensity, extended precipitation events from January through March. Pan evaporation rates are generally above 2300 mm per year. Biotic communities in the area are a mix of Sonoran Desert scrub and Chihuahuan Desert species.

Material Properties

The textural characteristics of the tailing material in the study area ranges from clay loam to sandy loam, with the predominant tailings texture being sandy loam. Extensive sampling was performed with 14 representative samples selected for laboratory saturated hydraulic conductivity (Ksat) and MRC testing. Based on particle size distribution, and Ksat and MRC data, the tailings were classified into three representative hydrologic units as shown in Table 1.

Due to the size of the tailings area, available borrow materials at the site are limited to the Gila group. The Gila group is a a Pleistocene-Miocene aged conglomerate rich geologic unit which can be classified as a gravelly, sandy loam. Because of the large percentage of rock fragments in the material, the Gila MRC curves show greater moisture retention (lower matric potential) than the defined tailing unit MRC curves (Figure 2), suggesting that only tailings hydrologic Unit 1 could act as a capillary barrier.

Table 1. Selected Hydraulic Parameters for Tailing Hydrologic Units

Tailing Hydrologic Unit	Texture Type[1]	Number of Samples	Mean Ksat (cm/sec)[2]	Standard Deviation (cm/sec)[2]	Dry Bulk Density (g/cm^3)	VWC_r[3] (cm^3/cm^3)	VWC_s[3] (cm^3/cm^3)	Alpha (1/cm)	N (dimension-less)
Unit 1 - High K	loamy sand	4	6.76E-04	1.95E-03	1.55	0.065	0.39	0.028	2
Unit 2 - Med K	sandy loam	6	3.20E-04	3.72E-04	1.73	0.115	0.36	0.035	1.5
Unit 3 - Low K	sandy clay loam	4	2.22E-05	3.60E-04	1.79	0.04	0.31	0.04	1.1

VWC_r = Residual Volumetric Water Content

VWC_s = Saturated Volumetric Water Content

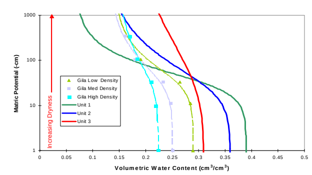
R^2 = Coefficient of Determination for Regression of Observed vs. Fitted Moisture Retention Values

[1] United States Department of Agriculture Classification System

[2] Geometric Mean

[3] Value Fixed During Best Fit Regression Analysis

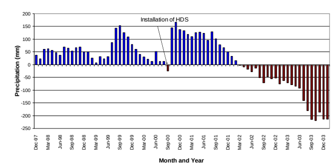
Figure 2. Moisture Retention Characteristics - Gila Cover and Representative Tailing Units



RESULTS

Monthly precipitation for the first two years of the experiments December 1997 through December 1999 was greater than the historic average. Precipitation was below average in 2000 until October, when several large precipitation events, including the maximum 24-hour event in the historical record (90 mm) occurred. As illustrated by Figure 3, an extended dry period has occurred from September 2001 through the present.

Figure 4. Cumulative Difference from Historical Average Precipitation[1]



[1] Based on Historic Monthly Average from Clifton AZ, 1893-2000

Soil Moisture Regime

Figures 4 and 5 compare the average matric potential record at each of the monitoring depths for test plots D and K. Matric potential data in September 2000 showed the subsurface to be extremely dry (< -500cm) to depths of 180 cm. Following the major precipitation event in October 2000, wetting of the profile was observed at all of the sensors, although the matric potentials at the 180 cm bgs sensors remained relatively dry (-270 to -360 cm). The uppermost sensors were most responsive to rapid wetting and drying with the lower sensors exhibiting attenuated response in relation to their depth from the surface. Similar behavior is observed in both cover systems except for the 60 cm sensor in test plot K which shows significant drying due to its placement in the cover system.

Figure 4. Average HDS Matric Potential - Test Plot D 30 cm Cover, Low Vegetation

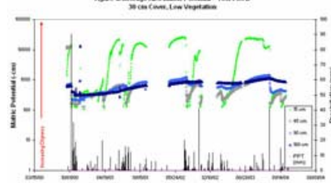
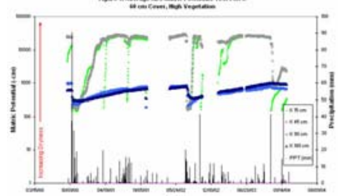


Figure 5. Average HDS Matric Potentials Test Plot K 60 cm Cover, High Vegetation



The average matric potentials observed through the first year of monitoring at the 90 cm depth (Figure 6) indicate that the sensors below the 60 cm and high vegetation covers remained drier than the 30 cm and low vegetation cover systems. Upon the start of the 2002 summer rainy season, the 90 cm bgs sensors in the high vegetation plots (E and K) showed greater pressure response to precipitation than the low vegetation plots in both the 30 and 60 cm cover systems. In contrast, in the winter of 2003-2004, the low vegetation, 30 cm cover system and the high vegetation plots all showed similar response. Figure 7 shows a similar pattern for the 180 cm bgs sensors. These results could be due to increased moisture retention in the high vegetation plots, increased cover soil hydraulic conductivity due to plant die-off and/or channeling of infiltration into root paths, or increased runoff and reduced infiltration into the low vegetation plots, or a combination of all factors.

Figure 6. Average HDS Matric Potentials - 90 cm Sensors, Various Treatments D (30 cm, low veg), E (30 cm, high veg), J (60 cm, low veg), K (60 cm, high veg)

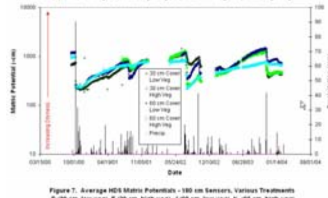
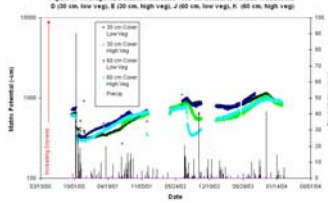


Figure 7. Average HDS Matric Potentials - 180 cm Sensors, Various Treatments D (30 cm, low veg), E (30 cm, high veg), J (60 cm, low veg), K (60 cm, high veg)



Hydraulic Gradients and Estimated Flux

One-dimensional flux estimates were made using the methods described in Milczarek, 2003. For the purpose of estimating deep percolation, only the flux between the 90 and 180 cm deep sensors is considered. Based on detailed boreholes logs collected during the HDS installation, a simplified two-layer hydrologic unit model was developed to describe the material properties at each HDS location (Table 2). Hydraulic gradients were determined by calculating the total pressure (matric + elevation head) difference at the 135 cm depth BGS for each day of record. Fluxes were calculated using the hydraulic gradient, total pressure and unsaturated hydraulic property data at each of the 90 cm and 180 cm sensor pairs.

Table 2. Hydrologic Units for Simple Two Layered Model

Sensor #	Top layer		Bottom layer	
	Interval Depth (cm)	Hydrologic Unit	Interval Depth (cm)	Hydrologic Unit
D1	85-110	3	110-190	1
D2	91-101	3	101-195	1
D3	0-170	2	170-185	3
E1	91-135	3	135-190	2
E2	0-135	1	135-185	3
E3	91-146	3	146-190	1
J1	90-170	1	170-185	2
J2	60-125	3	125-185	1
J3	54-190	2	54-190	2
K1	54-190	1	54-190	1
K2	56-190	1	56-190	1
K3	0-190	1	0-190	1

Table 3 presents statistics for the average hydraulic gradient determined from the replicate measurements in each plot. Depending on the plot, upward gradients at 135 cm were observed on approximately 11 to 60 percent of the dates with good data.

Table 3. Hydraulic Gradient Summary Statistics at 135 cm Below Ground Surface

Monitoring Period 9/14/00 - 10/23/02	Test Plot D (30 cm - low veg) Gradient	Test Plot E (30 cm - high veg) Gradient	Test Plot J (60 cm - low veg) Gradient	Test Plot K (60 cm - high veg) Gradient
Total days recorded	1013	1013	1013	1013
Good data day count	1003	725	932	1009
Downward flux day count	623	309	731	817
Upward flux day count	380	416	201	192
% of up flux day/good data day	38%	57%	22%	19%
% of down flux/good data day	62%	43%	78%	81%

Table 4 presents the total and average flux estimates for each of the sensor pairs using the simplified two-layer model. Predicted downward flux in the two-layer system at test plot D was typically one to two orders of magnitude lower than test plot K downward flux, most likely due to the presence of hydrologic Units 2 and 3 in the D sensor nest boreholes.

Table 4. Downward Flux Estimates - 2 Layer Scenario

Sensor Nest/ Plot Location	Total Est. Flux over Period (cm)	Average Annual Est. Flux (cm/year)	Average Annual Est. Flux Rate (cm/sec)	Est. Percent of Incident Precipitation
D1 - 30 cm cover, low vegetation	6.92E-02	0.03	7.97E-10	0.09%
D2 - 30 cm cover, low vegetation	7.74E-02	0.03	8.91E-10	0.10%
D3 - 30 cm cover, low vegetation	1.68E-01	0.06	1.93E-09	0.22%
D Average	**1.10E-01**	**0.04**	**1.27E-09**	**0.14%**
D Standard Deviation	**5.48E-02**	**0.02**	**6.31E-10**	**0.07%**
E1 - 30 cm cover, high vegetation	4.44E-02	0.02	7.09E-10	0.08%
E2 - 30 cm cover, high vegetation	4.03E-03	0.01	1.93E-10	0.02%
E3 - 30 cm cover, high vegetation	2.90E-02	0.01	4.63E-10	0.05%
E Average	**3.41E-02**	**0.02**	**5.44E-10**	**0.06%**
E Standard Deviation	**2.04E-02**	**0.01**	**2.58E-10**	**0.03%**
J1 - 60 cm cover, low vegetation	8.77E-01	0.34	1.09E-08	1.24%
J2 - 60 cm cover, low vegetation	3.61E-02	0.02	5.46E-10	0.06%
J3 - 60 cm cover, low vegetation	2.53E-01	0.10	3.15E-09	0.36%
J Average	**4.05E-01**	**0.16**	**5.03E-09**	**0.57%**
J Standard Deviation	**4.36E-01**	**0.17**	**5.38E-09**	**0.61%**
K1 - 60 cm cover, high vegetation	1.31E-01	0.05	1.50E-09	0.17%
K2 - 60 cm cover, high vegetation	4.40E-01	0.16	5.05E-09	0.57%
K3 - 60 cm cover, high vegetation	3.37E-01	0.12	3.87E-09	0.44%
K Average	**3.26E-01**	**0.12**	**3.74E-09**	**0.43%**
K Standard Deviation	**1.58E-01**	**0.06**	**1.81E-09**	**0.21%**

Average estimated flux rates range from 0.01 mm to 1.6 mm per year. Based on the observed standard deviations in predicted downward flux, the two-layer model approach appears to be most accurate for the D test plot HDS sensors, while improvement is needed for the other test plots. Nonetheless, these very low predicted flux estimates are conservative in that the downward flux estimates do not account for upward flow. Furthermore, the predicted flux is still well below the common regulatory threshold of 10-7 cm/sec and within the range of existing deep percolation estimates for inter-drainage areas in the Chihuahuan desert (Scanlon et al 1999).

CONCLUSIONS

Several important findings related to ET cover performance arise from this study. Estimated deep percolation ranged from 0.01 mm to 1.6 mm/year during the monitoring period. The vast majority of estimated deep percolation occurred in response to one high precipitation sequence during the 41 month period of record. During the subsequent periods of drought, little difference in matric potentials and predicted deep percolation fluxes were observed between the different cover depths and vegetation quality.

The data also indicate that drying of the soil moisture profile to depths of 180 cm or greater is occurring, and that atmospheric conditions and the hydraulic properties of the tailings have significant control on deep percolation. Furthermore, the lower boundary for upward flux (zero flux plane) may be greater than 2 meters from the surface.

For the monitoring period of record, these data and downward flux estimates indicate that a two-foot cover depth did not increase the efficiency relative to a one-foot ET cover system in controlling deep percolation. The apparent change in either moisture retention or hydraulic conductivity properties (or both) in the high vegetation test plots after 2001, supports the findings of other workers (Durham et al 2000) that ET cover systems are dynamic. Although, the estimated deep percolation rate from all plots is very low, continued monitoring is necessary to establish long-term performance under "typical" precipitation patterns.

The variability in material properties at these (or any) mine waste site is significant. The spread in hydraulic property and flux estimates suggests that numerous monitoring points are necessary to determine the effect of variability. Based on these data and the observations of other authors (Durham et al 2000, O'Kane et al 2000, Wels et al 2001a, 2001b), it is recommended that ET cover performance monitoring should account for variability through the use of replicate monitoring locations and multiple monitoring methods (i.e. multiple lysimeters and HDS nests).

Future study at this site will focus on evaluating deep percolation into tailings with no cover and/or with rock cover, and quantifying deep percolation in the existing plots with the use of additional monitoring methods. The potential for acidification and salinization of the monolayer cover system is also under investigation.

REFERENCES

Durham, A.J.P., G.W. Wilson, N. Currey, 2000. Field performance of two low infiltration cover systems in a semi-arid environment. *Fifth International Conference on Acid Rock Drainage, Denver, CO.*

Fayer, M.J., G.W. Gee, 1997. Hydrologic model test for landfill covers using field data. *In: Conference Proceedings, Landfill Capping in the Semi-arid West: Problems, Perspectives, and Solutions.* T.D. Reynolds and R.C. Morris, editors. Environmental Science and Research Foundation, Idaho Falls, Idaho. pg. 53-68.

Hammermeister, D.P., J.M. Liles, J.L. Boyer, 1999. Vadose zone monitoring to quantify recharge of saline irrigation water. *9th Biennial Symposium on Artificial Recharge of Groundwater, Tempe, Arizona. June 10-12, 1999.*

M. Milczarek, D. Hammermeister, J. Vinson, 2000. Myths, models and realities: performance of mine reclamation cover systems in controlling infiltration and seepage in the southwestern united states. *Fifth International Conference on Acid Rock Drainage, Denver, CO.*

M. Milczarek, M Yao, J. Vinson, J. Word, S. Kiessling, B. Musser, R. Mohr, 2003. Monitoring the Performance of Mono-layer Evapotranspirative Covers in Response to High Precipitation and Extended Drought Periods in the Southwestern United States *Sixth International Conference on Acid Rock Drainage, Cairns, Australia.*

O'Kane, M.O., D. Porterfield, A. Weir, L. Watkins, 2000. Cover system performance in a semi-arid climate on horizontal and sloped waste rock surfaces. *Fifth International Conference on Acid Rock Drainage, Denver, CO.*

Scanlon, B.R., R.P. Langford, R.S. Goldsmith, 1999. Relationship between geomorphic settings and unsaturated flow in an arid setting. *Water Res. Res. 35, 983-999.*

Simms, P.H. and E.K. Yanful, 2000. Challenges in modeling water flow in waste covers: Lysimeter analysis. *Fifth International Conference on Acid Rock Drainage, Denver, CO.*

Stromberg, J.C., J.A. Tress, S.D. Wilkins, S.D. Clark, 1992. Response of velvet mesquite to groundwater decline. *Journal of Arid Environments, 23:45-58.*

Vinson, J., B. Jones, M. Milczarek, D. Hammermeister, J. Word, 1999. Vegetation success, seepage and erosion on tailings sites reclaimed with cattle and biosolids. *16th Annual National Meeting, American Society for Surface Mining and Reclamation, August 13-19, 1999, Scottsdale, Arizona.*

Wels, C., M. O'Kane, S. Fortin, D. Christensen, 2001a. Infiltration test plot study for waste rock, New Mexico. *18th Annual National Meeting, American Society for Surface Mining and Reclamation, June 3-7, 2001, Albuquerque, New Mexico.*

Wels, C., M. O'Kane, S. Fortin, 2001b. Storage cover test plot study for Questa tailings facility, New Mexico. *18th Annual National Meeting, American Society for Surface Mining and Reclamation, June 3-7, 2001, Albuquerque, New Mexico.*

Wilson, G.V., W.H. Albright, G.W. Gee, M.J. Fayer, B. Ogan, 1999. Alternative cover assessment project: Phase I Report. *Prepared for US Environmental Protection Agency, Contract No. 44-0000-2038*