Performance of Mono-Layer Evapotranspirative Covers in Response to High Precipitation and Extended Drought Periods in the Southwestern United States

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ABSTRACT

Properly designed evapotranspirative (ET) cover systems can greatly reduce the amount of infiltration and groundwater recharge (deep percolation) into potential acid generating mine waste. In arid and semi-arid environments, infrequent precipitation, low measurable subsurface fluxes, spatial variability within mine waste and cover material, and evapotranspiration from below the cover system create challenges to monitoring moisture flux in these systems. Sloped ET single-layer (monolayer) cover depths and a variety of reclamation treatments are being studied at a copper tailing impoundment in Arizona, USA. To monitor the performance of different ET cover systems in response to precipitation patterns, four different test plots consisting of two different cover depths and two different vegetation densities were 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. Data collection occurs twice daily and is ongoing.

Weather during the 26-month monitoring period was characterised by two months of greater than normal precipitation followed by nine months of normal precipitation and 15 months of abnormally dry conditions. Monitoring data indicate that deep percolation occurs in response to periods of extended precipitation, however, drying was observed to depths of six feet 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 (<1.6 mm/year) average annual deep percolation rates. Prior to the abnormally dry period, increased cover depth and dense vegetation reduced the amount of moisture reaching the deeper sensors. During the abnormally dry period, little difference in the soil moisture regime was observed between cover depths and vegetation. Subsequent to the dry period, observed wetting and predicted deep percolation in the dense vegetation test plots was slightly greater than in the sparse vegetation test plots, indicating that the ET cover system performance is dynamic. Additional long-term monitoring and installation of deeper and replicate monitoring sensors into tailings without cover systems are recommended to evaluate the long-term ET cover system performance and develop a better understanding of deep percolation rates at the sites.

INTRODUCTION

Evapotranspirative (ET) cover systems, also known as moisture store and release covers, can reduce infiltration and deep percolation of precipitation into mining and landfill wastes. ET cover systems rely on the moisture retention characteristics of the cover material to retain water for subsequent surface evaporation and evapotranspiration by vegetation. Moisture that flows past the maximum ET depth is considered to be deep percolation. Factors that influence the performance of these systems include variability in cover and waste material properties and long-term stability and consistency in cover vegetation. 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. In attempts to better understand the performance of ET cover systems, field monitoring is ongoing at a number of mine sites world-wide (Timms and Bennett 2000; O'Kane *et al*, 2000; Durham *et al*, 2000; Wels *et al*, 2001a, b).

Performance monitoring of ET cover systems in arid and semi-arid environments presents a number of challenges. Infrequent precipitation, low subsurface fluxes, spatial variability within mine waste and cover material, and evapotranspiration from below the cover system make reliable flux estimates difficult. 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; Wels *et al*, 2001a, b) or the construction of lysimeter test facilities (Wilson *et al*, 1999). As noted by Bew *et al* (1997), 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. These phenomena occur depending on the backfill material properties and the tank geometry, with fine-grained material causing convergence and coarse-grained material causing divergence (Bew *et al*, 1997; Simms and Yanful, 2000). 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. This presents two potential sources of error. 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 ten metres (Stromberg *et al*, 1992), and evapotranspiration from the common shrub four-wing saltbush (*Atriplex, c.*) has been observed to depths greater than three metres (Hammermeister *et al*, 1999).

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Other sources of error can result from the effect of lysimeter walls on fluid flow dynamics. Edge effects may induce preferential flow, and in rocky material with large voids (waste rock) the confined environment will tend to reduce the natural convection of air through the waste and the pressure increase in a sealed chamber during infiltration could cause the wetting front to become unstable (White *et al*, 1976). These effects could 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 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) or soil-water characteristic 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, deep percolation flux rates in arid environments are generally so low (millimetres per year), that one-dimensional modeling based on pressure potential data and material properties can provide reasonable deep percolation estimates.

While the aforementioned methods provide estimates of deep percolation, they cannot completely eliminate boundary effects or fully account for flow heterogeneity inherent in mine waste and cover material. In conclusion, all of the factors discussed above require consideration during the design of monitoring systems and in the interpretation of monitoring data.

APPROACH

Tailings at the Phelps Dodge Morenci Inc. (PDMI) mine in Morenci, Arizona, USA are acidic and areally extensive, covering approximately 7000 acres. Approximately 30 per cent of the tailing footprint has 4:1 side slopes; the remainder consists of gently sloping pond areas. In order to develop environmentally sound and cost-effective reclamation strategies, a series of tailings reclamation experiments were initiated on the eastern side-slope (4:1) of Tailings 4W. From 1997 to 1999, 66 test plots were established to conduct eight experiments (in triplicate). A detailed description of the various reclamation experiments was previously presented by Vinson *et al* (1999).

One of the primary goals of the PDMI reclamation study is to define an optimum cover depth that will limit infiltration and deep percolation. In order to develop a field data set, monolayer cover depths of 30 cm and 60 cm are being investigated. In addition, the reclamation treatments have produced a range of vegetative success such that the effect of low and high vegetative success (sparse and dense vegetation, respectively) on the cover performance can also be compared. In September 2000, a cover performance monitoring system was installed in each of the following test plots:

- Test Plot D = 30 cm cover with sparse vegetative cover.
- Test Plot E = 30 cm cover with dense vegetative cover.
- Test Plot J = 60 cm cover with sparse vegetative cover.
- Test Plot K = 60 cm cover with sparse vegetative cover.

Cover performance is being monitored through the use of Heat Dissipation Sensor (HDS) nests (Figure 1) placed at depths of 15, 45, 90 and 180 cm below ground surface (bgs), in triplicate into each of the test plots. Heat dissipation sensors heat a ceramic element and measure the change in temperature over time. The change in temperature is directly related to the moisture content in the ceramic element. Each HDS ceramic element has a unique MRC that is determined through laboratory calibration, therefore matric potential can be directly measured, assuming the HDS ceramic is in equilibrium with the surrounding waste or cover material. Based on the measured matric potential at various depths in the cover and tailings profile, hydraulic gradients can be calculated and one-dimensional fluxes estimated as described below. This *in situ* soil water potential monitoring scheme gives us the opportunity to observe the major deep percolation and drying events, and thus improve our estimates for long term performance of ET cover systems.

Climatic regime

Precipitation and temperature data collected in the nearby town of Clifton from 1893 to 2000 indicate that the mean monthly temperature ranges from a maximum of 27.2°C to a minimum of 10.9°C; the mean annual temperature is 18.9°C. From June through September, the average maximum air temperature exceeds 34°C. On average, the area is frost-free 235 days a year, with the earliest frost occurring in early to mid-November and the latest frost occurring in early to mid-March. Biotic communities in the area are a mix of Sonoran Desert scrub and Chihuahuan Desert species.

Average annual precipitation is approximately 328 mm. Precipitation is bimodal, with approximately 55 per cent 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 greater than 2300 mm per year.

Material properties

Preliminary characterisation work showed the tailing material in the reclamation study area to be randomly layered (GSA 1997). Textural characteristics of the tailing layers range from clay loam to sandy loam, with the predominant tailings texture being sandy loam. Saturated hydraulic conductivity (Ksat) and MRC data were determined from 5 cm diameter *in situ* core tailing samples using constant head and pressure plate methods, respectively. Figure 2 illustrates the variability in tailing MRC properties. The computer code RETC (van Genuchten *et al*, 1991) was used to calculate the parameters necessary to estimate the unsaturated hydraulic conductivity and moisture content relationship from matric potential. The residual water content was fixed in cases where predicted values were unreasonably low. Based on particle size distribution, Ksat and MRC data, the tailings were classified into three hydrologic units with the representative hydraulic properties shown in Table 1. The dimensionless output parameters alpha, n, and R^2 from RETC are also included in Table 1 for reference.

The sole candidate cover material at the site is from the Gila Group, a Pleistocene-Miocene aged conglomerate-rich geologic unit. The textural properties of the cover material used in these experiments can be classified as cobbly, gravelly sandy loam. Saturated hydraulic conductivity and MRC data were determined for -2 inch sieved Gila material at different densities in large 15 cm diameter × 30 cm length Tempe cells. Because of the large percentage of rock fragments in the material, the Gila MRC curves show greater moisture retention (lower matric potential) than the tailing hydrologic Unit 1, MRC curve (Figure 3), suggesting that the predominant tailings hydrologic unit (Unit 1) could act as a capillary barrier. In contrast, the lower conductivity and finer-grained Units 2 and 3 have similar moisture retention characteristics to the cover material.

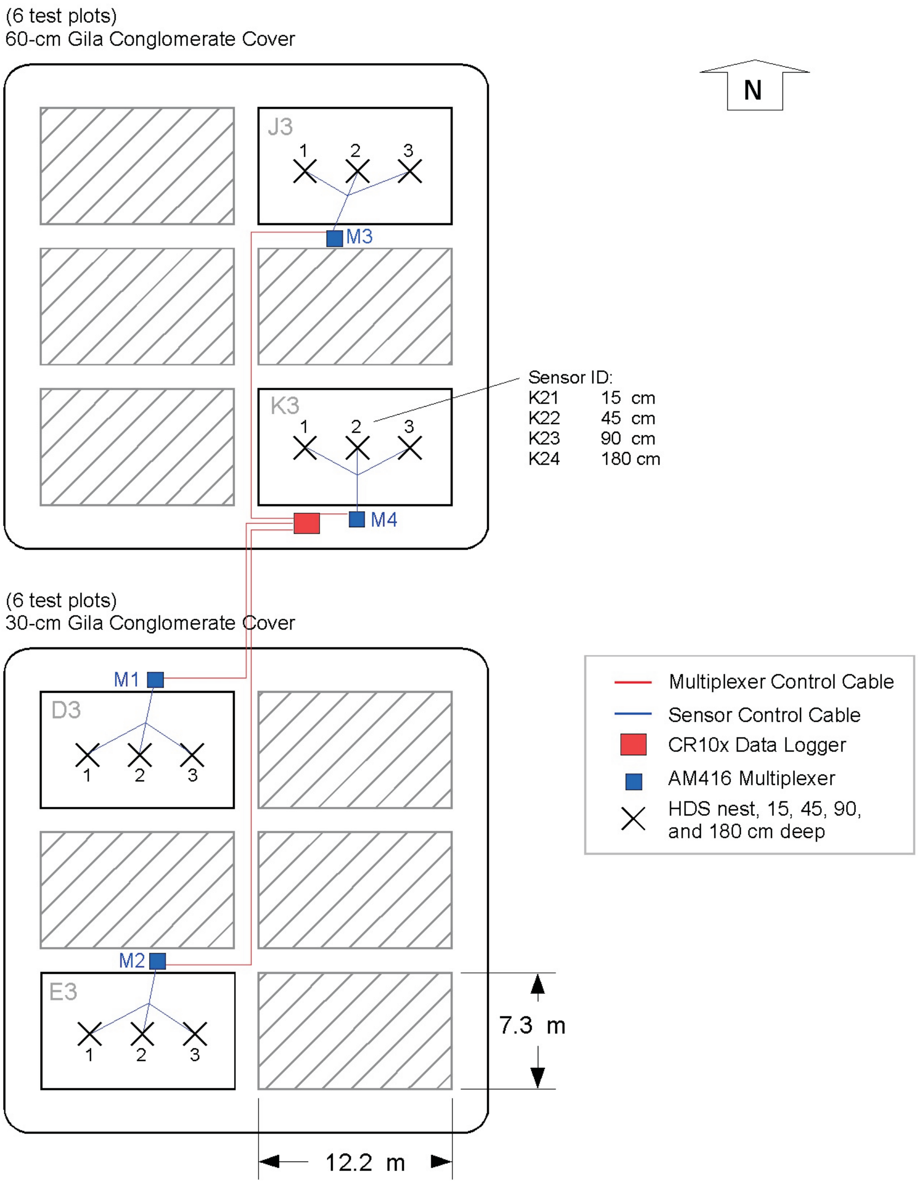

FIG 1 - Schematic for heat dissipation sensor installation.

TABLE 1

Selected hydraulic parameters for tailing hydrologic unit.

Tailing hydrologic unit	Texture type*	Sample #	Ksat (cm/sec)	Dry bulk density (g/cm^3)	VWC$_r$** (cm^3/cm^3)	VWC$_s$** (cm^3/cm^3)	Alpha (1/cm)	N (dimensionless)	R^2
Unit 1 – High K	Loamy sand	G270 (9)	5.40E-04	1.625	0.02	0.36	0.034	1.73	0.993
Unit 2 – Med K	Sandy loam	E175 (10)	7.60E-05	1.7	0.1	0.33	0.048	1.47	0.956
Unit 3 – Low K	Sandy clay loam	F125 (11)	2.70E-06	1.595	0.1	0.3	0.1	1.17	0.986

VWC_r = Residual volumetric water content
VWC_s = Saturated volumetric water content
R^2 = Coefficient of determination for regression of observed versus fitted moisture retention values
* United States Department of Agriculture Classification System
** Value fixed during best fit regression analysis

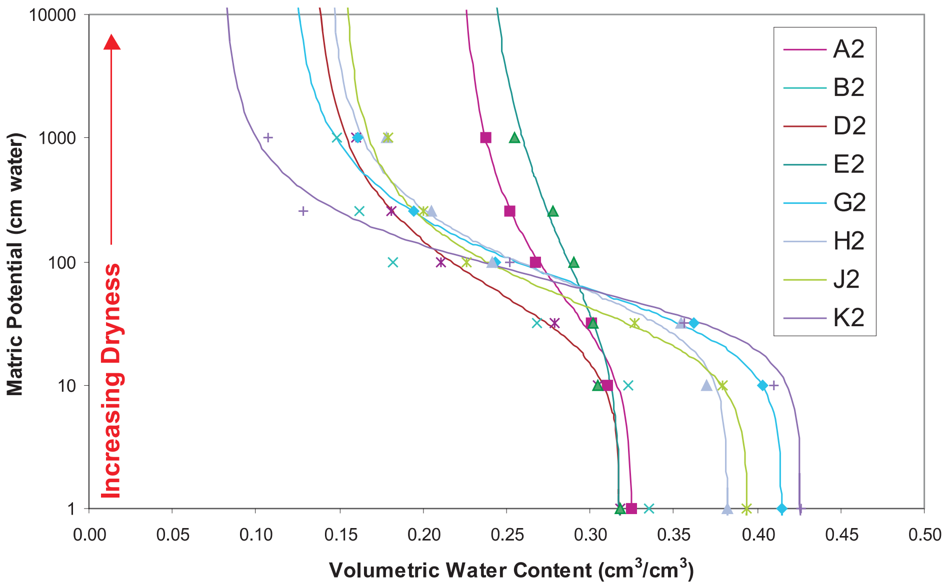

FIG 2 - Moisture retention characteristics selected tailings samples.

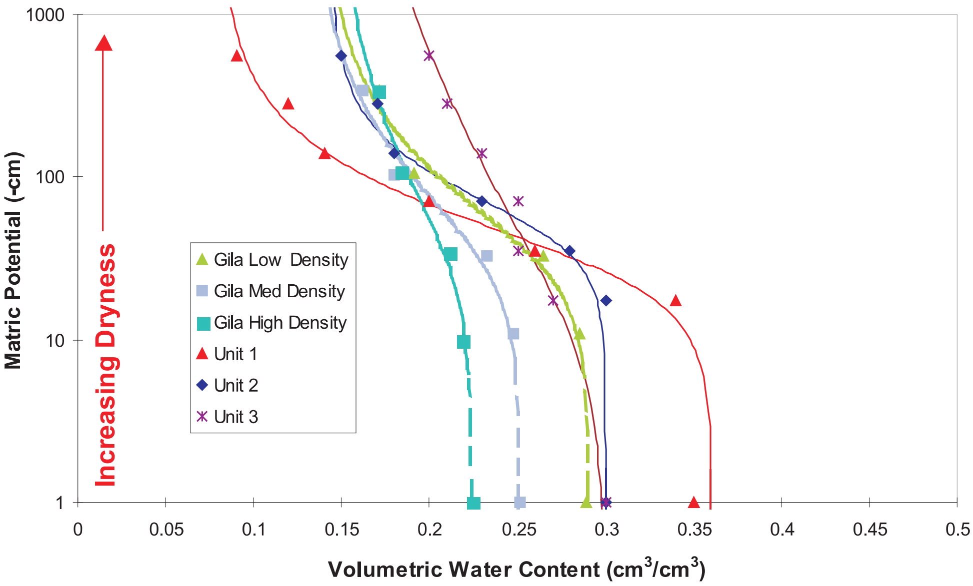

FIG 3 - Moisture retention characteristics – Gila cover and tailings hydrologic units.

Monitoring program

Individual HDS (Campbell Scientific, Inc, model 229-L) were calibrated to known pressure potentials in the GSA laboratory, and installed in shallow hand-augered boreholes to depths of 180 cm bgs at the locations shown in Figure 1. For each nest, sensors were placed at 15, 45, 90 and 180 cm bgs in September 2000. Each sensor was placed in a silica flour/tailings mixture to ensure good hydraulic contact. In addition, a 5 cm bentonite plug was placed above and below each sensor to prevent preferential flow down the borehole walls.

HDS cables were routed to AM416 multiplexers and a solar powered CR10X (Campbell Scientific Inc) data logger (Figure 1). All cables were buried in conduit to prevent destruction by burrowing animals. Soil temperature and matric potential data are collected twice daily. Approximately six months of HDS data were lost between November 2001 and April 2002 due to a data logger malfunction. In May 2002, a telemetry system was added to minimise the potential for further data loss. A meteorological station approximately 200 metres from the study area collects temperature, precipitation, pan evaporation and wind speed data.

Flux estimation

Several assumptions were made to derive one-dimensional flux estimates from matric potential data:

- Darcy's Law for steady-state equilibrium and one-dimensional flow applies, as modified by Buckingham (1907) for unsaturated flow.
- Van Genuchten's (1980) closed-form analytical solution to Mualem's (1976) theoretical model of the relationship between unsaturated hydraulic conductivity and pressure potential applies.
- The unsaturated hydraulic conductivity in the monitoring intervals is approximated by Bouwer's (1978) harmonic mean equation for saturated hydraulic conductivity in layered systems.

Flux calculations between adjacent heat dissipation sensors

The downward flux between two monitoring depths was estimated using the following approach. First, the soil water potential at each monitoring depth and the total hydraulic gradient between sensors for that interval were determined from the HDS data. The equivalent unsaturated conductivity for the soil (or tailing) layers at each depth interval was then determined from the HDS matric potential data according to van Genuchten (1980), using the van-Genuchten parameters generated from RETC listed in Table 1. Finally, the harmonic mean was calculated to determine the effective unsaturated hydraulic conductivity in the soil layers across the interval. Using Darcy's law modified for unsaturated flow (Buckingham, 1907) and the estimated unsaturated conductivity and hydraulic gradient, the flux at the midpoint between the two monitoring depths was calculated.

Fluxes were estimated at all depths for which the necessary data were available, specifically, the midpoint between HDS pairs, or 27.5, 67.5, and 135 cm bgs. Hydraulic gradients were calculated by summing the pressure and elevation potential at each HDS, calculating the difference in sums, and dividing the difference by the distance between HDS. To determine the hydraulic properties of the hydrologic units between HDS pairs, the depth interval between HDSs was divided into sub-intervals corresponding to observed material layering (hydrologic unit). If the entire depth interval was one hydrologic unit, the interval was divided into two equal-thickness sub-intervals. The pressure potential at the center of each sub-interval was calculated by linear interpolation between the measured pressure potentials at the two HDS.

If the pressure potential at the center of a sub-interval was negative in value, unsaturated hydraulic conductivity was calculated from the Mualem/van Genuchten closed-form equation (van Genuchten, 1980) using measured K_{sat} and unsaturated flow parameters. If the pressure potential was greater than or equal to zero for a sub-interval, the hydraulic conductivity was assumed equal to the measured K_{sat}. The harmonic mean of all sub-interval hydraulic conductivities was assumed to be equal to the hydraulic conductivity of the entire depth interval.

RESULTS

Monthly precipitation for the first two years of the experiments (December 1997 through December 1999) was greater than the historic average (Figure 4). Vigorous plant establishment occurred during this period and significant differences in vegetative success between the various treatments were observed. 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 4, an extended dry period occurred from September 2001 through November 2002.

Soil moisture regime

Measured matric potentials correspond well with the precipitation patterns. Figures 5 and 6 compare the matric potential record at each of the monitoring depths for test plots D and K, respectively. Matric potential data in September 2000 showed the subsurface to be extremely dry (< -500 cm) to depths of 180 cm. Following the precipitation events of October 2000, wetting of the profile was observed at all of the sensors, although the matric potentials at the 180 cm sensors remained relatively dry (-270 to -360 cm). In the plot with a 30 cm cover and sparse vegetation, the uppermost sensor (30 cm) was most responsive to rapid wetting and drying in response to precipitation events (Figure 5), with the deeper sensors exhibiting attenuated response in relation to their depth from the surface. The plot with a 60 cm cover and dense vegetation showed similar behavior (Figure 6) except for the 60 cm sensor, which showed significant drying due to its location in the cover system.

Throughout the first year of monitoring, the 60 cm and dense vegetation covers were more effective at drying the cover and limiting infiltration to the lower depth of the tailings. Figures 7 and 8 compare the average matric potentials observed at each test plot at the 90 and 180 cm depths, respectively. As anticipated, the average matric potentials observed at the 90 cm depth (Figure 7) indicate that the sensors below the 60 cm and dense vegetation covers remained drier than the 30 cm and sparse vegetation cover systems. From August 2001 through August 2002, the 180 cm sensors below the cover systems indicate a strong drying trend

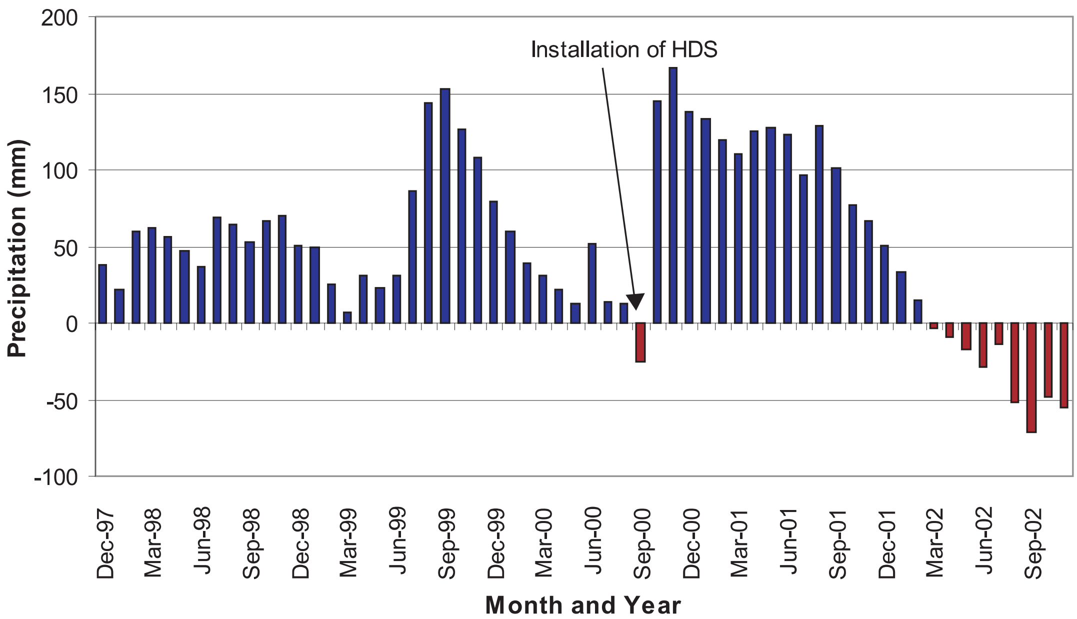

FIG 4 - Cumulative difference from historical average precipitation†, December 1997 to November 2002 († historic monthly average from Clifton AZ, 1893 - 2000).

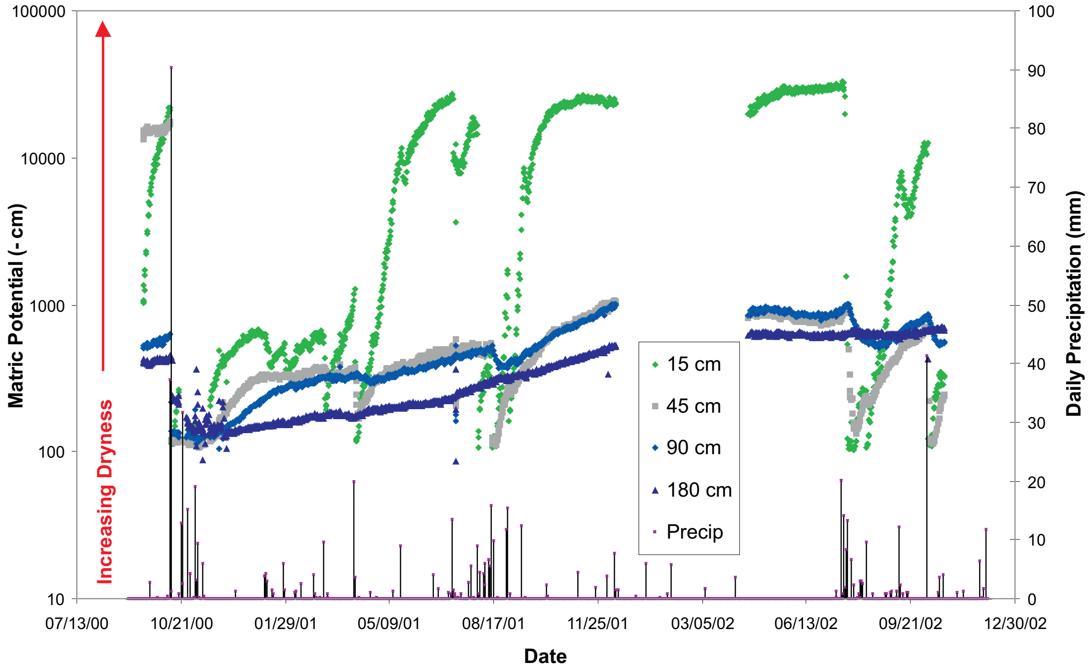

FIG 5 - Average HDS matric potential – test plot D, 30 cm cover, poor vegetation.

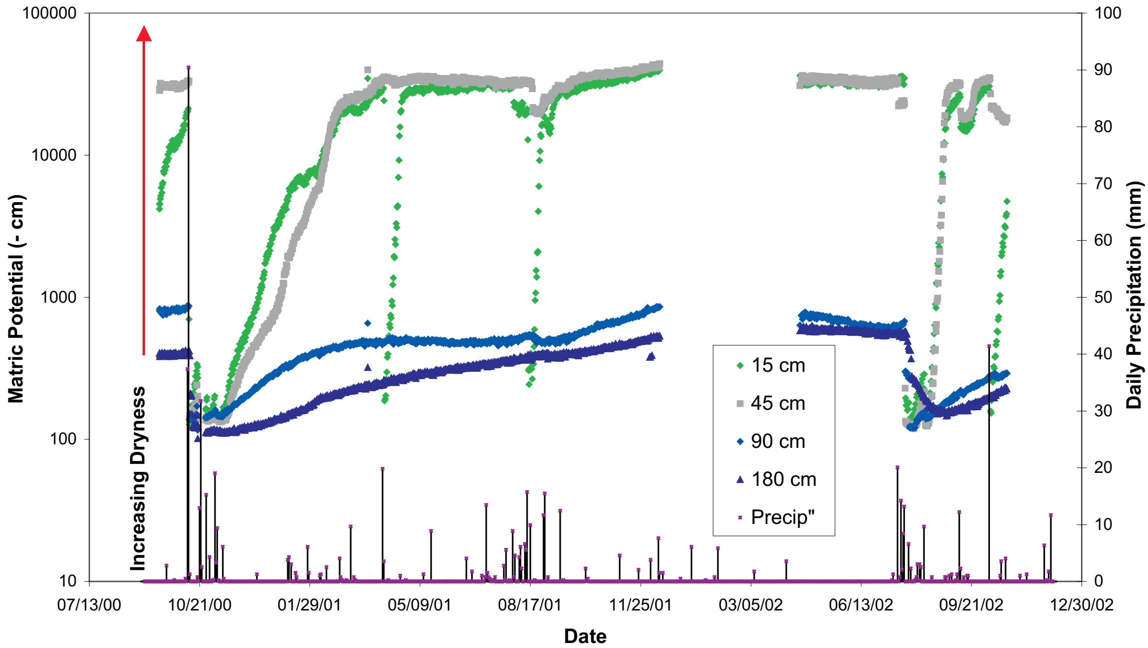

FIG 6 - Average HDS matric potential – test plot K, 60 cm cover, good vegetation.

(Figure 8). Precipitation during this period was approximately 40 per cent of normal, and some plant mortality was observed. Upon the start of the 2002 summer rainy season, the matric potential response at the deeper sensors changed. In particular, the dense vegetation plots (E and K) showed greater pressure response at depth than the sparse vegetation plots in both the 30 and 60 cm cover systems. This result could be due to increased moisture retention from greater organic matter contents in the dense vegetation plots, or increased cover hydraulic conductivity due to plant die-off and/or channeling of infiltration into root paths, or reduced infiltration into the sparse vegetation plots, or a combination of all factors.

Hydraulic gradients and estimated flux

For the purpose of estimating deep percolation, only the flux between the 90 and 180 cm deep sensors was 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.

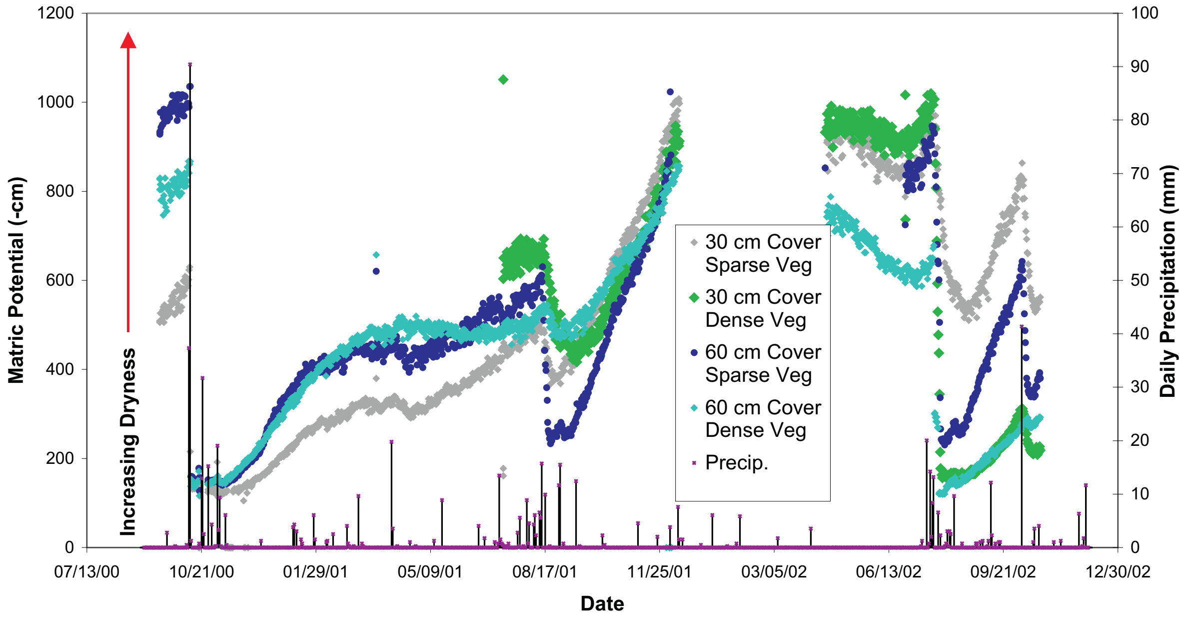

FIG 7 - Average HDS matric potentials – 90 cm sensors, various treatments. D (30 cm, poor vegetation), E (30 cm, good vegetation), J (60 cm, poor vegetation), K (60 cm, good vegetation).

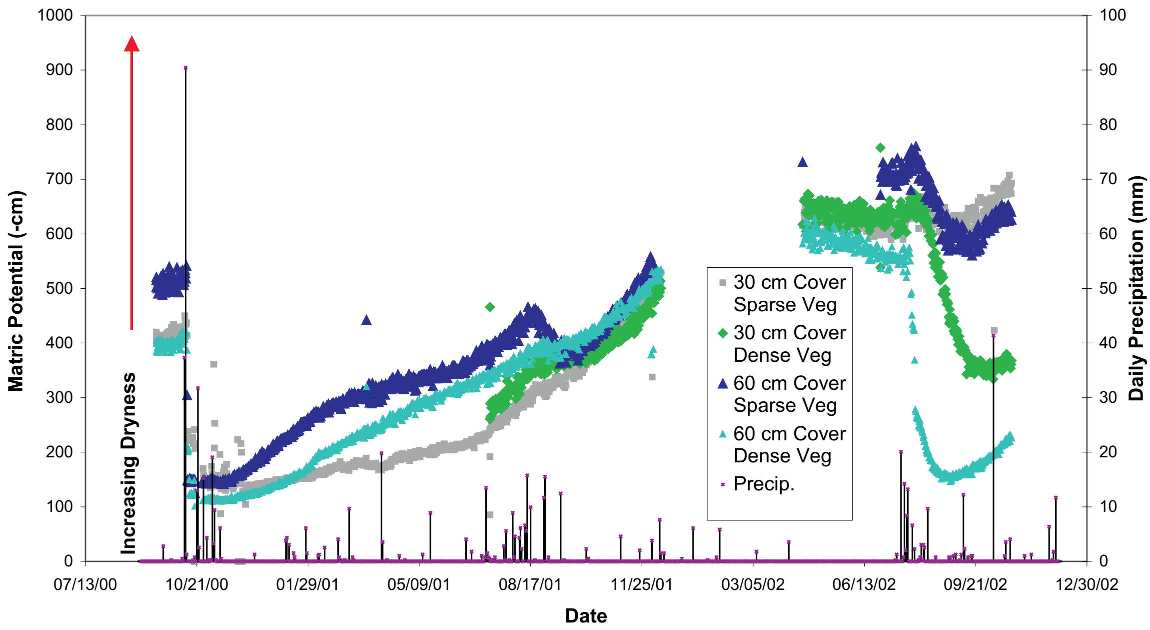

FIG 8 - Average HDS matric potentials – 180 cm sensors, various treatments. D (30 cm, poor vegetation), E (30 cm, good vegetation), J (60 cm, poor vegetation), K (60 cm, good vegetation).

Table 3 summarises statistics for the average hydraulic gradient determined from the replicate measurements in each plot. Depending on the test plot, upward gradients at 135 cm were observed on approximately 11 to 60 per cent of the days.

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 in the plot with 30 cm cover and sparse vegetation (test plot D) was typically one to two orders of magnitude lower than that in the plot with 60 cm cover and dense vegetation (test plot K), most likely due to the presence of hydrologic units 2 and 3 in the sensor nest boreholes of test plot D. Average estimated flux rates range from 0.01 mm to 1.6 mm per year due to the variability in estimated hydraulic conductivity properties of the tailings. Based on the observed standard deviations in predicted downward flux, the two-layer model approach appears to be most accurate for the HDS sensors in the plot containing 30 cm cover and sparse vegetation. These very low predicted flux estimates are conservative in that the downward flux estimates do not account for downward flux that may have been returned to the surface by upward flow.

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

Measured hydraulic gradient summary statistics.

Monitoring period 14 Sept 2000 - 23 Oct 2002	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
Valid days in record	629	349	560	634
Downward flux day count	408	141	499	411
Upward flux day count	221	208	61	223
% of up flux days	35%	60%	11%	35%
% of down flux days	65%	40%	89%	65%

A 'worst case' scenario of tailings consisting solely of hydrologic Unit 1 (sandy loam tailings) was also calculated. Table 5 presents the total and average flux estimates for each of the sensor pairs using the worst-case single-layer hydrologic Unit 1 model. Flux estimates are similar for all cases, ranging from 1.2 to 1.6 mm year. Figures 9 and 10 compare the estimated downward flux at each sensor pair for the test plot with 30 cm cover and sparse vegetation (D) with the plot containing 60 cm cover and dense vegetation (K). The predicted downward flux is extremely low in both plots throughout the monitoring period, with peak flux estimates of less than 10^{-7} cm/sec in response to infiltration events. In addition, the presence of upward gradients during the period of September 2001 to September 2002 in nests D2, D3 and K1 can be observed in Figures 9 and 10.

Even under this worst-case scenario, the predicted flux is still extremely low and well below the common regulatory threshold of 10^{-7} cm/sec. It should be noted that the downward flux estimates for both the two-layer and worst-case scenarios are 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 experimental data collected at the PDMI mine tailing reclamation study. Estimated deep percolation ranged from 0.01 mm to 1.6 mm/year during the monitoring period. The majority of estimated deep percolation occurred in reponse to high precipitation occurring over a short time period. During periods of extended drought, little difference in the observed matric potentials and predicted deep percolation were observed between the different cover depths and vegetation quality. The data also suggest that drying of the soil moisture profile to depths of 180 cm or greater is occurring, and 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 two metres beneath the surface. Considering that the root depth does not exceed the cover depth at this site, observed drying of the tailings is significant.

For the monitoring period of record, these data and downward flux estimates indicate that a two-foot ET cover depth did not increase the efficiency relative to a one-foot cover system in controlling deep percolation. Furthermore, the predicted flux during the dry season does not significantly contribute to the total flux. The apparent change in either moisture retention or hydraulic conductivity properties (or both) in the dense vegetation test plots after 2001 supports the findings of others (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 'average' precipitation patterns.

It must be emphasised that the variability in material properties at these (or any) tailings is significant. Hydraulic conductivity properties for the observed hydrologic units vary by orders of magnitude, and consequently the predicted fluxes also range over orders of magnitude. The spread in flux estimates suggests that several monitoring points are necessary to determine the effect of

TABLE 4

Downward flux estimates – two layer scenario.

Sensor nest/plot location	Total estimated flux over period (cm)	Average annual estimated flux (cm)	Average annual estimated flux rate (cm/sec)
D1 - 30 cm cover, low vegetation	0.003	0.002	4.79E-11
D2 - 30 cm cover, low vegetation	0.002	0.001	4.48E-11
D3 - 30 cm cover, low vegetation	0.003	0.002	4.91E-11
D Average	**0.003**	**0.001**	**4.73E-11**
D Standard Deviation	**0.000**	**0.000**	**2.21E-12**
E1 - 30 cm cover, high vegetation	0.001	0.001	2.55E-11
E2 - 30 cm cover, high vegetation	0.000	0.001	2.15E-11
E3 - 30 cm cover, high vegetation	0.001	0.001	3.62E-11
E Average	**0.001**	**0.001**	**2.78E-11**
E Standard Deviation	**0.001**	**0.000**	**7.61E-12**
J1 - 60 cm cover, low vegetation	0.175	0.114	3.62E-09
J2 - 60 cm cover, low vegetation	0.002	0.001	3.61E-11
J3 - 60 cm cover, low vegetation	0.019	0.012	3.85E-10
J Average	**0.065**	**0.042**	**1.35E-09**
J Standard Deviation	**0.096**	**0.062**	**1.98E-09**
K1 - 60 cm cover, high vegetation	0.122	0.070	2.22E-09
K2 - 60 cm cover, high vegetation	0.446	0.257	8.15E-09
K3 - 60 cm cover, high vegetation	0.286	0.164	5.22E-09
K Average	**0.285**	**0.164**	**5.20E-09**
K Standard Deviation	**0.162**	**0.093**	**2.96E-09**

TABLE 5

Downward flux estimates – worst case scenario, Unit 1 only.

Sensor nest/plot description	Total estimated flux over period (cm)	Average annual estimated flux (cm)	Average annual estimated flux rate (cm/sec)
D1 - 30 cm cover, low vegetation	0.188	0.109	3.47E-09
D2 - 30 cm cover, low vegetation	0.165	0.096	3.03E-09
D3 - 30 cm cover, low vegetation	0.373	0.216	6.86E-09
D Average	**0.242**	**0.140**	**4.45E-09**
D Standard Deviation	**0.114**	**0.066**	**2.09E-09**
E1 - 30 cm cover, high vegetation	0.071	0.074	2.35E-09
E2 - 30 cm cover, high vegetation	0.006	0.295	9.37E-09
E3 - 30 cm cover, high vegetation	0.116	0.122	3.85E-09
E Average	**0.064**	**0.164**	**5.19E-09**
E Standard Deviation	**0.056**	**0.117**	**3.70E-09**
J1 - 60 cm cover, low vegetation	0.314	0.205	6.50E-09
J2 - 60 cm cover, low vegetation	0.115	0.075	2.37E-09
J3 - 60 cm cover, low vegetation	0.150	0.097	3.09E-09
J Average	**0.193**	**0.126**	**3.98E-09**
J Standard Deviation	**0.107**	**0.070**	**2.21E-09**
K1 - 60 cm cover, high vegetation	0.122	0.070	2.22E-09
K2 - 60 cm cover, high vegetation	0.446	0.257	8.15E-09
K3 - 60 cm cover, high vegetation	0.286	0.164	5.22E-09
K Average	**0.285**	**0.164**	**5.20E-09**
K Standard Deviation	**0.162**	**0.093**	**2.96E-09**

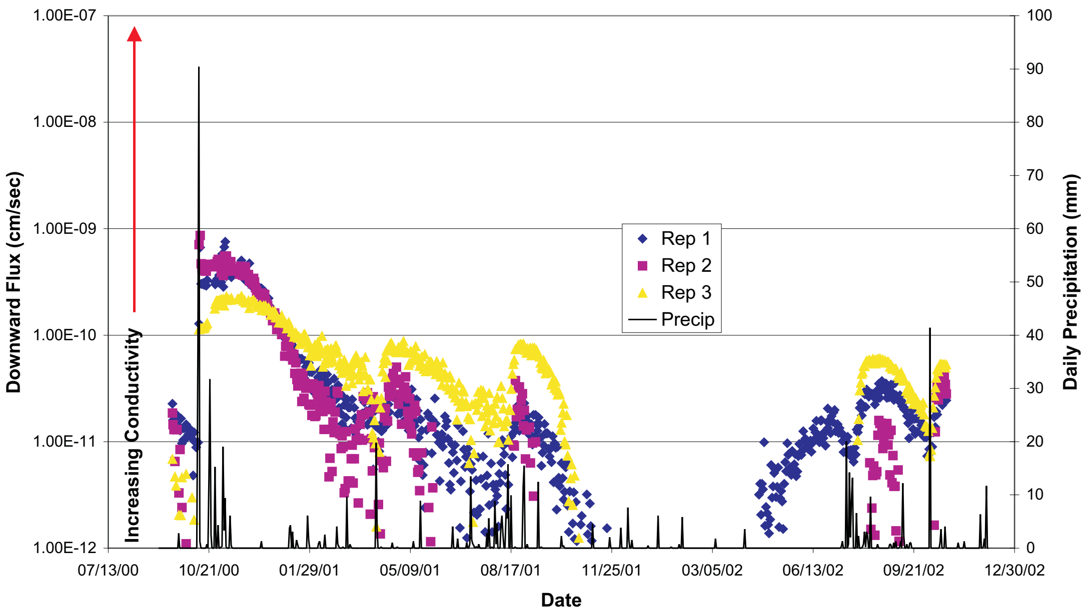

FIG 9 - Estimated downward flux at 135 cm in test plot D, 30 cm cover, poor vegetation.

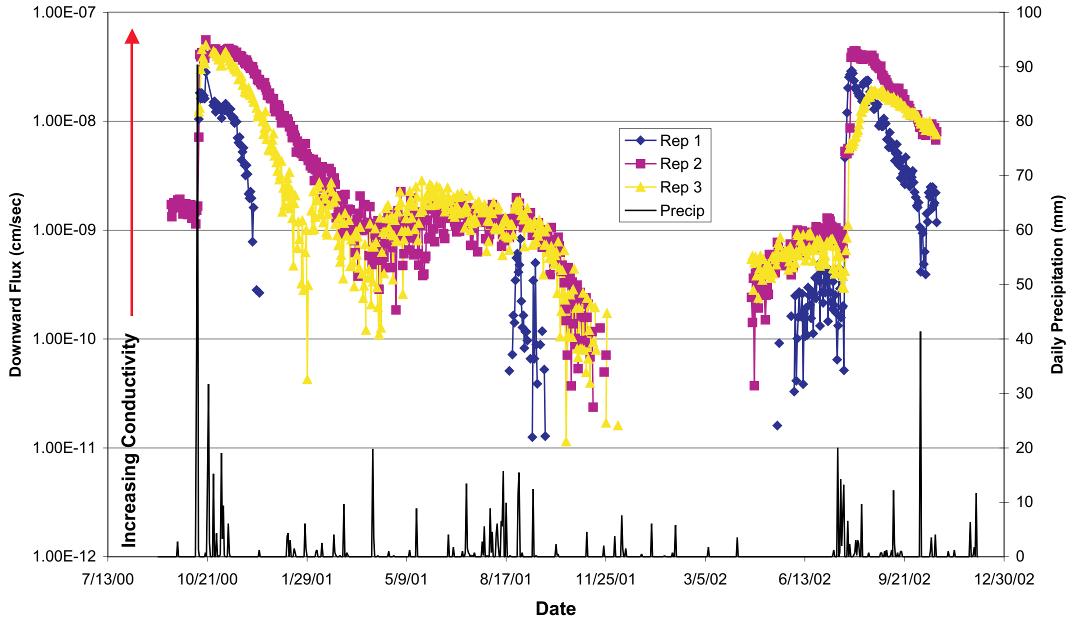

FIG 10 - Estimated downward flux at 135 cm in test plot K, 60 cm cover, good vegetation.

variability. Based on these data and the observations of others (Durham *et al*, 2000; O'Kane *et al*, 2000; Wels *et al*, 2001a, b), it is recommended that ET cover performance monitoring incorporate replicate monitoring locations and multiple monitoring methods (such as lysimeters and multiple HDS nests capable of recording reliable wetter range data) in order to account for site-specific variability.

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 salinisation of the monolayer cover system is also under investigation.

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