

Modeling of Alternative Cover Scenarios for Mine Rock Piles at the Zortman and Landusky Mine Sites

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ABSTRACT

Reclamation of the Zortman and Landusky gold and silver mines in the little Rocky Mountains of north-central Montana is currently on-going under the direction of the Montana Department of Environmental Quality and the U.S. BLM. As part of this process various reclamation alternatives were evaluated using a Multiple Accounts Analysis (MAA) (Shaw et al. these proceedings). This paper describes the results of cover performance modeling carried out in support of this decision analysis. Potential cover materials were collected from local sources and characterized in the laboratory to provide realistic input parameters for cover performance modeling. One-dimensional (SoilCover) and two-dimensional (SEEP/W) models were used to estimate the rate of net infiltration for various alternative cover scenarios. The cover performance model was calibrated against observed flows captured from a covered mine rock pile. One-dimensional modeling results suggest that the rate of net infiltration is more influenced by the precipitation pattern, (i.e. wet versus dry year), than by the different cover materials. Two-dimensional modeling of cover performance on a sloped surface suggested that placement of a fine layer on coarse waste rock would significantly reduce net infiltration due to the capillary break effect. However, the presence of the capillary break effect was found to be very sensitive to material properties and would require significant quality control during construction. Cover performance modeling proved to be a useful tool for comparing alternative closure measures in the context of a multiple accounts analysis.

INTRODUCTION

The Zortman and Landusky gold and silver mines are located in the little Rocky Mountains of north-central Montana, approximately 155 miles north of Billings. Historic mining has occurred in the area over the past century. In 1979, large-scale open pit mining and heap leach operations began and continued until 1996 when the company became insolvent. As a result, reclamation of the site fell under the direction of the Montana Department of Environmental Quality and the

U.S. Bureau of Land Management. As part of the reclamation process, various reclamation alternatives were evaluated using a Multiple Accounts Analysis (MAA)¹.

The cover modeling was aimed at evaluating alternative cover designs that are “affordable” and can be constructed with locally available material. There were two phases for the cover performance modeling. Phase 1 was aimed at reviewing of a wide range of cover options and comparing water barrier to water storage covers². Phase 2 modeling made a detailed comparison of seven water storage cover scenarios for the final MAA³. The two material types selected for the Phase 2 modeling were a “topsoil” material (represented by a sample from the Mill Gulch topsoil stockpile, “MG-TS Top”) and the “tailings” material (represented by a sample of coarse tailings from Ruby Gulch, “Z-1”). The tailings provided a capillary break effect in the cover.

This paper summarizes the results of Phase 2. The main objective of the Phase 2 cover performance modeling study was to estimate net percolation (“cover flux”) for specific covers selected in various reclamation alternatives for the Zortman and Landusky mine sites. The net percolation was to be estimated for “average” and “very wet” climate conditions. In addition, estimates were to be provided for flat surfaces (top and benches of covered rock piles/leach pads) as well as for sloped surfaces (resloped, covered rock piles/leach pads).

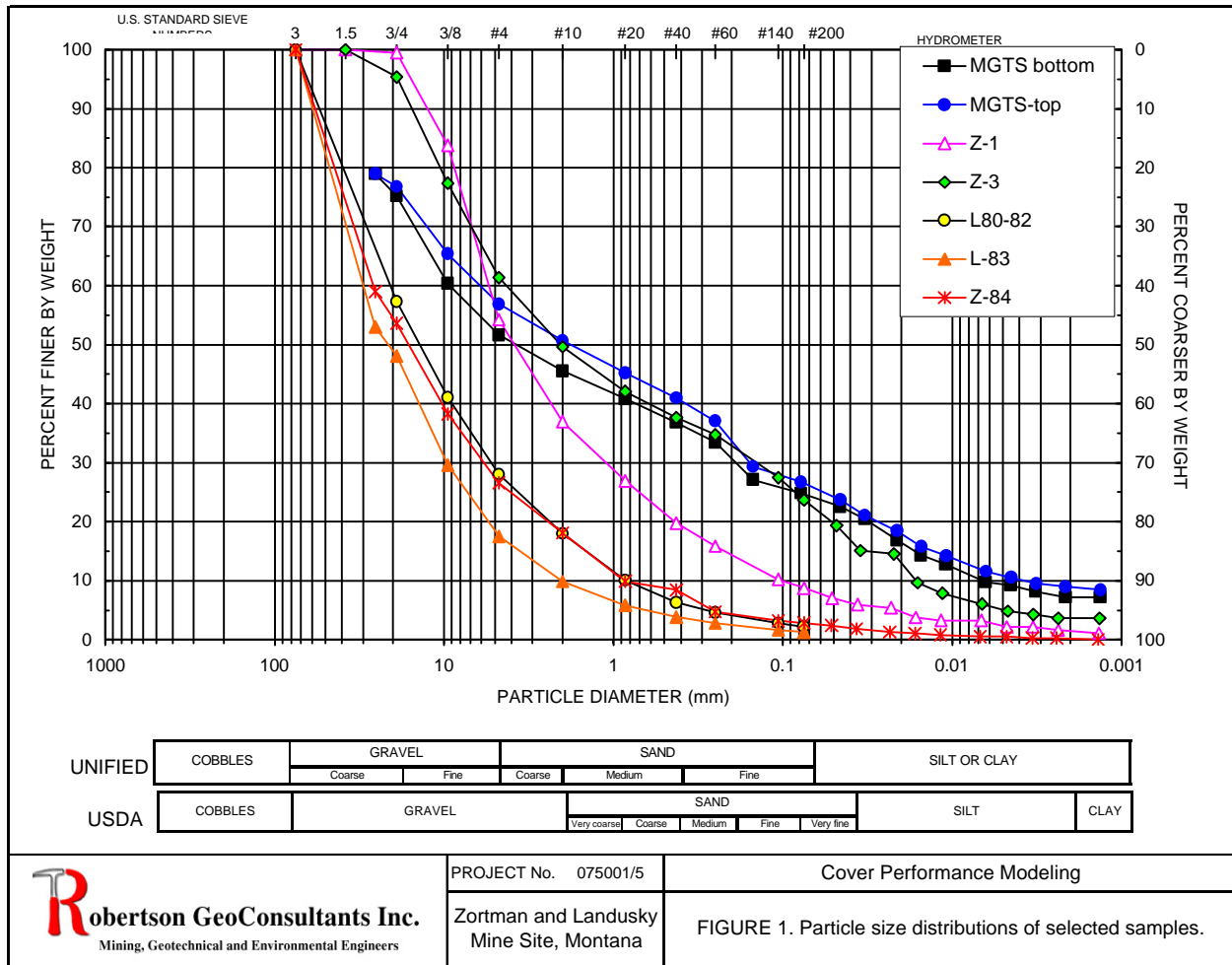
Based on the above objectives the following scope of work was developed for the Phase 2 modeling study:

- Calibrate the soil-atmosphere model (SoilCover⁴) using observed discharge rates in the Carter Gulch Capture system for the very wet observation period 1997-1998;
- Use calibrated SoilCover model (1D) to simulate net percolation for seven cover scenarios (for flat surfaces);
- Use the two-dimensional SEEP/W model⁵ to estimate cover performance for sloped surfaces; and
- Estimate the likely range of net percolation for all cover alternatives considered in the alternatives evaluation for the Zortman and Landusky mine sites based on the above modeling results.

METHODS

A total of 18 samples of potential cover materials and mine rock material (from leach pads) were collected for laboratory testing during the 1999 field season². The emphasis of field sampling was on potential cover materials and included fine-grained material from the Goslin Flats area (4 samples), stockpiled topsoil (2 samples), Emerson shale from stockpile and pit (3 samples) and Ruby Gulch tailings (3 samples). Mine rock samples were taken from two leach pads at Landusky (LP 80/82 and LP 83) and one leach pad at Zortman (LP 84). The majority of samples were taken from shallow test pits (3-6ft deep) using a backhoe.

Grain size analyses were performed on all samples. Based on the results of the grain size analyses, samples were selected for more detailed testing including initial bulk density, compaction tests (Standard proctor), permeability testing, and soil moisture retention. The soil moisture retention tests were performed using a variety of methods (hanging column, pressure plate, thermocouple and RH box) in order to cover a wide range of suction values and thus determine the full soil water characteristic curve (SWCC). The particle size distributions and the



SWCCs for the topsoil, tailings and mine rock samples are shown in Figure 1 and 2, respectively. The hydraulic conductivity function (permeability as a function of suction) was estimated from the SWCC and the saturated permeability (Figure 3).

The one-dimensional finite element numerical model SoilCover³ was used to assess alternative cover scenarios for flat (or nearly flat) surfaces. The model is a coupled heat and mass transfer, saturated-unsaturated model, which couples soil conditions to atmospheric conditions. SoilCover is capable of predicting actual evapotranspiration from the soil profile. The model input parameters include daily climate parameters (air temperature, relative humidity, pan evaporation, and precipitation) as well as soil parameters (SWCC, Ksat, hydraulic conductivity function).

The climate parameters of air temperature and relative humidity (daily min/max values) were obtained from the nearby BLM Zortman Station. The daily precipitation values were taken from the Zortman station to provide a direct comparison with the observed outflow in the Carter Gulch capture system.

The freeze/thaw module of SoilCover³ was not used due to the apparent lack of significant snow pack development at Zortman-Landusky. Hence, all precipitation during the winter months was conservatively assumed to occur as rainfall (and allowed to infiltrate during the same day).

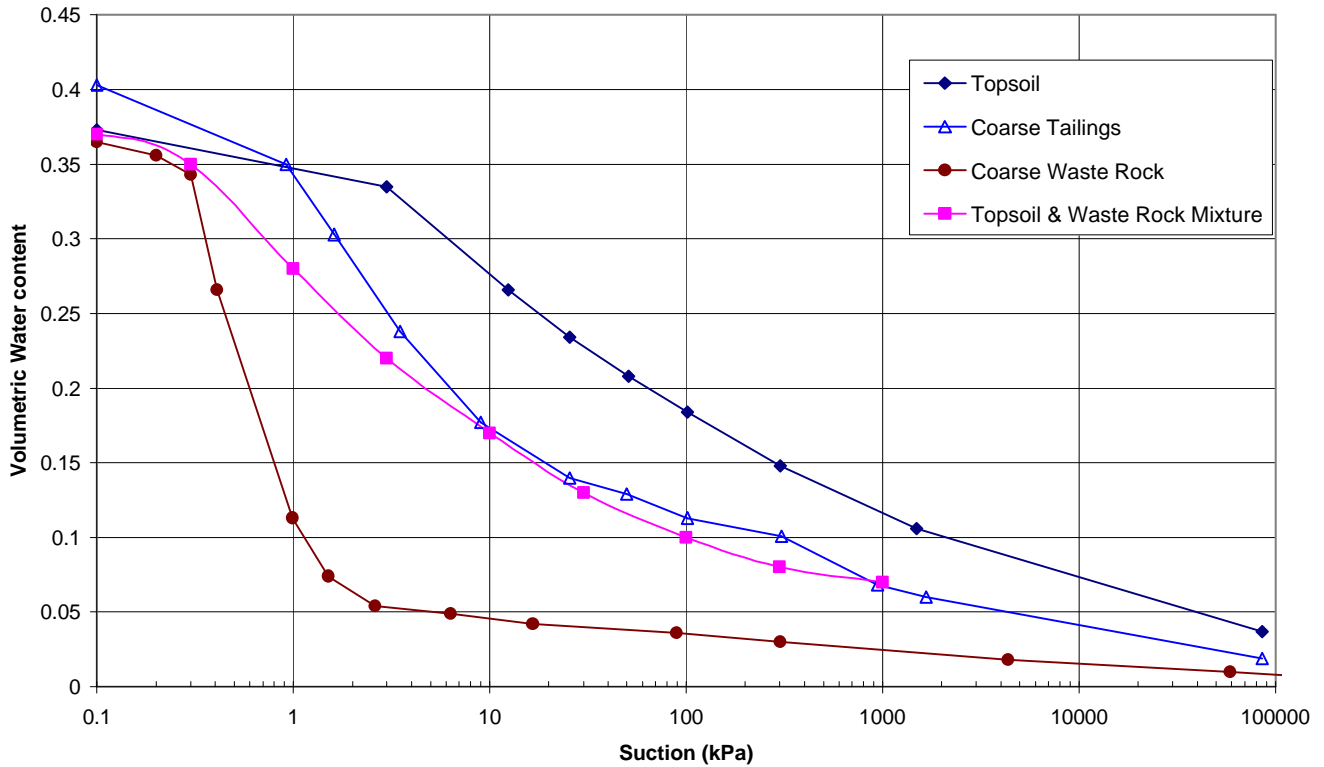


Figure 2. Soil-Water Characteristic curve for the topsoil, tailings and mine rock samples.

The daily potential evaporation (PE) was estimated from pan evaporation measured at the Mocassin Experimental Station (located about 150 km to the southwest). The rate of PE was used as a calibration parameter, i.e. was adjusted to provide a better fit with the observed outflow in the Carter Gulch capture system. In all cases the pan evaporation rate measured at Mocassin was used as a baseline for PE. Adjustments were then made to daily PE values in an attempt to reflect climate differences between the Mocassin Experimental Station and the Zortman site. In all cases a pan factor of 0.65 was used to convert the pan evaporation rates to PE.

All simulations assumed no vegetation, representative of early conditions after cover placement. In other words, transpiration by plants was assumed to be zero so that evaporation is the only mechanism removing moisture from the soil profile. Evaporation was assumed to occur only from April 1st to September 30th in 1997-1998. While there is likely some (small) amount of evaporation during the winter months (on sunny days) no data were available to estimate the potential evaporation rates.

MODEL CALIBRATION

For calibration of the SoilCover model the captured flows for the Carter Gulch were selected because the drainage system appeared to be well defined with no apparent contribution of irreducible baseflow⁶. The Carter Gulch system collects drainage from the Carter Gulch (Alder) waste rock dump (total drainage area of 38 acres with about 50% natural drainage and 50% waste rock area). Water balance calculations carried out for the Zortman site by Spectrum Engineering suggested that about 41.4% of the total flow captured in Carter Gulch originated

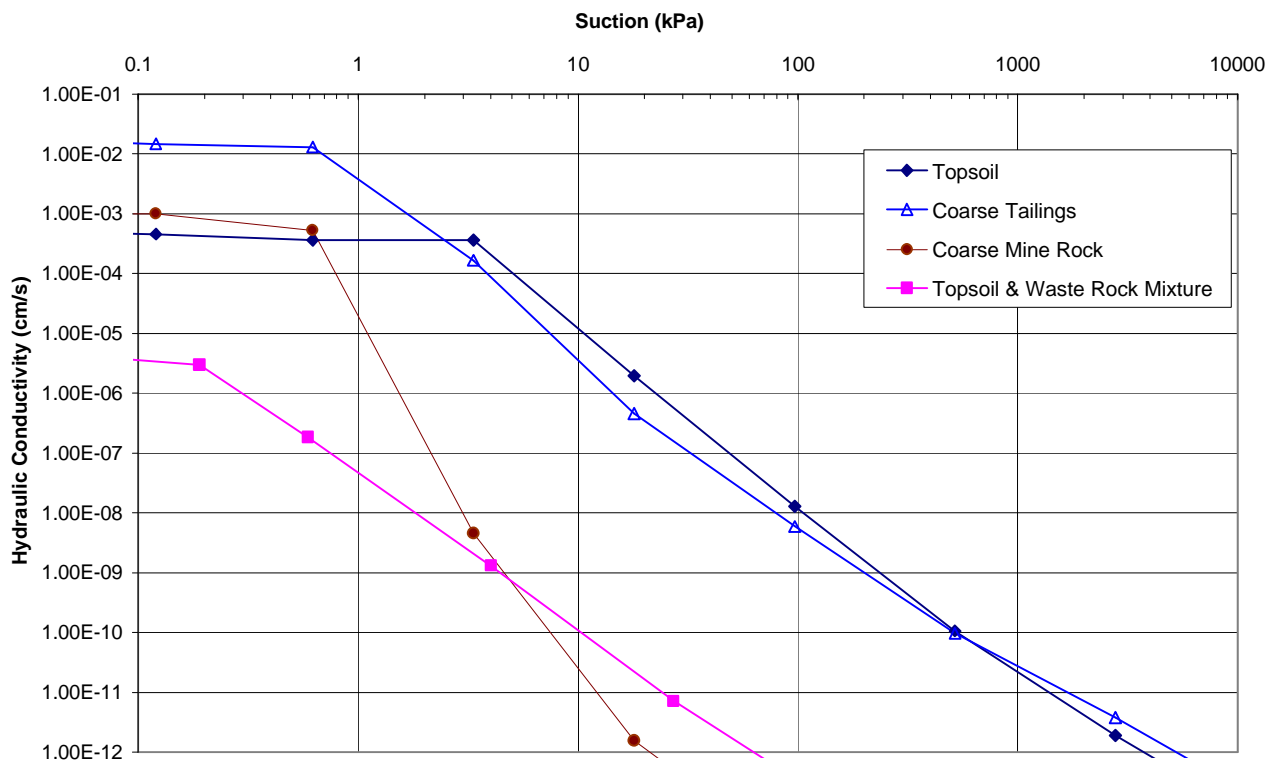


Figure 3. Hydraulic Conductivity for topsoil, tailings and mine rock samples.

from the natural drainage area (plus roads) with the remaining 58.6% representing seepage from the Carter Gulch (Alder) waste rock dump⁶. Assuming storage effects are negligible the seepage collected at the base of the mine rock pile (in the capture system) should equal the rate of net percolation through the cover (“cover flux”). While seasonal storage effects can be expected in a mine rock pile due to the variability in precipitation, they are expected to average out over a longer time period (months-years).

Over the period October 22nd 1997 to December 31st 1999, a total of 65 inches of precipitation was recorded at the Zortman precipitation gage. Over the same time period an equivalent of 30.8 inches (i.e. about 47.5 % of the total precipitation) were collected in the Carter Gulch capture system⁵.

For the Phase 2 cover performance modeling it was decided to use the flows monitored in these capture systems as a target against which to “calibrate” the SoilCover model. Note that this approach resulted in conservative (high) estimates of cover flux since it is still uncertain how much of the captured flow actually represents infiltration through the cover. The apparent lack of QA/QC during past cover placements (likely resulting in higher cover fluxes than could ideally be achieved) further provides a conservative element when using these capture rates for calibration.

Due to storage effects and the variability in travel time from the top to the bottom of the rock pile, a day-to-day comparison of simulated (daily) cover fluxes and observed seepage (captured at the toe of the rock pile) was not attempted. Instead, the simulated daily cover fluxes were

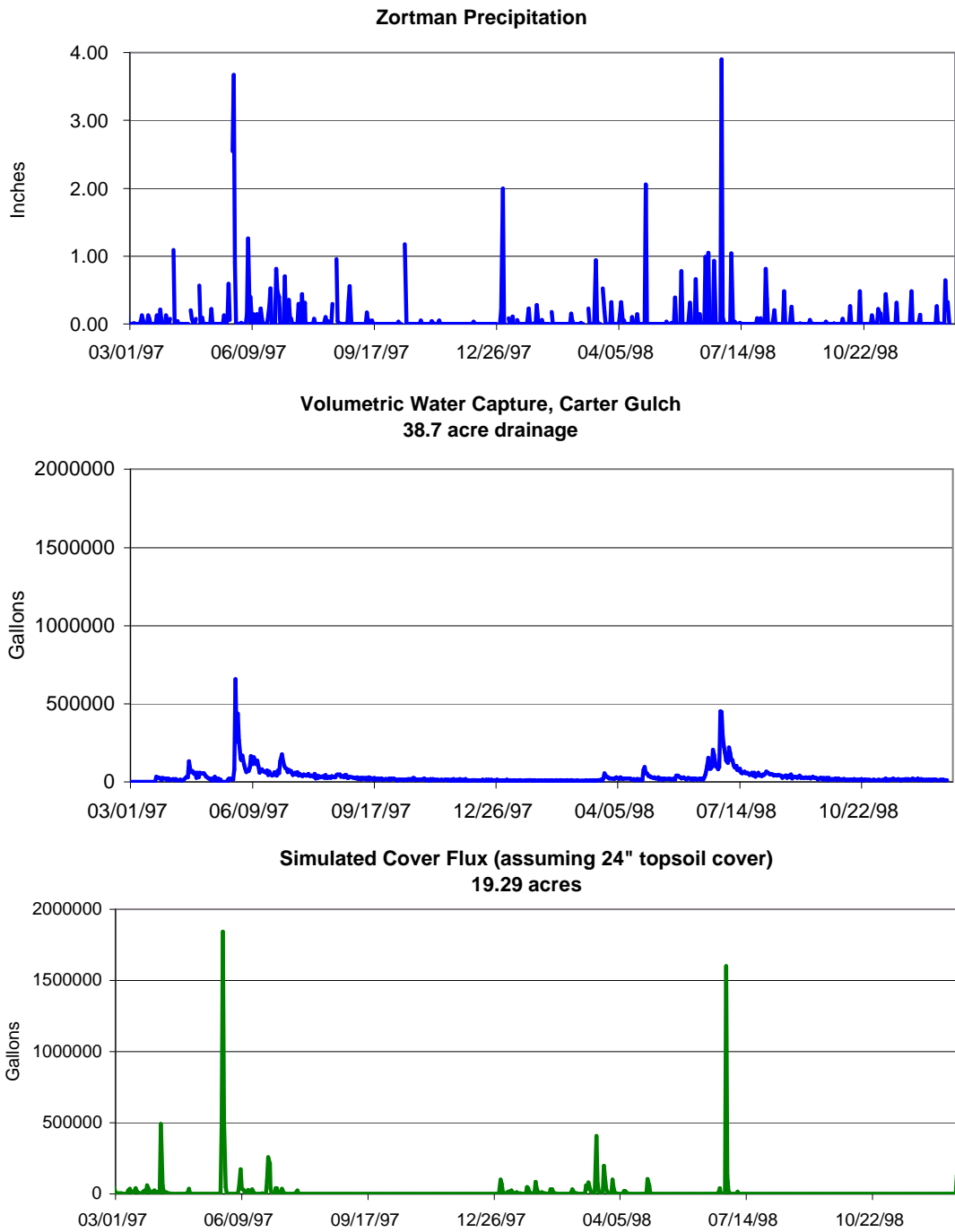


Figure 4. Daily precipitation (upper), observed flows captured in Carter Gulch (middle) and simulated net percolation (lower) through a 24" thick topsoil cover.

integrated over an extended time period (2 years), the total flux then converted to a volume (prorated to the surface area of the Carter Gulch waste dump) and this total volume compared to that portion of the flow (in gallons) captured in the Carter Gulch Capture System, which was believed to originate from the mine rock pile. The observation period March 1997 to December

1998 was selected for this calibration. Compared to precipitation data from other years, 1997-1998 was very wet with high precipitation rates in May and June, i.e. early in the growing season. These conditions would favor unusually high rates of net percolation and therefore can be considered a “worst-case” scenario.

The Carter Gulch (Alder) waste rock pile was covered with a topsoil cover ranging in thickness from 0.5-3.0 ft in the mid-1990s. For calibration against the observed discharge of the capture system at Carter Gulch, a 24-inch thick cover of topsoil was assumed representing an “average” cover thickness. Alternative cover scenarios were subsequently simulated using the “calibrated” SoilCover model for the purpose of alternatives evaluation.

Figure 4 summarizes daily precipitation (upper panel), observed flows captured in Carter Gulch (middle panel) and simulated net percolation (cover flux) through a 24 inch thick topsoil cover for the calibration period 03/01/97 to 31/12/1998. The observed capture flows show a strong seasonal trend with most of the discharge occurring in the late spring/early summer period (typically from early May to mid-July). A comparison of the precipitation data and capture flows suggests that the response to precipitation in the capture system is very fast during this period. In both years, the peak flows occurred within one day following very heavy rainfall events (>3 inches). In contrast, precipitation events, which occurred in late summer, fall and winter, caused very little runoff.

The simulated cover flux shows an even more pronounced response to precipitation than the observed capture flows. According to the SoilCover model significant net percolation through the topsoil cover would only occur during the spring rains (March-April) and very heavy rain events in the early summer (typically May-June). Note that the simulated cover flux tends to be significantly higher than the observed discharge for those days of high precipitation. For example, the simulated peak cover flux occurred on May 25, 1997 (1.9 Mio gallons prorated over 19.29 acres) whereas the captured peak flow (on May 26, 1997) for the entire drainage area (38.7 acres) amounted only to 0.65 Mio gallons.

The discrepancy in observed and simulated daily fluxes can be explained by flow and storage effects within the Carter Gulch waste rock pile. It is generally accepted that flow through a rock pile has two components: i.e. macropore flow through open channels and matrix flow through the soil matrix of the mine rock⁷. Macropore flow is characterized by turbulent (non-Darcian) flow and is typically very fast (in the order of many tens of meters per day). In contrast, matrix flow is significantly slower (typically in the order of centimeters to a few meters per day). In addition, some of the incoming cover flux may not result in any seepage at the toe of the rock pile because it replenishes storage deficits somewhere in the rock pile (typically near the surface).

Figure 5 shows the proportion of cumulative flow captured in Carter Gulch attributed to seepage from the Carter Gulch waste rock pile. For the purpose of this calibration we have assumed that the estimated contribution of seepage from the covered Carter Gulch waste rock dump (i.e. 58.6% of all flow captured⁶) may be overestimated by as much as 25%. The dashed line in Figure 5 represents our estimated lower bound of cumulative seepage from the Carter Gulch waste rock dump.

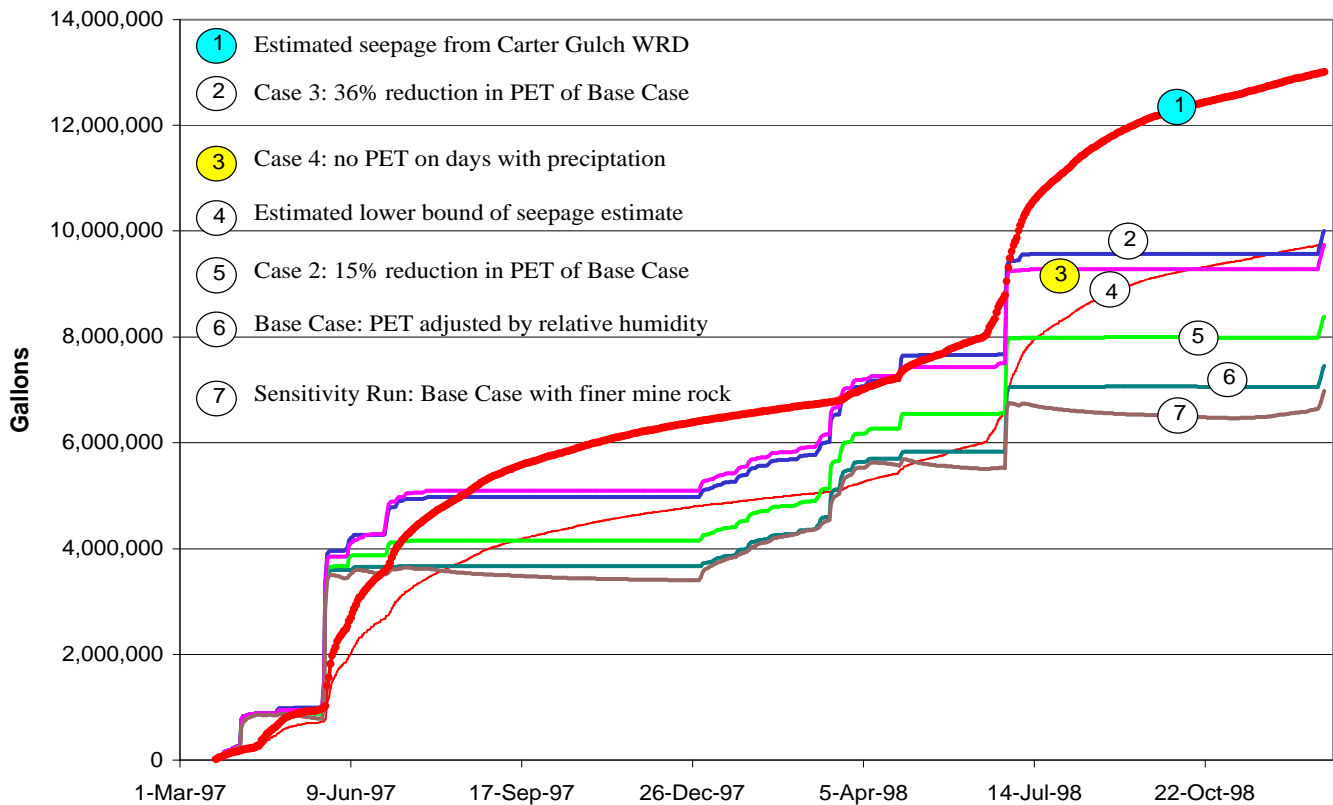


Figure 5. Observed cumulative discharge (Carter Gulch) versus simulated cover flux for various potential ET rates.

The following four calibration runs were carried out:

- “Base case” with PE rates adjusted using relative humidity (RH) as assumed for Phase 1 cover performance modeling, i.e. 25% reduction in PE^2 for days with maximum RH=100% and $PE=0$ for days with minimum RH=100%;
- “Case 2” assuming a 15% reduction in PE rates assumed for “base case”;
- “Case 3” assuming a 36% reduction in PE rates assumed for “base case”;
- “Case 4” assuming $PE=0$ for days with precipitation.

All four calibration runs were carried out using default material properties (as used in the Phase 1 cover modeling²). A fifth calibration run was carried out using adjusted material properties in order to assess the sensitivity of the results to the assumed material properties of the waste rock. For this sensitivity run the material property of a hypothetical, finer-grained mine rock was used (see “topsoil and waste rock mixture” material shown in Figures 3&4).

As expected the simulated total cover flux for the calibration period varied significantly depending on the assumed PE rates. The base case (PE rates from Mocassin adjusted to local RH conditions) represented the lowest cover flux with only about 7.45 Mio gallons prorated over 19.29 acres). The highest cover flux (about 10.0 Mio gallons prorated over 19.29 acres) was calculated for the scenario with a 36% reduction of daily PE rates used as base case. A very similar total cover flux (9.7 Mio gallons) was simulated for the case where PE from Mocassin

was used for those days when no precipitation occurred and assuming no evaporation for the days when precipitation was recorded at Zortman.

Note that all calibration runs yielded cumulative cover fluxes significantly lower than the estimated total seepage from the Carter Gulch waste rock pile. The highest simulated cover fluxes were about 75% of the estimated seepage flows, i.e. fell just within our estimated lower bound of seepage estimates for the Carter Gulch waste rock dump. A better fit to the estimated seepage from Carter Gulch could have been obtained by further reducing the assumed PE rates. However, this approach was not taken because the resulting PE rates were judged to be unrealistically low for actual site conditions. A further reduction in PE rates did not appear to be justified considering the overall uncertainty in both approaches to estimating the rate of net percolation (i.e. water balance and cover modeling).

Among the two scenarios most closely matching the observed outflow at the Carter Gulch capture system (Cases 3 & 4), the scenario that provided a correlation with local precipitation data (i.e. Case 4 with no evaporation assumed for days with precipitation at Zortman) was judged to be more realistic than the scenario with a flat 36% reduction of daily PE measured at Mocassin (Case 3). Hence, the former scenario (Case 4) was used for all subsequent Phase 2 cover performance modeling with SoilCover.

The sensitivity run with adjusted material properties for the mine rock showed a relatively small influence on the overall rate of net percolation (this sensitivity run was carried out assuming that PE is adjusted by local RH conditions, hence should be compared directly with the base case). This sensitivity run confirmed earlier sensitivity analyses, which suggested that uncertainty in local climate conditions outweigh uncertainties in material properties².

In the above calibration process it was assumed that the SoilCover model simulates all relevant physical processes controlling net percolation through the topsoil cover placed on the Carter Gulch waste rock pile. Perhaps the greatest uncertainty in this approach relates to the assumption of Darcian (laminar matrix) flow and vertical movement of soil moisture in the cover layer (1D model). The potential for lateral movement of soil moisture in a sloped soil cover and its influence on overall net percolation was evaluated using the 2D SEEP/W model (see below). The influence of non-Darcian (turbulent) flow through macropores and other channels on net percolation can be very significant, in particular, if the cover was poorly placed and/or is poorly maintained (as was apparently the case at Zortman). Hence, the existence of macropore flow in the soil cover placed on the Carter Gulch waste rock dump can certainly not be ruled out. In fact, macropore flow may explain some or all of the remaining discrepancy between observed seepage and simulated cover flux.

While there is still some uncertainty as to the absolute values of net percolation through a soil cover, the “calibrated” SoilCover model was considered adequate for providing estimates of net percolation for various cover scenarios for the purposes of alternatives evaluation.

COVER PERFORMANCE ON FLAT SURFACES

The calibrated SoilCover model was used to simulate cover performance on a flat surface for a seven cover scenarios considered in the multiple accounts analysis (MAA) for the Zortman-Landusky mines:

- 36” of topsoil;
- 24” of topsoil;
- 12” of topsoil
- 8” of topsoil;
- 18” of topsoil over 6” of tailings;
- 8” of topsoil over 10” of tailings; and
- 11” of topsoil over 7” of tailings.

All seven cover scenarios were evaluated for an average precipitation year (1989) and the very wet calibration period (i.e. 1997 and 1998). In 1989 a total of 19.71 inches fell at the BLM Zortman climate station. This amount is close to the long-term average precipitation for the Zortman town site (the only met station at Zortman and Landusky with a sufficiently long record to provide meaningful long-term averages). The total precipitation simulated for 1989 represents about 75% of the total precipitation recorded in the very wet year 1997.

The net percolation for the seven alternative cover scenarios were simulated using the “calibrated” SoilCover, i.e. using the same material properties and climate input parameters as assumed for the “best fit” of the 24” cover scenario to the estimated seepage from the Carter Gulch waste rock dump (Case 4). In the 1997 and 1998 runs the only adjustments made to the various cover scenarios included the thickness of the cover layer(s) and alternative cover materials (tailings), where applicable.

Two sets of simulations were run for the 1989 model year. In the first set, the PE rates from Mocassin were adjusted to local RH conditions (observed at the BLM Zortman station), i.e. PE rates were reduced by 25% on days when max. RH =100% and PE rates were assumed to be zero for days when min RH=100% (representing the “Base Case”). In the second set, the PE rates from Mocassin were adjusted to the local precipitation (observed at the BLM Zortman station), i.e. PE rates were set equal to zero for days with rainfall (representing the calibration run “Case 4”). The former approach had been used in the Phase 1 cover performance modeling (using 1989 data) whereas the latter approach was found to provide a better fit to the estimated seepage from the Carter Gulch Capture System for the very wet conditions in 1997-1998 (see above). At this point it is uncertain which approach would be more appropriate for the drier climate conditions encountered in 1989 (no flow data from the Carter Gulch Capture System were available for this time period to allow a direct calibration).

Table 1 summarizes the rates of net percolation simulated for the various cover scenarios using the 1989, 1997 and 1998 climate data, respectively. As expected, the rate of net percolation (“cover flux”) decreased with an increase in the thickness of the storage cover. The modeling results suggested very little difference in terms of net percolation between the use of the topsoil and the Ruby Gulch tailings in the storage cover.

Table 1. Summary of SoilCover simulations for wet period (1997 and 1998) and average year (1989).

Cover Scenario	Simulated Net Percolation							
	1989 - "Base Case" ¹		1989 - "Case 4" ²		1997 - "Case 4" ²		1998 - "Case 4" ²	
	inches	% of precip.	inches	% of precip.	inches	% of precip.	inches	% of precip.
36" topsoil	2.8	14%	5.2	26%	11.1	43%	7.5	31%
24" topsoil	3.2	16%	5.8	30%	11.3	44%	8.6	36%
12" topsoil	4.7	24%	7.1	36%	13.0	50%	10.9	46%
8" topsoil	5.5	28%	8.3	42%	14.0	54%	12.1	50%
18" topsoil over 6" tailings	3.0	15%	5.3	27%	10.9	42%	7.9	33%
8" topsoil over 10" tailings	3.5	18%	5.9	30%	11.2	43%	8.9	37%
11" topsoil over 7" tailings	3.3	17%	5.9	30%	11.3	44%	8.9	37%

Notes

- (1) PET from Mocassin reduced by 25% on days with max RH=100% and PET=0 on days with min RH=100%
- (2) PET from Mocassin = 0 on days with precipitation

The generally higher rate of simulated net percolation in 1997 (for all cover scenarios) was not only a result of the slightly higher total precipitation (25.8 in 1997 vs. 23.95 inches in 1998) but also the seasonal pattern of precipitation with significantly more precipitation in the spring/early summer (Figure 4). Note that the simulated rates of net percolation for 1989 were significantly lower than those simulated for the wetter years 1997 and 1998. For example, the simulated total net percolation through a 24 inch topsoil cover was only 5.8 inches (29.5% of precipitation) in 1989 compared to 11.3 inches (44% of precipitation) in 1997 and 8.6 inches (36.0% of precipitation) in 1998. As expected the approach of adjusting PE rates based on precipitation ("Case 4") in 1989 resulted in higher rates of net percolation compared to using the "base case" (adjustment by RH).

The observed difference in cover performance between years with different climate conditions (in particular magnitude, timing and intensity of precipitation) was consistent with the results of the Phase 1 modeling. These results imply that significant variations in cover flux can be expected for these water storage covers from year to year. Such variations in cover performance can be expected to decrease with an increase in the thickness of the storage layer.

COVER PERFORMANCE ON SLOPED SUFACES

In the previous analyses it was assumed that the soil cover is placed on a flat (or nearly flat) surface resulting in essentially vertical infiltration. However, a significant proportion of the surface area of the mine rock dumps and leach pads at the Zortman-Landusky mine sites are sloped and/or will be resloped for cover placement. The two-dimensional finite-element code SEEP/W was used to assess the performance of a water storage cover on such sloped surfaces. SEEP/W is commercially available through GeoSlope in Calgary, Alberta, and simulates two-dimensional saturated and/or unsaturated flow using Darcy's Law⁴. The model allows the definition of sub regions within the model domain for which the material functions (soil water characteristic curve and hydraulic conductivity characteristic curves) are specified. For the purpose of this modeling a 24-inch thick topsoil cover was assumed to be placed on a mine rock pile (or leach pad) resloped at 3:1.

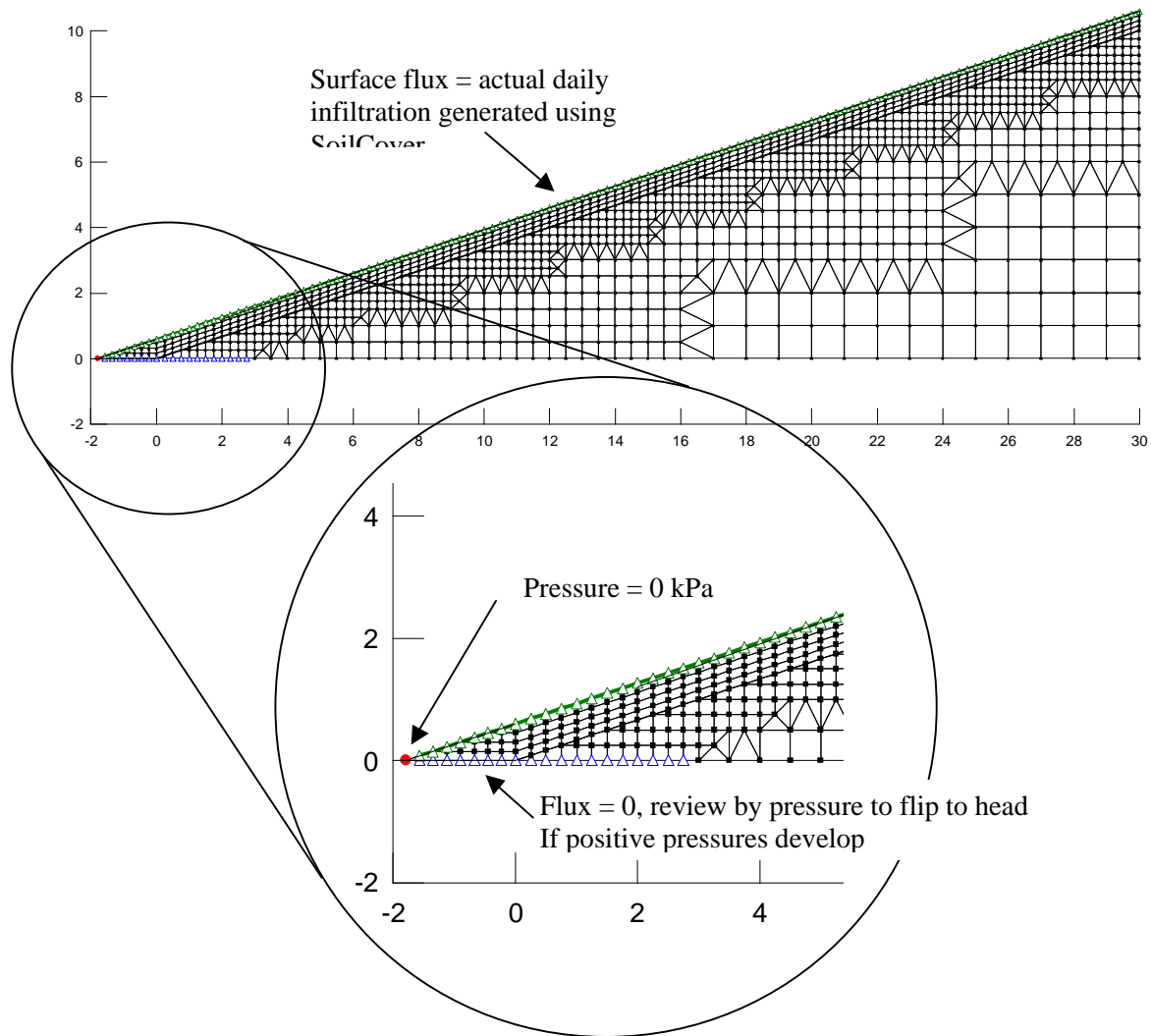


Figure 6. The finite element model and boundary conditions used to simulated cover performance (24" topsoil cover) on a sloped surface.

This conceptual cover design uses the capillary break created between the coarse mine rock material and the overlying finer-grained topsoil material, which functions as a water storage and drain layer. This capillary break prevents infiltration into the waste rock as long as soil suction in the finer-grained soil is greater than the air entry value of the underlying waste rock.

Figure 6 shows the finite element model and boundary conditions used to simulate cover performance of the 24-inch thick topsoil cover on a sloped surface. The model domain consisted of a continuous slope (without drainage ditch or road) with a slope length of 100 ft (at the base) and a slope angle of 3:1. A finite element mesh was discretized within the drawing boundaries and material properties for both the topsoil and waste rock were applied to the elements. The required material properties for the two materials (K_{sat} , SWCC and relative hydraulic conductivity function) were the same as used for the one-dimensional SoilCover modeling (see Figures 2&3).

Note that an erosion layer (consisting of durable oxidized mine rock or other coarse material) may have to be placed in the field to protect the finer-textured topsoil from erosion. However, this (optional) protection layer would not have a significant effect on cover infiltration and/or movement of soil moisture within the cover layer (due to its coarse nature) and thus was not included in the finite element model.

A head boundary of pressure equal to 0 kPa was applied at the toe of the slope just beneath the cover (see inset in Figure 6). This base boundary is typical of what may be experienced in the field and it has been used successfully in other slope seepage modeling analyses carried out by the author.

Note that SEEP/W is not capable of calculating the net infiltration at the surface, i.e. the net flux resulting from precipitation minus evapotranspiration and runoff. As a first approximation the surface flux applied on the slope was assumed to be equal to the surface flux (i.e. precipitation minus actual evaporation) computed by SoilCover (see above). The use of the surface fluxes calculated with SoilCover, however, provides a good first estimate of the net infiltration. The actual rate of net infiltration on a sloped surface may be lower than calculated with SoilCover (for a flat surface) due to the higher potential for surface runoff on a sloped surface. Hence, our approach tends to provide conservative (high) estimates of cover flux for a cover on a sloped surface.

In the Phase 1 cover modeling the performance of a water storage cover on a sloped surface had been evaluated for “average recharge conditions” (5.9 inches over 8 months or about 0.02 inches/day) as well as for single precipitation events of high to very high intensity². In the Phase 2 study the transient response over a full runoff season was evaluated². The time period simulated represented the major recharge period during the model year 1989, i.e. the period May 1 - July 8 (days 120 – 190 of the calendar year). The transient seepage model was run in hourly time steps. The surface flux boundary condition (at the top of the cover) was updated daily using the respective surface flux calculated for that day using SoilCover (w/ PE rates adjusted by RH, “Base case”). Here we only present the results of the transient modeling carried out in Phase 2.

Figures 2 and 3 show the material properties of the topsoil and mine rock used as input to the SEEP/W model. Two different scenarios were modeled to evaluate the sensitivity of the model predictions to the material properties of the mine rock underlying the cover. In the first scenario the default material properties representing coarse mine rock were used (labeled “waste rock” in Figures 2 and 3). These default material properties had already been used in the Phase 1 modeling² and in the majority of the Phase 2 SoilCover modeling (see above). In the second scenario, a somewhat finer waste rock material was assumed to be present in the rock pile. Such a finer mine rock can be expected to develop over time due to movement of fines from the topsoil cover layer into the mine rock and/or weathering of the mine rock over time. The material properties for this finer mine rock are also shown in Figures 2 and 3 (labeled “topsoil and waste rock mixture”).

Figure 7 shows the pressure profile for the covered mine rock pile (3:1 slope) after 10 days (i.e. on day 130 of 1989) using the default mine rock material properties. Also shown are the computed fluxes for various flux sections defined beneath the cover (parallel to the slope) and at the base of the cover (perpendicular to the cover). The simulation indicates that the flow within

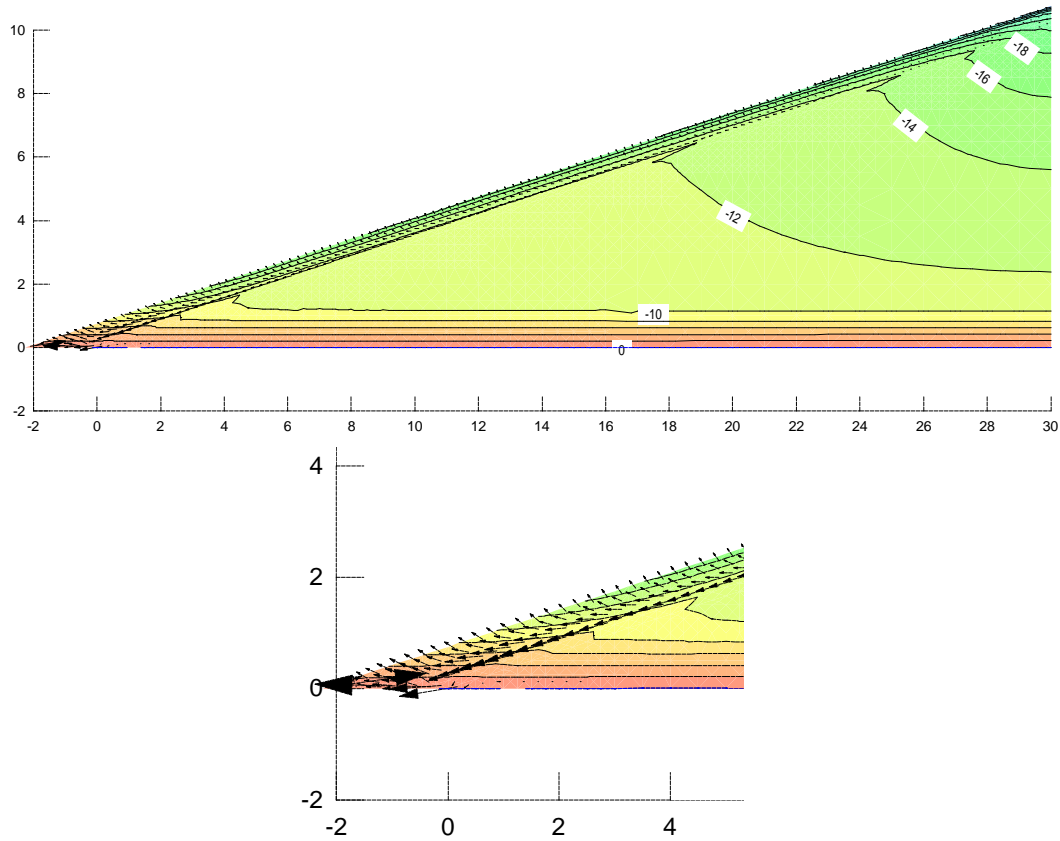


Figure 7. Pressure profile for the covered mine rock pile (3:1 slope) after 10 days (default mine rock material properties).

the cover (parallel to the slope) is more than an order of magnitude greater (i.e. $4.36\text{E-}03$ units) than all inflow into the mine rock (flow perpendicular to the slope) combined (i.e. $3.15\text{E-}04$ units). The daily fluxes for lateral flow (within the cover) and vertical flux into mine rock (i.e. net percolation) were summed up and plotted against time to evaluate the cover performance for the entire 70 day simulation period.

Figure 8 summarizes the results of the SEEP/W cover modeling analysis showing cumulative fluxes of infiltration (upper panel), as well as simulated lateral flow within the cover and vertical flux into waste rock for the default mine rock parameters (middle panel) and the finer mine rock properties (lower panel). Note that the infiltration flux is a user-defined input to the SEEP/W model (i.e. representing the net infiltration calculated with the SoilCover model). The lateral flow within the cover represents the flux of water flowing within the soil cover (parallel to the slope face) and emerging at the toe of the covered mine rock pile (see Figure 7). The vertical flux into waste rock represents the net percolation into the mine rock (expressed as a unit flux over the entire slope length of 100 ft).

Figure 8 (middle panel) illustrates that the vast majority (>95%) of infiltrating water is moving laterally within the cover (parallel to the slope) and exits at the toe of the mine rock pile without entering the mine rock. In other words the interface between the finer-grained topsoil and the coarse mine rock represents a very effective capillary break which inhibits vertical movement of

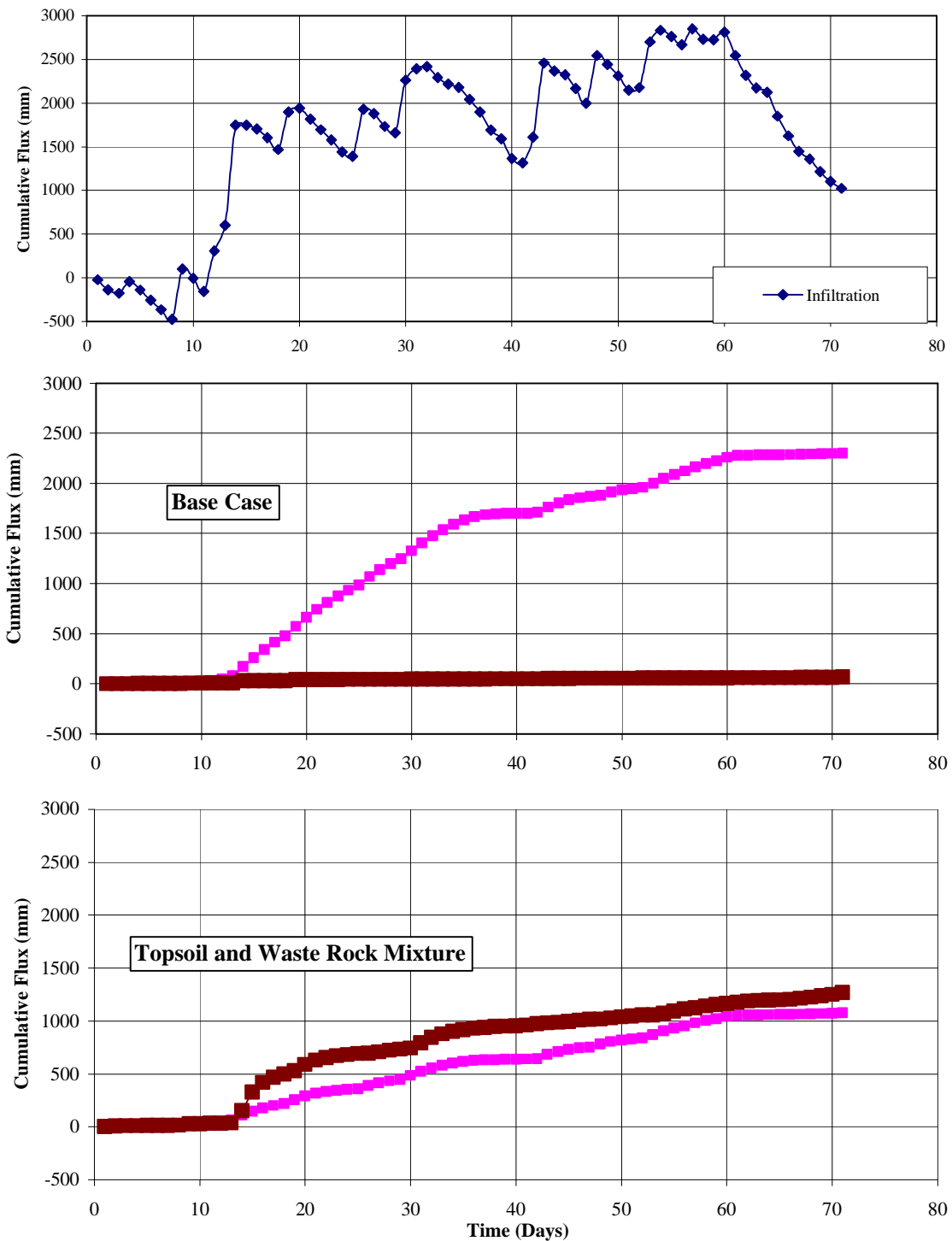


Figure 8. Cumulative fluxes for sloped mine rock (3:1) covered with 24" of topsoil with default mine rock properties (middle) and "finer" mine rock (lower).

soil moisture into the rock pile. Note that during most of the modeled time period (days 12-62) the infiltration is greater than the lateral flux out of the base of the cover, i.e. the cover stores incoming precipitation. In subsequent days the cumulative infiltration drops below the lateral

flux out of the base of the cover, i.e. the soil moisture stored within the cover is depleted due to evapotranspiration. In these periods of negative surface flux (i.e. evapotranspiration dominates over precipitation) there is no flow out of the base of the cover (Figure 8).

Note that the 2D cover modeling results for the default mine rock parameters are not consistent with field observations in capture systems from Carter Gulch and other leach pads (which are predominantly sloped rather than flat). As mentioned earlier a water balance analysis of the captured flows suggest a rate of net percolation in the order of >50% of precipitation. In contrast, the 2D modeling results would suggest that, if a capillary break effect was present, the net percolation into the covered mine rock pile on sloped surfaces should be very small (i.e. less than say 5% of precipitation). However, the capillary break effect is known to be very sensitive to material properties and a high quality control during construction (in terms of materials used and cover thickness/continuity) is required to ensure proper functioning of such a cover.

Figure 8 (bottom panel) summarizes the results of the sensitivity run of using a finer mine rock material (“topsoil-mine rock mixture”) instead of the coarse mine rock. It is seen that the presence of a finer-grained mine rock greatly reduces the efficacy of a capillary break between the topsoil and the mine rock. In this scenario the amount of lateral flow (within the soil cover) is greatly reduced and the vertical flux into the mine rock (i.e. net percolation) is greatly increased. In fact for this simulation period the two cumulative fluxes are approximately equal. In this scenario the capillary break effect on the sloped surface would still result in a ~50% reduction of net percolation relative to what would be expected on a flat surface.

It should be recognized that the 2D cover mine rock profile modeled with SEEP/W represents a significant simplification of actual field conditions and as such there is a significant uncertainty attached to the model results. This uncertainty is demonstrated by the large difference in the simulated net percolation (cover flux) in the two sensitivity runs.

One of the greatest concerns with the reliance on a capillary break layer is the long-term performance. With time, fines can be expected to move from the cover layer into the upper profile of the coarse mine rock resulting in a deterioration of the capillary break effect. In general, the use of a geofabric placed between the cover layer and the mine rock would greatly facilitate initial placement of the soil cover and would prevent entrainment of finer particles into the mine rock (at least for the life time of the geofabric). In addition, erosion of the topsoil may result in a breakdown of the capillary break effect, in particular if relatively thin covers are utilized (say 18 inches or less).

With these limitations in mind, no attempt was made to simulate all seven cover alternatives with a 2D geometry in order to obtain direct estimates of net percolation for sloped surfaces. Instead, the 2D model results were used to develop simple guidelines for estimating the rate of net percolation for sloped surfaces:

- Assume 50% reduction in net percolation for sloped surfaces if geofabric is placed between cover layer and mine rock;
- Assume 25% reduction in net percolation if a thick soil cover (24” or greater) is placed on mine rock;

- Assume 10% % reduction in net percolation if a thinner soil cover (<24”) is placed on mine rock;
- Assume 15% reduction in net percolation if a layered topsoil/tailings cover is placed on mine rock;

CONCLUSIONS

The results of the laboratory testing on the locally available materials collected in 1999 were used as inputs for the SoilCover and SEEP/W modeling. The climate parameters of air temperature and relative humidity were obtained from the nearby BLM Zortman Station. The precipitation values were measured at the Zortman Station. The daily potential evaporation was estimated from pan evaporation measured at the Mocassin Experimental Station.

The captured flows from Carter Gulch were used to calibrate the SoilCover model. Significant adjustments (reduction in potential evaporation rates) had to be made to the “base case” in order to predict the observed outflow rates. The calibrated material properties and climate input parameters were used for evaluating the performance of alternative cover scenarios for flat and sloped surfaces. SoilCover predicted similar rates of net infiltration for the seven cover types studied relative to the uncertainties within the model input. Sensitivity analysis suggested that the greatest variability in cover performance was due to the variability in the climatic conditions (i.e. wet versus dry years). SEEP/W predicted that a capillary break might substantially reduce infiltration on a sloped surface; however, this effect is very sensitive to the material properties of the cover material and the underlying mine rock. Sensitivity analyses with the 2D seepage model suggested that movement of fines from the topsoil into the coarse mine rock would substantially reduce the effect of a capillary break. General guidelines were developed for estimating the reduction of net percolation (cover flux) for sloped surfaces relative to rates of net percolation simulated for a cover placed on a flat surface.

Based on the results of this cover modeling study, it was determined that regardless of the cover type chosen, the control of acid generation and migration (‘source control’) could not effectively eliminate the need for water collection and treatment on either site. Therefore, the various reclamation alternatives were developed such that water treatment was anticipated for the long term. The cover types were varied between alternatives and were selected with different objectives in mind (e.g. maximizing revegetation potential vs. minimizing the volume of water management in certain facilities vs. minimizing overall cost etc). The relative benefits of each cover type with respect to the overall reclamation success of each alternative was evaluated in the context of a multiple accounts analysis (MAA)¹.

REFERENCES

1. Shaw, S.C., Robertson, A.MacG., Maehl, W.C., Kuipers, J. and Haight S. (2001), *Review of the Multiple Accounts Alternatives Evaluation Process Completed for the Reclamation of the Zortman and Landusky Mine Sites*, These Proceedings.
2. Robertson GeoConsultants Inc. (2000a), *Cover Performance Modeling Zortman & Landusky Mine Sites, Montana*, prepared for Spectrum Engineering, 1413 4th Ave. North, Billings, Montana, USA, 59101.

3. Robertson GeoConsultants Inc. (2000b). *Phase 2 Cover Performance Modeling, Zortman & Landusky Mine Sites, Montana*, prepared for Spectrum Engineering, 1413 4th Ave. North, Billings, Montana, USA, 59101.
4. GeoAnalysis 2000 Ltd. (2000), *SoilCover User's manual*, May 2000.
5. GeoSlope Int., (2000) *SEEP/W for Finite Element Seepage Analysis, Version 4.3*, Calgary, Alberta, Canada.
6. Spectrum Engineering (2000a). *Zortman Mine Water Balance and Chemical Mass Loading*. Report prepared for Montana Department of Environmental Quality and the Bureau of Land Management, April 13th, 2000
7. Smith, L., D. Lopez, R. Beckie, K. Morin, R. Dawson, and W. Price, 1995. *Hydrology of Waste Rock Dumps*, Final Report submitted to Department of Natural Resources Canada, July 1995.