WM2013 Conference, February 24 – 28, 2013, Phoenix, Arizona USA

Long-Term Performance of Uranium Tailings Disposal Cells – 13340

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ABSTRACT

Recently, there has been interest in the performance and evolution of Uranium Mill Tailings Remedial Action (UMTRA) Project disposal cell covers because some sites are not compliant with groundwater standards. Field observations of UMTRA disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the upper portion of radon barriers may increase due to freeze/thaw cycles and biointrusion. This paper describes the results of modeling that addresses whether these potential changes and transient drainage of moisture in the tailings affect overall performance of the disposal cells. A numerical unsaturated/saturated 3-dimensional flow model was used to simulate whether increases in saturated conductivities in radon barriers with rock covers affect the overall performance of the disposal cells using field data from the Shiprock, NM, UMTRA site. A unique modeling approach allowed simulation with daily climatic conditions to determine changes in moisture and moisture flux from the disposal cell. Modeling results indicated that increases in the saturated conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings restricts flux in the worst case to the saturated conductivity of that material. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time. The significance of this modeling is that operation and maintenance of the disposal cells can be minimized if they are allowed to progress to a natural condition with some vegetation and soil genesis. Because the covers and underlying tailings have a very low saturated hydraulic conductivity after transient drainage, eventually the amount of moisture leaving the tailings has a negligible effect on groundwater quality. Although some of the UMTRA sites are not in compliance with the groundwater standards, the explanation may be legacy contamination from mining, or earlier higher fluxes from the tailings or unlined processing ponds. Investigation of other legacy sources at the UMTRA sites may help explain persistent groundwater contamination.

INTRODUCTION

Recently, there has been interest in the performance and evolution of Uranium Mill Tailings Remedial Action (UMTRA) Project disposal cell covers because some sites are not compliant with groundwater standards. Field observations of UMTRA disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the upper portion of radon barriers may increase due to freeze/thaw cycles and biointrusion. This paper describes the results of modeling that addresses whether these potential changes and transient drainage of moisture in the tailings affect overall performance of the disposal cells. A numerical unsaturated/saturated 3-D flow model was used to simulate whether increases in saturated conductivities in radon barriers with rock covers affect the overall performance of the disposal cells using field data from the Shiprock, NM, UMTRA site. A unique modeling approach allowed simulation with daily climatic conditions to determine changes in moisture and moisture flux from the disposal cell. Modeling results indicated that increases in the saturated conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings or tailings restricts flux in the worst case to the saturated conductivity of that material. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time.

Recent field observations of Uranium Mill Tailings Remedial Action UMTRA (Project) disposal cells indicate that rock covers tend to become vegetated and that saturated conductivities in the radon barriers increase with time. Possible reasons that standard construction and quality assurance practices used for construction of compacted clay soil barriers were not achieving or maintaining design permeabilities include (1,2):

- Clay soils were compacted dry of optimum water content.
- Clay clod formation.
- Insufficient bonding between lifts.
- Desiccation cracking.
- Shrink-swell cracking.
- Freeze-thaw cracking.
- Biointrusion.

This paper describes field testing and the results of modeling at the Shiprock UMTRA site near Shiprock NM, that address whether increases in saturated conductivities in the cover and transient drainage of moisture in the tailings affect overall performance of the disposal cells. The modeling approach is unique in that it evaluates a 3-dimensional flow system with daily climatic conditions and is not subject to the limitations of static upper or lower boundary conditions used in previous one- or two-dimensional models. The results of this modeling can be used to evaluate whether UMTRA rock covers can evolve naturally towards vegetated evapotranspirational covers and still maintain performance. This would eliminate costs of retrofitting covers and reduce maintenance costs for removal of vegetation on disposal cells

BACKGROUND

The UMTRA Project involved remediation of 24 uranium tailings sites between the 1980s and 1990s, most of which are in the western United States. The first covers on uranium tailings and other contaminated materials generally consisted of a one- to two-meter thick clay radon barrier overlain by 15 centimeters (cm) of filter sand and 30 cm of erosion protection riprap (Figure 1). The radon barrier in the cover generally has a saturated hydraulic conductivity on the order of 10^{-7} centimeter per second (cm/s). The filter layer consists of sand with a hydraulic conductivity of 0.001 to 1.0 cm/s that protects the radon barrier from erosion, facilitates drainage off the radon barrier, and allows for evaporation of residual moisture. Tailings that were remediated in place at this time may have had perched phreatic surfaces in low permeability tailings slimes. Tailings that were relocated from flood plains were compacted wet of optimum and heavily watered for dust control. These practices may have contributed to high percentages of saturation in the relocated tailings. Figure 1 shows a typical rock cover radon barrier at the UMTRA tailings disposal cell in Shiprock, New Mexico.

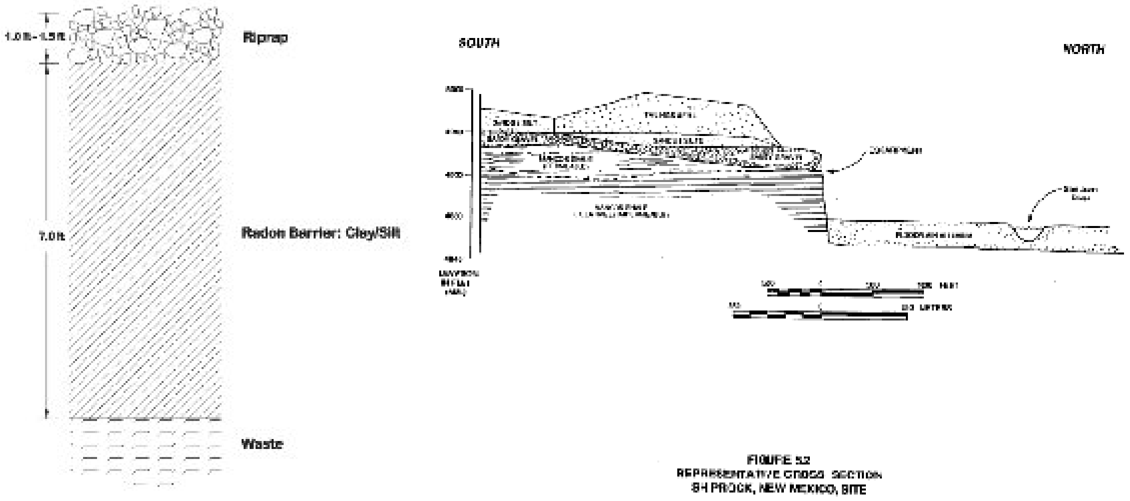

Figure 1 Generalized Early UMTRA Rock Cover over a Radon Barrier Used and representative cross section at the Shiprock Site

Mid-way through the project in1988, the DOE began to comply with U.S. Environmental Protection Agency (EPA) groundwater standards applicable to the UMTRA Project (40 CFR 192). They established concentration limits for hazardous constituents that cannot be exceeded at the downward gradient limit of the disposal facility (the point of compliance, or POC). Cover designs changed to eliminate freeze thaw cycles and potential bionstrusion by plants or vegetation in the radon barrier that might change the hydraulic properties. At this point, relocated tailings and cell covers were compacted dry of optimum and watering for dust control was minimized to eliminate water entrained in the tailings.

Seepage rates through the radon barrier at a rock-covered disposal cell are equal to the product of the hydraulic conductivity (a function of the moisture content) and the hydraulic gradient. For moisture contents that are vertically uniform, the hydraulic gradient is unity. However, using the saturated hydraulic conductivity of 10^{-7} cm/s in the radon barrier for the purpose of calculating seepage rates is highly conservative and in some cases precludes demonstrating compliance with the groundwater standards. If the radon barrier is unsaturated, operational hydraulic conductivities of the radon barrier and long-term seepage rates from the facility may be several orders of magnitude lower.

While the more recent UMTRA disposal cell designs and construction practices recognized the need to prevent infiltration and accumulation of water in the disposal cell, there have been concerns about whether earlier rock covered disposal cells function in regards to the groundwater standards. Presently, the earlier covers are maintained to prevent vegetation. However, as a vegetated cover is a probable plant succession end state, questions have arisen whether the covers will perform as vegetation encroaches and whether pedogenesis in cover layers occurs and affects disposal cell performance. Generally, anywhere there is an annual moisture deficit and the disposal cell cover is shaped to shed surface water runoff, covers will be unsaturated. However, there is concern whether rock rip-rap is increasing percent saturations and downward moisture flux.

The hydrologic conditions at the site, and more specifically the moisture deficit within the soil column may reduce orders of magnitudes the saturated hydraulic conductivity of the cover and the tailings. Three major transient processes affect the moisture distribution within the column: infiltration from surface water (rainfall and snow melting), evapotranspiration, and depth to groundwater levels. Therefore the distribution of moisture has transient character, in addition of being spatially distributed along the height of the soil column. The temporal and spatial character of the moisture distribution in vertical direction, (i.e. hydraulic conductivity of the tailings and the cover, and corresponding infiltration from the surface to the saturated zone) require analysis of the entire spectrum of hydrologic events with respect to time and better understanding of the behavior of the system with respect to hydrological events. Furthermore, vegetation must be taken into account considering that vegetation roots act as conveyors for extracting water from the subsurface to air when the thermodynamic potential forces water conveyance through vegetation stems. In order to accurately determine flow and transport of chemical constituents through radon cover, the protective rip rap, tailings and saturated zone, an integrated numerical model is required to provide coupling between all of the above processes.

Early UMTRA Infiltration Cover Studies

In 1985, Colorado State University performed geotechnical testing on the tailings at the Shiprock, NM, UMTRA site (3) that included in situ and remolded index properties, strength properties, and consolidation characteristics From fifteen borings made in 1981, four interpretive cross-sections were developed that identified areas of sands and slimes. The cross sections provide the basis for the modeling described in this paper. An aerial view of the Shiprock UMTRA site in 1965 and after completions of disposal cell in 1986 is presented in Figure 2.

Figure 2 Aerial View of the Shiprock UMTRA Site in 1965 and after Completions of Disposal Cell in 1986 Disposal Cell

After remediation of the cell in 1986, a field study was undertaken in 1988 to evaluate moisture conditions in the disposal cell cover at the Shiprock, New Mexico site (Figure 2) (4). Limited field data also were obtained for the disposal cell covers at the Clive, Utah, and Burrell, Pennsylvania, sites for comparison. The field study by the U.S. Department of Energy (DOE) to determine whether the rock-covered tailings disposal cells could continue to be used as a design that would allow compliance with the proposed EPA groundwater protection standards. Percent saturation profiles were developed for the clay radon barriers at all three disposal cells, and capillary moisture curves and unsaturated hydraulic conductivity curves were developed for the Shiprock radon barrier. The radon barriers of all three disposal cells were found to be unsaturated within three years of placement and average percent saturation ranged was less than 84 percent. As part of the field study, the Shiprock disposal cell was instrumented to monitor meteorological stresses, relative soil tension, and moisture content profiles in the filter layer and radon barrier.

Geotechnical testing conducted during the 1988 study indicated that the average percent saturation of the radon barrier is 83.6 percent (12.6 percent by weight), with moisture contents relatively uniform with depth. The construction moisture content of the radon barrier was 14.9 percent by weight, indicating some drying of the radon barrier may have occurred. Evidence from neutron logging of the radon barrier in the 1988 study supported this conclusion (Figure 3).

During the 1988 field study, seasonal field evaporation experiments demonstrated that the potential evaporation from the filter layer exceeds the annual precipitation at the Shiprock site, and evaporation may be the primary mechanism for removing excess water from the filter layer. Monitoring of relative soil tensions with time indicated that relative soil tensions in the filter layer and upper portion of the radon barrier are controlled by meteorological stresses. Relative soil tensions in the filter layer decreased during winter, but were generally high the remainder of the year, except after precipitation events. Relative soil tensions were highly variable in the upper portion of the radon barrier, but remained relatively constant below a depth of 100 cm. long-term moisture contents in the Shiprock radon barrier were simulated using the finite element unsaturated flow model UNSAT2. The modeling demonstrated that soil tensions propagate relatively rapidly through the radon barrier, equilibrating to steady state conditions within a few years. By applying a cyclical upper boundary condition based on measured monthly average tensions in the upper portion of the radon barrier and using a seepage face as a lower boundary, soil tensions in the radon barrier were simulated for 100 years (Figure 3). The modeling indicated that soil tensions in the radon barrier were currently at or near equilibrium, and that the radon barrier will remain unsaturated with time. The long-term percent saturation of the Shiprock radon barrier was predicted to be slightly less than the average 83.6 percent saturation measured in analyses of core samples in 1988. The modeling also showed that if the filter layer were to remain saturated year-round, then the saturated moisture front would propagate downward through the entire radon barrier within a year. However, it was surmised that saturation of the radon barrier in the future is unlikely, as its low hydraulic conductivity limits downward migration of water, and evaporation removes excess water from the filter layer. The modeling was limited in that didn't account for flow properties of the tailings or evolution of cover properties with time.

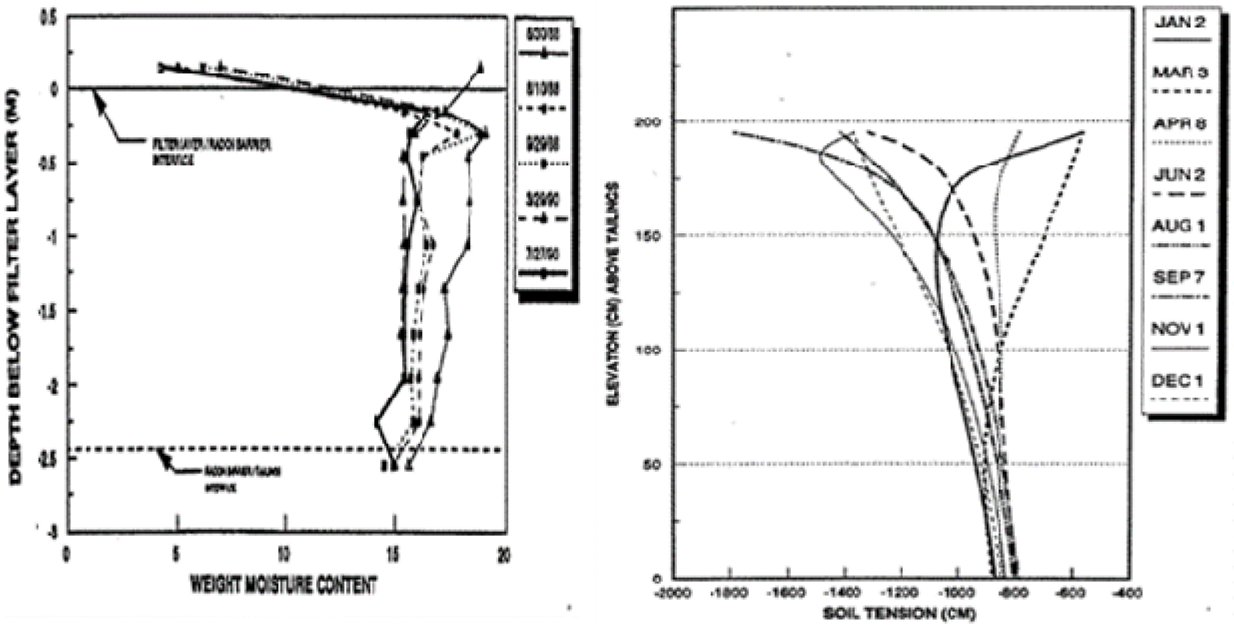

Figure 3 Relative moisture content measured with a neutron moisture meter and simulated soil tension in the Radon Barrier for 1988 Study Using UNSAT2

Based on data from the field study at Shiprock and the unsaturated flow modeling, it was concluded that the operating unsaturated hydraulic conductivity of the Shiprock radon barrier is approximately 10^{-8} cm/second, and moisture conditions within the radon barrier are approaching a state of dynamic equilibrium. Radon barriers of similar UMTRA Project disposal cells in similar climates are also likely to remain unsaturated if potential evaporation from the filter layer exceeds precipitation for most of the year (4).

Recent UMTRA Cover Studies

In 1995, the results of a lysimeter study by Sackshewsky et al. showed that significant percolation occurs in landfill covers consisting of nonvegetated soils covered with clean gravel and rock even under very low annual precipitation (160 millimeters per year (mm/yr)) (5). By comparison, no percolation occurred through a vegetated soil-rock cover even under high annual precipitation (450 mm/yr per year). This study generated concern about whether infiltration rates were increasing through early rock cover radon barriers.

In 2001, the DOE reported on the results of six saturated hydraulic conductivity (Ksat) measurements taken in the radon barrier with an air-entry permeameter in the upper portion of the cover on the north side slope in areas where vegetation had encroached on the rock cover (6). The Ksat ranged from 1.19×10^{-4} cm/s to 4.76×10^{-8} cm/s, revealing a high degree of uncertainty. Moisture contents were measured in the same neutron probe tubes that DOE installed through the radon barrier into the tailings in 1988. The paper reported that neutron moisture readings and soil samples from borrow pits indicate saturation throughout the radon barrier and that the neutron probe was dripping wet when extracted from the tubes. The report described that approximately half of the depth of the rock layers was filled with windblown silt. Review of the paper indicates saturation in the cover may be local to areas over slime tailings that limit the downward migration of infiltration. Moisture data from samples collected in vegetated areas suggests there are areas in the cover where moisture contents range from 46 to 90 percent saturation. In addition there was no mention of borrow pits in the cover filling with water that would indicate saturation in the cover. Water in and around the neutron logging tubes may be related to an incomplete seal in the annulus with the cover that allows water in the rock layer from a storm event to penetrate vertically along the annulus of the tube. If this is the case, the neutron data are invalid. Furthermore, neutron moisture data are relative calibrated data and should only be used to determine change in moisture content. Inspection of the 2001 data in Figure 4 indicates the same uniform profile as the 1988 data shown on Figure 3, The conclusion that the cover is saturated in the 2001 study is invalid because two of only three soil samples from test pits with 90 percent saturation were averaged with a 107 percent saturation sample that should have been discarded.

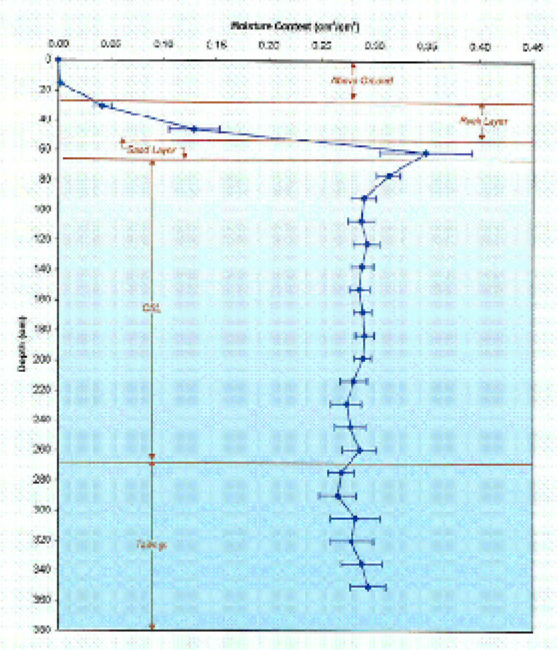

Figure 4 Neutron Moisture Meter Logging Measurements in the Radon Barrier from the 2001 Shiprock Study

A piezocone investigation was conducted on the Shiprock disposal cell in 2001 to determine if free water was present in the cell (7). Twenty-nine soundings were attempted in a more-or-less equally spaced grid over the cover. Eight soundings were able to penetrate the cover below a meter. Refusal in the 18 other soundings was attributed to a former highly compacted interim cover (three soundings were made in off-pile locations in ditches surrounding the disposal cell). Saturated slimes (indicated by a positive pore pressure during the sounding that did not fully dissipate) were observed in six of the soundings; thicknesses varied from 76 cm to 305 cm, median of 152 cm.

Knight Piėsold Consulting in a 2002 report .analyzed infiltration through the Shiprock radon barrier using the EPA's HELP computer code (8). Model results indicate that approximately 20 percent of precipitation falling at the site infiltrates the existing cover, resulting in a flux from the base of the disposal of 22 liters/minute. This flux from the cell occurs over the entire 28.3 hectare base of the modeled cell. According to the model, modifying the existing riprap cover to a vegetation cover will essentially eliminate recharge to the tailings. However, some assumptions made to use this model are questionable; for example, the model does not incorporate drainage of tailings materials. Unsaturated conditions or temporal (transient) conditions are also ignored. The report provides a good discussion of expected moisture contents within the disposal cell.

In 2012 DOE (9) reported on HYDRUS-1D modeling of the Shiprock Disposal Cell for conditions in the northeast portion of the pile that may contain saturated slimes. Results of the modeling indicated that when the influx is greater than the saturated hydraulic conductivity of the slimes, moisture mounds above the slimes. When the influx was less than the saturated hydraulic conductivity of the slimes, steady-state drainage from the slimes was equal to the influx occurs within 5 years for the modeled conditions. When near-zero influx was specified, the tailings drain to residual moisture contents in approximately 20–30 years, dependent on the saturated hydraulic conductivity of the slimes. Drainage rate from the slimes after 20–30 years is around 10^{-9} cm/s under near-zero influx conditions. Drainage from the non-slime material is expected to be nearly constant at the value determined by the Knight Piésold study of 10^{-7} cm/s.

Recent Modeling of Evolution of Disposal Cell Covers and Transient Drainage

Potential effects on evolved disposal cell covers on disposal cell performance resulting from an increase in saturated conductivity in the radon barrier with time were recently simulated with the MIKESHE model. In these simulations, material properties for tailings measured at the Shiprock site were placed below the cover at the average percent saturation measured in the field.

The numerical model is based on the MIKE SHE/MIKE 11 modeling system from DHI Water & Environment [6]. It consists of a coupled surface/subsurface flow model using MIKE SHE (a 3-dimensional saturated and unsaturated groundwater flow, 2-dimensional overland/sheet flow model) and MIKE 11 (1-dimensional river flow model which includes structure operation and schedules). MIKE SHE is a distributed hydrological modeling system [7], which solves the subsurface flow and transport using the law of conservation of mass and the laws of momentum and energy (3-D Boussinesq and transport equations). The model requires data in standard GIS format. Spatial data for Shiprock was obtained from USGS[1] National Map Viewer.

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[1] http://nationalmap.gov/viewer.html

Model Domain

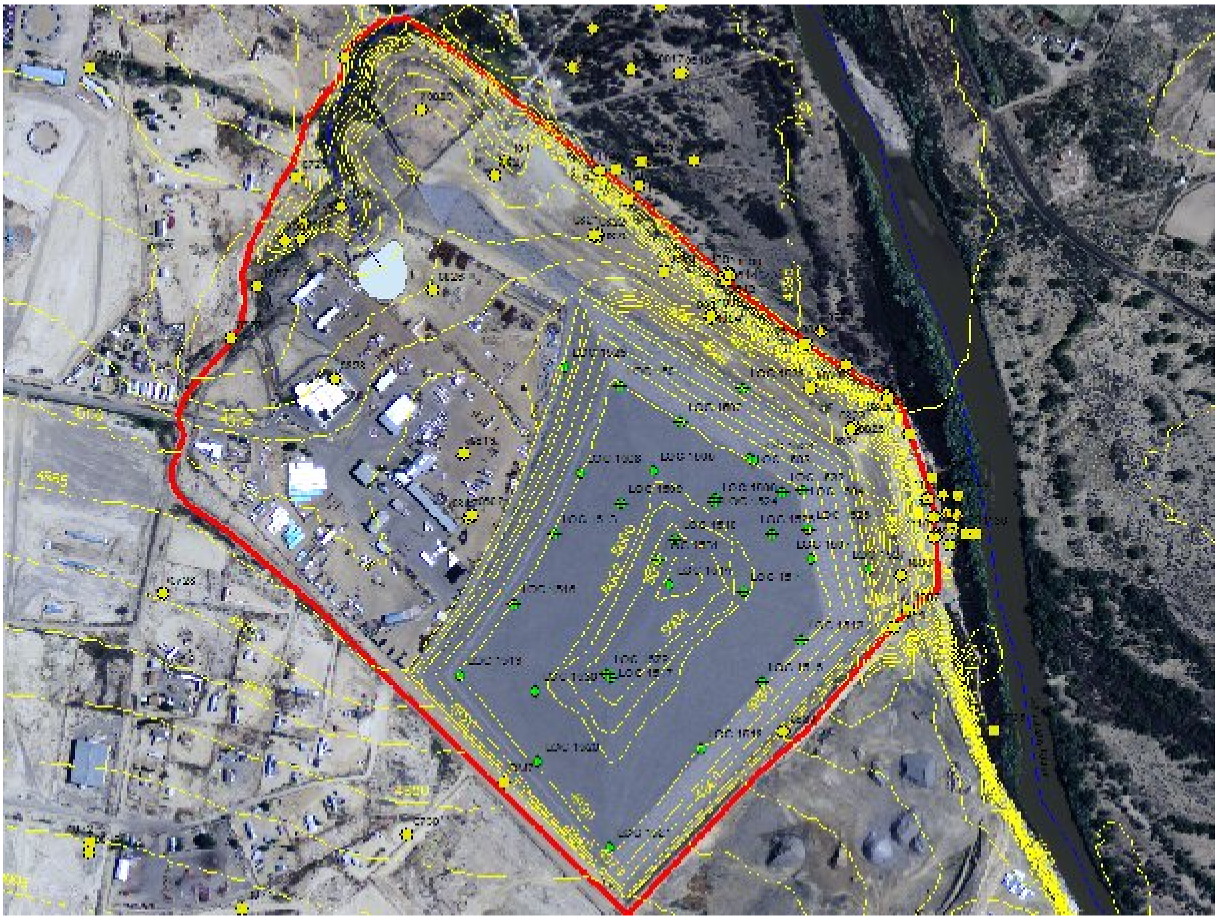

Figure 5 Model domain

Some of the more extreme rainfall events were 1.5 inches on Oct. 22, 1969; 1.9 inches on Sept. 5-6, 1970; 2.7 inches on July 20-23, 1986; 1.9 inches on April 4-5, 1997; and 3.0 inches on Sept. 2-4, 2002. The annual precipitation extremes ranged from a low of 3.57 inches in 1976 to a high of 14.65 inches in 1986 (10). Reference ET (ETo) refers to the ET of a reference crop such as grass or alfalfa that is of a certain height and is growing under optimum conditions for maximum production. ETo is correlated with weather parameters, and it is calculated when these parameters are available. From 1996 to 2003, average daily ETo (using WS-2 data and a modified, grassreferenced Penman formula from the New Mexico Climate Center: http://weather.nmsu.edu/pmcomp.htm) ranged from 0.08 inch/day in January and December to 0.38 inch/day in June, while the total annual ETo averaged 80.5 inches. From May through August, the active growing season for many crops, ETo averaged 10.4 inches/month or 0.34 inch/day. The model domain is shown on Figure 5. The model used prescribed head boundary conditions for all boundaries. The top of the model used prescribed rainfall (Figure 6) and prescribed evapotranspiration (Figure 7).

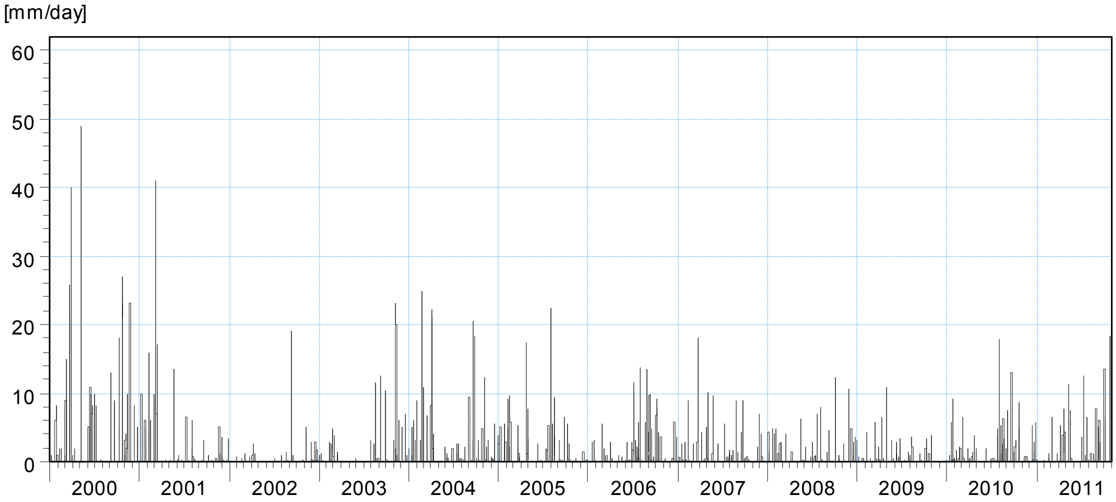

Figure 6 Precipitation events recorded in the period 1981-2008 (Western Regional Climate Center[2])

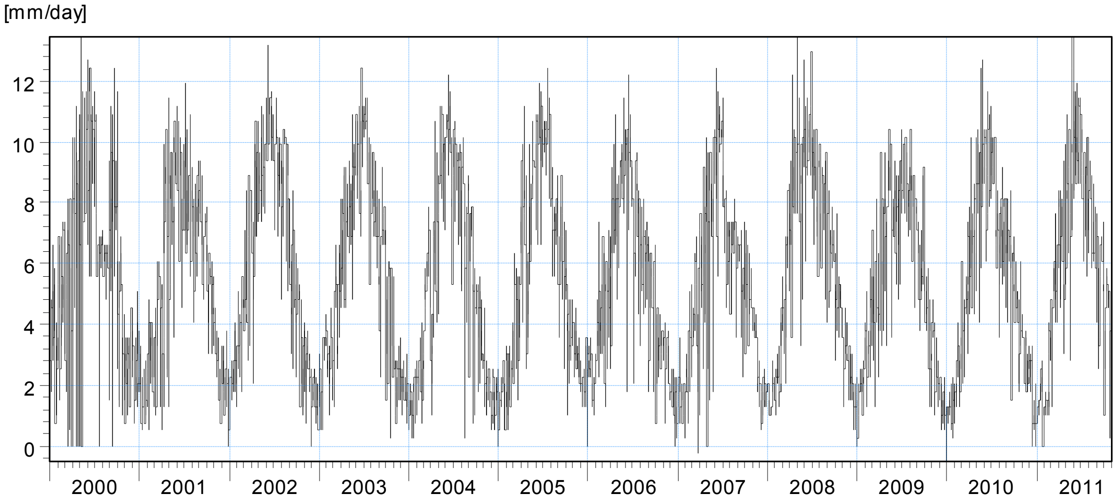

Figure 7 Evapotranspiration daily timeseries for 1981-2008 (Western Regional Climate Center[3])

Unsaturated Properties of Soil

The unsaturated hydraulic properties are often described using the pore size distribution model of Mualem (1976) for the hydraulic conductivity in combination with a water retention function introduced by Van Genuchten (1980). The soil water retention equation, θ (Ψ), and the hydraulic conductivity are given by equations (a) and (b) respectively.

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[2] http://www.wrcc.dri.edu/

[3] http://www.wrcc.dri.edu/

$$\theta(\psi) = \theta_r + \frac{(\theta_s - \theta_r)}{\left[1 + (\alpha\psi)^n\right]^m} \quad \text{(Eq. a)}$$

$$K(\psi) = K_s \frac{\left(\left(1 + |\alpha\psi|^n\right)^m - |\alpha\psi|^{n-1}\right)^2}{\left(1 + |\alpha\psi|^n\right)^{m(l+2)}} \quad \text{(Eq. b)}$$

where θ is the volumetric water content ($ft^3\ ft^{-3}$) at pressure head Ψ (ft); θ_r and θ_s are the residual and saturated water contents, respectively ($ft^3\ ft^{-3}$); α (in ft^{-1}) is related to the inverse of the air-entry pressure; *n* is a measure of the pore-size distribution (Van Genuchten, 1980); $m = 1\text{-}1/n$; and $K(\Psi)$ is hydraulic conductivity ($ft\ s^{-1}$). Both equations show strong dependence and a variation of the hydraulic conductivity with several orders of magnitude.

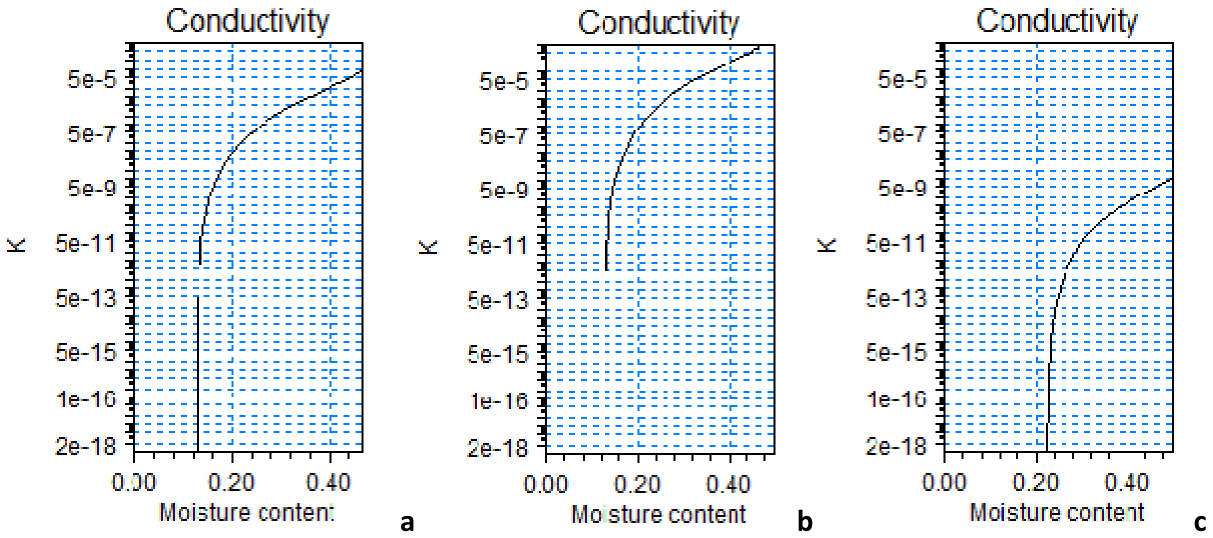

Figure 8 Hydraulic conductivity as function of moisture content: a) upper rip-rap layer, b) sand layer c) radon barrier layer

Table 1 shows the relation between the moisture content of the soil and the hydraulic conductivity at each layer. In the upper rip-rap layer the hydraulic conductivity value ranges from 10^{-6} to 10^{-4}, the sand layer hydraulic conductivity ranges from 10^{-5} to 10^{-3}, and the radon barrier layer hydraulic conductivity ranges from 10^{-11} to 10^{-8}.

Table 1 Hydraulic conductivity in m/s as function of moisture content: a) upper rip-rap layer, b) sand layer c) radon barrier

	Upper rip-rap layer	Sand layer	Radon barrier layer
0.20	1×10^{-6}	4×10^{-5}	6×10^{-11}
0.30	8×10^{-5}	2×10^{-4}	4×10^{-9}
0.40	1×10^{-4}	6×10^{-3}	1×10^{-8}

A series of simulations were conducted using a ten year period using daily timeseries for precipitation and evapotranspiration. The objective of the simulations were to determine the range of variability of infiltration fluxes, and moisture content within the height of the soil column. Figure 9 shows analysis of moisture content for three selected sol column depths for a ten year period (using 0.1, 0.2 and 0.7 ft). At depth 0.1 ft the highest moisture content reached is 0.5, at depth 0.2 ft the highest moisture content reached is 0.35, and at depth 0.7 ft the moisture content is very low, the value obtained from the model is 0.2.

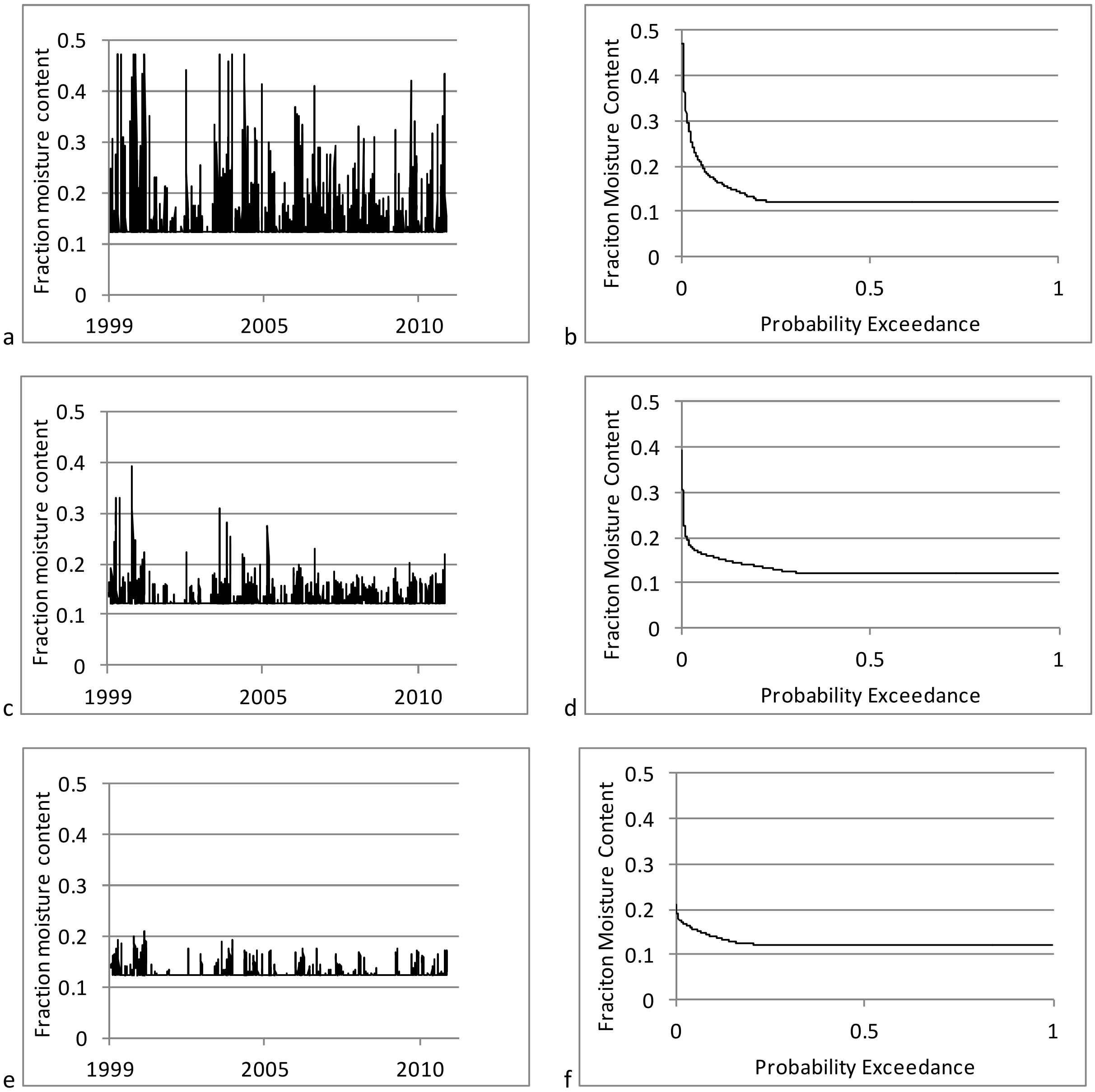

Figure 9 Timeseries of moisture content at depth a) 0.1 ft, c) 0.2 ft, e) 0.7 ft and Probability exceedance of moisture content at depth b) 0.1 ft, d) 0.2 ft, f) 0.7 ft

Similarly, Figure 10 shows the timeseries of infiltration rate from the surface to unsaturated zone over a period of 10 years. The water balance between rainfall, infiltration and evaporation over a period of 10 years is shown in Figure 11. There is a direct correlation between rainfall events and infiltration rates.

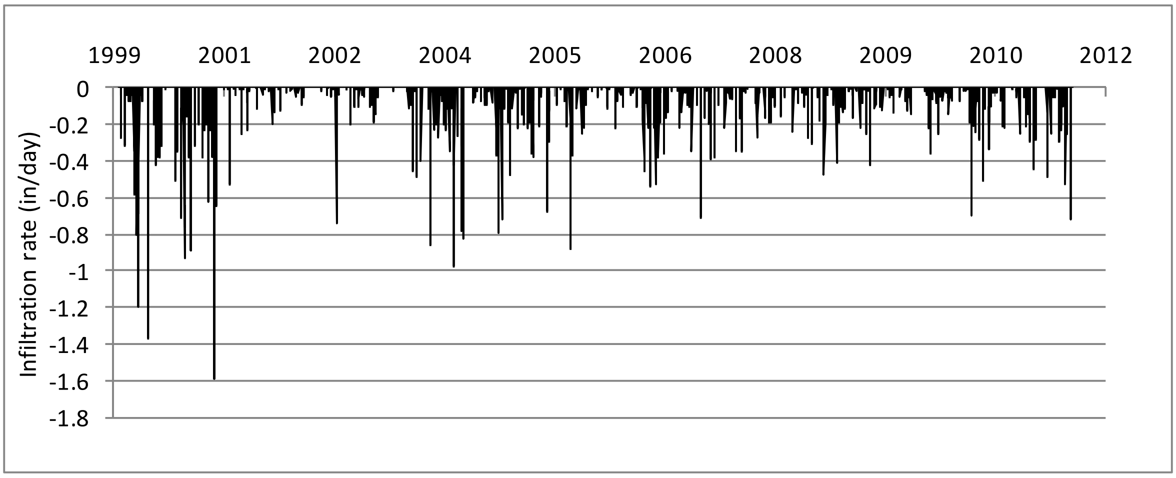

Figure 10 Infiltration to unsaturated zone

In Figure 11 the water balance demonstrate that the accumulated infiltration downwards through the surface of the tailings is equivalent to the accumulated evapotranspiration from the soil, which implies that there is no water reaching the water table in the tailings, since there is no further downward moisture flux.

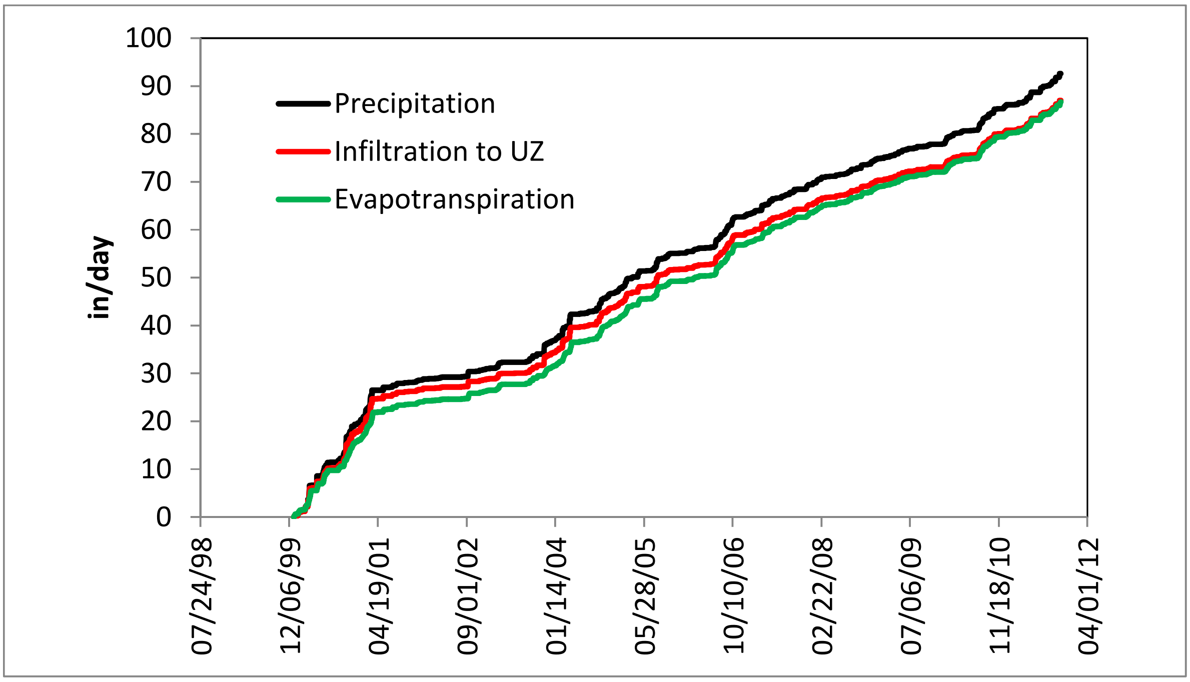

Figure 11 Accumulative water balance at the top of the soil

Figure 12 shows the depth of the unsaturated zone from the surface. At the location of the disposal cell the depth of unsaturated zone (saturation less than is extended to more than 20 ft from the top of the soil.

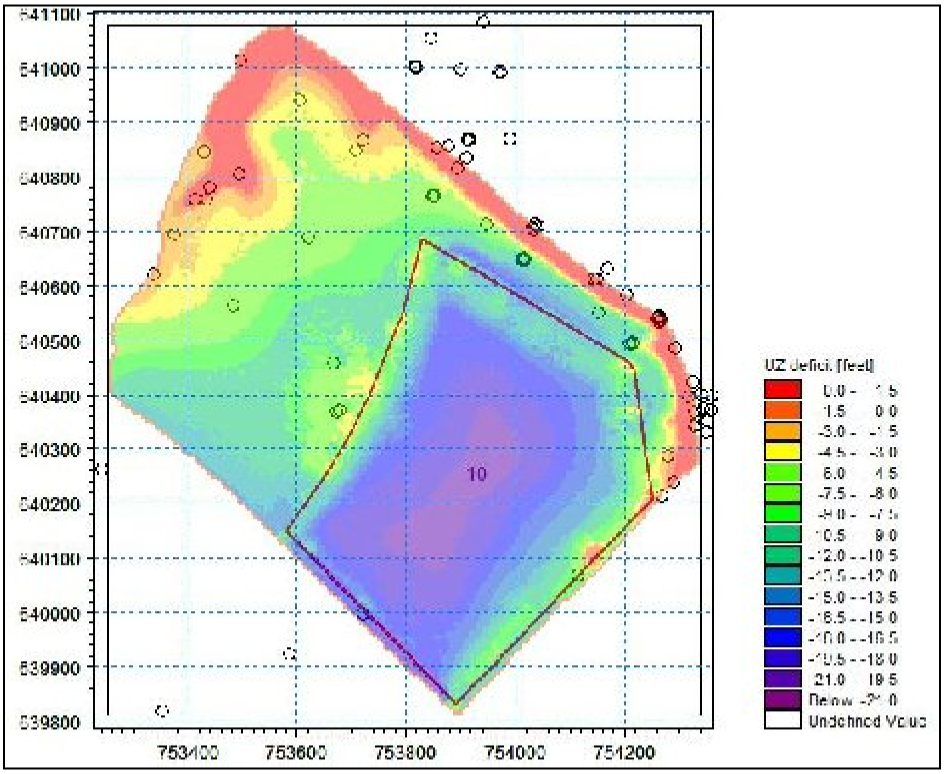

Figure 12 Distance of depth of unsaturated zone (ft)

CONCLUSION

To understand the dynamics of the system and changes in moisture and moisture flux it is important to consider the stochastic variation of all hydrological events that control flow and transport at the site. A unique modeling approach simulated the daily climatic conditions and determined the changes in moisture and moisture flux from the disposal cell for a period of ten years. Modeling results indicated that increases in the saturated conductivity at the top of radon barrier do not influence flux from the tailings with time because the tailings behave similar hydraulically to the radon barrier. The presence of a thin layer of low conductivity material anywhere in the cover or tailings restricts flux in the worst case to the saturated conductivity of that material. Furthermore, the precipitation is equivalent to the evapotranspiration losses from the surface layer. Where materials are unsaturated at depth within the radon barrier of tailings slimes, conductivities are typically less than 10^{-8} centimeters per second. If the low conductivity layer is deep within the disposal cell, its saturated properties are less likely to change with time. The model confirmed the following trends:

a) **Infiltration and evapotranspiration**: The accumulated infiltration is equivalent to the accumulated evapotranspiration, resulting in no water reaching the groundwater tailings under the conditions simulated (daily precipitation and evapotranspiration). In general, for the hydrologic conditions at the site, the water from precipitation infiltrates in the shallow surface zone, where it is lost from evapotranspiration.

b) **Extent of Infiltration:** At depth of 0.7 ft in the rip-rap layer (1st layer) the moisture content is very low implying that there is a low possibility of water reaching past that layer (hydraulic conductivity is in the order of 10^{-10} m/s.

c) **Vegetation:** the vegetation affects the rate of evapotranspiration increasing the amount of evaporation thus reducing the amount of water that infiltrates through the layer.

d) **Land cover:** the rip-rap rock cover variations in hydraulic conductivity ranges from 10^{-6} to 10^{-4}. There is no concern that rock rip-rap is increasing percent saturations and downward moisture flux.

The significance of this modeling approach is that the stochastic variations of a variety of hydrologic events are taken under consideration and provide a better understanding of the flow and transport within the site. Therefore, both the operation and the maintenance of the disposal cells can be minimized if they are allowed to progress to a natural condition with some vegetation and soil genesis. Because the covers and underlying tailings have a very low saturated hydraulic conductivity after transient drainage, eventually the amount of moisture leaving the tailings has a negligible effect on groundwater quality. Although some of the UMTRA sites are not in compliance with the groundwater standards, the explanation may be legacy contamination from mining, or earlier higher fluxes from the tailings or unlined processing ponds. Investigation of other legacy sources at the UMTRA sites may help explain persistent groundwater contamination.

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