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ESTIMATION OF THE SPATIAL DISTRIBUTION OF INFILTRATION FACTORS AT YUCCA MOUNTAIN, NV

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ABSTRACT

Yucca Mountain, in an arid climate located approximately 160 kilometers northwest of Las Vegas, NV, is composed of layers of volcanic tuff, dipping to the east. Rock units range from densely welded and highly fractured tuffs to less-fractured non- and moderately welded units. Surficial units are deeply incised with washes, particularly on the eastern flank of the Yucca Mountain ridge. A thin coating of alluvium/colluvium covers much of Yucca Mountain, achieving depths of tens of meters in some of the larger washes. Yucca Mountain has been selected as a candidate High Level Waste repository site because, among other reasons, it is characterized by up to 700 meters of unsaturated rock. Thus, the proposed repository, at a depth of approximately 400 m, is considered to be well protected from processes occurring at the surface and the water table. The favorable geochemical and hydrologic environment provided by the unsaturated zone suggests that high fluxes of water may not readily penetrate the repository, thereby lessening waste-package degradation rates and transfer of dissolved spent fuel.

Determining compliance with regulatory performance objectives for both the engineered barriers and the geological setting requires prediction of groundwater flow. Since infiltration is the primary source of water in the subsurface, the amounts and locations of infiltration are controlling factors in the movement of groundwater throughout the geological setting. The net annual infiltration from rainfall and surface water over Yucca Mountain has not yet been determined, but it has been hypothesized to vary from -1.0 to +5.0 mm/yr, with a mean annual rainfall at Yucca Mountain of approximately 150 mm/yr. Precipitation is known to vary substantially over the Yucca Mountain region, both spatially and temporally, as is typical of arid and semiarid regions. Locally larger rainfall and infiltration rates may occur due to climatic fluctuations, interannual fluctuations, interseasonal fluctuations, and individual storms, or due to highly focused recharge conditions. Accordingly, assessments of the performance of the proposed repository using groundwater flow predictions based on simplistic time- and space-averaged infiltration rates need to be tested for purposes of compliance demonstration.

This paper documents a method for estimating the spatial distribution of infiltration. A Geographical Information System (GIS) is used to manipulate infiltration-affecting factors at the Yucca Mountain site. The sensitivity of long-term net infiltration to each recharge-affecting factor is first estimated using detailed numerical simulations of the shallow subsurface. The calculated sensitivity is generic, thus is not dependent on a particular spatial location. Then, each of the infiltration-affecting factors is evaluated on a fine grid over the entire Yucca Mountain area. Potential infiltration-affecting parameters include air temperature, atmospheric vapor pressure, wind speed profile, incident solar radiation, surface soil and rock texture, plant activity, surficial temperature, and surficial moisture content, all of which may vary widely both in space and time. Finally, the previously calculated sensitivity information is used to estimate net infiltration over the fine grid. The fine-scale estimates can then serve as boundary conditions for numerical simulations involving flow and transport processes at the deep subsurface near the proposed repository. In addition, the impact of spatial variability and uncertainty in the infiltration-affecting factors can be investigated using the available sensitivity information without recourse to performing additional costly detailed numerical simulations.

For demonstrating the methodology, sensitivities are estimated using one-dimensional vertical simulations. To obtain an upper-bound estimate for infiltration, vegetation is not considered and all fractures are assumed to be unfilled. Results of simulations examining the sensitivity of long-term net infiltration to meteorological factors and to depth of alluvium overlying a fracture continuum are presented. The spatial distribution of annual average precipitation, temperature, vapor density, and solar radiation are estimated over the subregional area based on a 30 m x 30 m resolution digital elevation map, and the impact of the spatial distribution of these factors is examined assuming a uniform distribution of semi-infinite alluvium throughout the subregional area. The spatial distribution of alluvium depth is estimated using a combination of a regressed formula for depth of alluvium based on slope for deep alluvium, and a mass-wasting simulation for shallow alluvium. Infiltration is found to primarily occur in areas where alluvial cover is minimal, such as ridgetops and side slopes. The sensitivity simulations suggest that depth of alluvial cover is critical for determining infiltration, and that infiltration is much less sensitive to meteorological factors.

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INTRODUCTION

Yucca Mountain, in an arid climate located approximately 160 kilometers northwest of Las Vegas, NV, is composed of layers of volcanic tuff, dipping to the east. The region is in the tectonically active Basin and Range Province, and a number of extensional faults are present within a few kilometers of the proposed repository footprint. Rock units range from densely welded and highly fractured tuffs to less-fractured non- and moderately welded units. Surficial units are deeply incised with washes, particularly on the eastern flank of the Yucca Mountain ridge. A thin coating of alluvium/colluvium covers much of Yucca Mountain, achieving depths of tens of meters in some of the larger washes. Yucca Mountain has been selected as a candidate High Level Waste repository site because, among other reasons, it is characterized by up to 700 meters of unsaturated rock. Thus, the proposed repository, at a depth of approximately 400 m, is considered to be well protected from processes occurring at the surface and the water table. The favorable geochemical and hydrologic environment provided by the unsaturated zone suggests that high fluxes of water may not readily penetrate the repository, thereby lessening waste-package degradation rates and transfer of dissolved spent fuel.

Determining compliance with regulatory performance objectives for both the engineered barriers and the geological setting requires prediction of groundwater flow. Under ambient conditions, it is likely that radionuclides released from the repository zone will be transported predominantly in the unsaturated flow regime, which is characterized by low fluxes. Since infiltration is a primary source of water in the subsurface, the amounts and locations of infiltration are controlling factors in the movement of groundwater throughout the geological setting. The net annual infiltration from rainfall and surface water over Yucca Mountain has not yet been determined, but it has been hypothesized to vary from -1.0 to +5.0 mm/yr, with a mean annual rainfall at Yucca Mountain of approximately 150 mm/yr. Precipitation is known to vary substantially over the Yucca Mountain region, both spatially and temporally, as is typical of arid and semiarid regions (Hevesi et al., 1992). Locally larger rainfall and infiltration rates may occur due to climatic fluctuations, interannual fluctuations, interseasonal fluctuations, and individual storms, or due to highly focused infiltration conditions. Accordingly, assessments of the performance of the proposed repository using groundwater flow predictions based on simplistic time- and space-averaged infiltration rates need to be tested for purposes of compliance demonstration.

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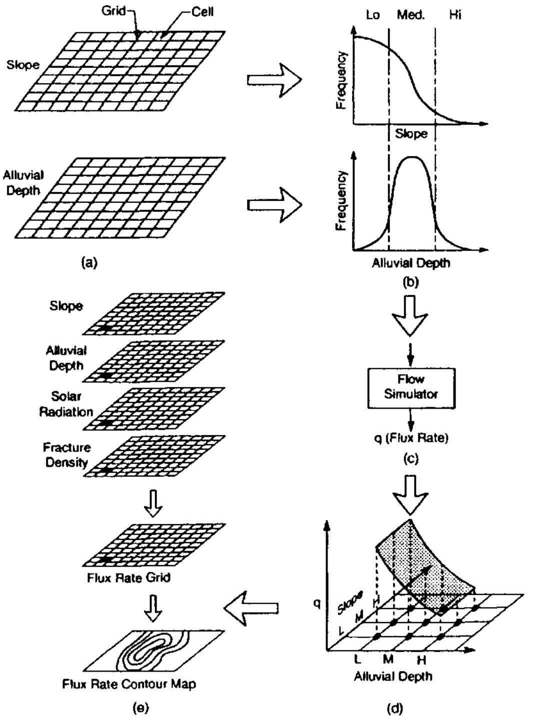

Figure 1: Schematic of the GIS-based infiltration evaluation strategy.

In order to demonstrate the methodology, sensitivities are estimated using one-dimensional vertical simulations. To obtain an upper-bound estimate for infiltration, vegetation is not considered and all fractures are assumed to be unfilled. With these assumptions, the sensitivity simulations suggest that depth of alluvial cover is critical for determining infiltration and infiltration is much less sensitive to meteorological factors.

GEOLOGICAL FRAMEWORK MODEL AND GEOGRAPHICAL INFORMATION SYSTEM

In order to estimate infiltration over the surface of Yucca Mountain, knowledge of certain properties of the shallow near-surface environment is required. Such properties include hydraulic properties of the near surface, surface and bedding dips, fault locations, vegetation, and atmospheric conditions. The site characterization information that is available comes from many sources, and at many scales, and may be in both electronic and hard copy form. Placing such sources of information into an electronic database is underway at the CNWRA, especially geologic information, topographic information, and site characterization data, using the ARC/INFO GIS. Based on the Scott and Bonk (1984) survey of Yucca Mountain, the work of Ortiz et al. (1985), and borehole data, an integrative 3D geologic framework model (GFM) of Yucca Mountain is also being developed at the CNWRA (Stirewalt and Henderson, 1995), using the EarthVision software (Dynamic Graphics, Inc., 1994). The GFM database and the GIS database are referenced to the same coordinate system and are able to exchange information.

For this preliminary estimate of the spatial distribution of infiltration, the geologic units are grouped into three categories: welded tuff, non- and partially welded tuff, and alluvium, as shown in Figure 2. The hydraulic behavior of faults is not explicitly considered in this work. Each unit is assumed to consist of a single homogeneous porous medium. There is considerable variability in hydraulic parameters within each unit at Yucca Mountain, but this issue will be explored in future work.

NUMERICAL MODEL

A one-dimensional finite-element simulator, BREATH (Stothoff, 1995), was used for all simulations. The simulator considers the coupled flow of moisture and energy. In the subsurface, it is assumed that the Richards equation assumptions are valid to describe liquid transport, while vapor transport is assumed to occur through molecular diffusion in a stagnant air phase. Vapor is assumed

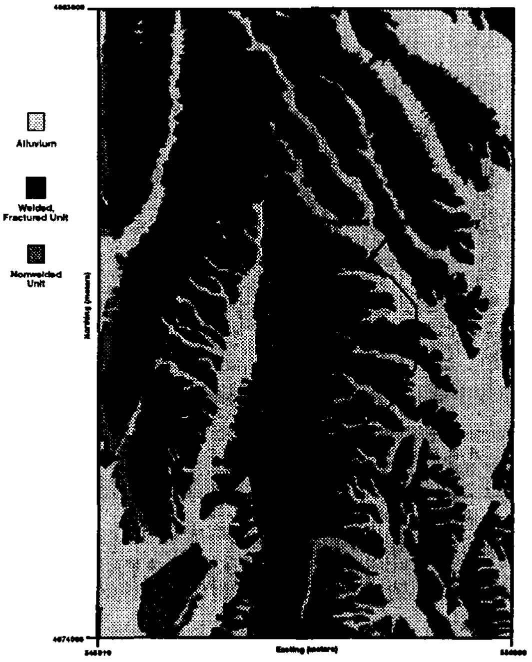

Figure 2: Unit classification used to estimate the spatial distribution of infiltration, based on the CNWRA 3D GFM.

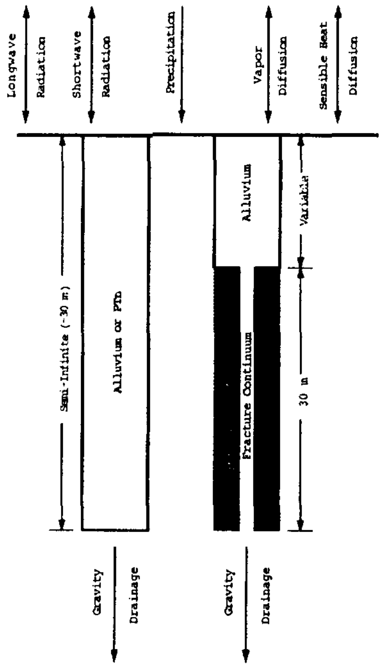

Figure 3: Schematic of the 1D simulations.

to be in equilibrium with the liquid phase everywhere. Both conductive and advective energy transport in the subsurface are simulated, with the solid and liquid phases contributing to conduction and the liquid and vapor contributing to advection. The subsurface is coupled to the atmosphere through exchanges of longwave and shortwave radiation, diffusion of vapor and sensible heat through an atmospheric boundary layer, and through precipitation events. It is assumed that the bottom boundary is sufficiently far from the surface that gravity drainage (zero saturation gradient) occurs and thermal perturbations damp out. Energy is transported advectively with the liquid drainage. Geothermal-gradient fluxes are neglected, so that vapor transport is negligible at the bottom boundary and conductive transport of heat is zero. In the simulations presented here, vapor transport is only found to be significant in the top tens of centimeters and at material interfaces. Vapor transport due to the geothermal gradient should only be significant in cases with extremely low infiltration rates.

The conceptual models for all simulations are described in Figure 3, which depicts two hypothetical media representations in schematic form. The first column is used for sensitivity analyses of a semi-infinite column of alluvium, and for analyses of the Paintbrush nonwelded tuff. The second column is used to calculate the impact of varying depths of alluvium overlying a fractured welded matrix. It is assumed that the hydraulic behavior of the fractures can be described using Darcy's law in a fracture continuum, and that the welded matrix is impermeable compared to the fractures.

SENSITIVITY TO ATMOSPHERIC FORCING

A series of simulations were performed to assess the sensitivity of infiltration predictions to various atmospheric forcings. As with all of the simulations presented here, a ten-year sequence of forcings was used, based on measurements at a National Weather Service station, at the Desert Rock, NV, airport, roughly 30 km from Yucca Mountain (National Climatic Data Center, 1994). The data includes hourly readings of air temperature, relative humidity, wind speed, cloud cover, and rainfall class, plus daily precipitation totals. Vapor density was calculated from air temperature and relative humidity. Precipitation was disaggregated into hourly values based on the rainfall class and the daily total precipitation. Snow was not reported for the Desert Rock data, although it does occur at Yucca Mountain; all precipitation was assumed to occur as rain. Simple formulae were used to estimate longwave and shortwave radiation, based on latitude, air temperature and cloud cover. Extensive testing indicated that using hourly values of meteorological parameters has a significant impact on infiltration predictions during precipitation events, as vapor density, air temperature, and cloud cover are different than their average values; however, during evaporation periods long-term averaged values are usually acceptable. For computational efficiency, hourly values of meteorologic inputs were used for a day before and after each precipitation event; otherwise, monthly average values were used.

In order to examine the sensitivity of infiltration predictions to atmospheric conditions, a simulated column of homogeneous alluvium was subjected to the ten-year sequence of atmospheric forcings, cycling the boundary conditions until the infiltration response approached a cyclic steady state. For each sensitivity calculation, one of the boundary conditions was scaled uniformly (precipitation, vapor density, wind speed, longwave radiation) or shifted uniformly (air temperature), while holding all others fixed. The effects of shortwave radiation were examined by assuming the ground surface was rotated 30 degrees to the north, south, east, or west. The resultant sensitivity to each boundary condition is demonstrated for a low- and high-permeability alluvium in Figure 4a and b, respectively. Each alluvium has a porosity of 0.3, bubbling pressure of 2.0×10^5 Pa, and van Genuchten m of 0.2, with permeabilities of 10^{-5} and 10^{-2} cm^2, respectively. The horizontal lines represent the base cases, which use the unscaled Desert Rock data. The high-permeability alluvium allows significantly greater evaporation than the low-permeability alluvium, thus decreasing net infiltration by more than an order of magnitude in this arid environment.

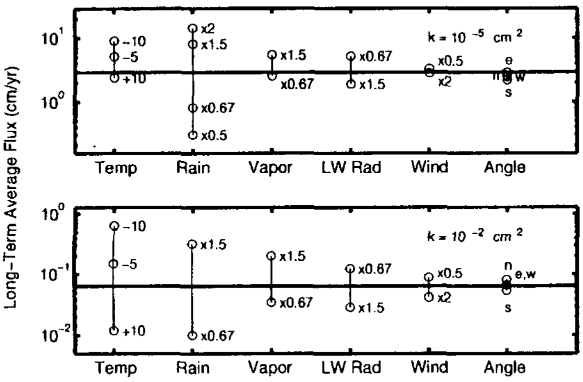

Figure 4: Sensitivity of long-term infiltration flux predictions to meteorologic forcings. (a) Low-permeability medium. (b) High-permeability medium.

The meteorologic influences on infiltration are affected by topography, primarily elevation. In order to estimate the spatial distribution of the meteorologic influences, formulae based on elevation are used here. Annual average precipitation is estimated by an exponential expression regressed by Hevesi et al. (1992), based on cokriged elevation and annual average precipitation for southwestern Nevada. the Desert Rock station and a central Nevada meteorological station at elevation 7200 feet (McKinley and Oliver, 1994) are used to estimate annual average temperature and annual average vapor density, assuming temperature decreases linearly with elevation and vapor density decreases exponentially with elevation. The sensitivity of infiltration to these factors is estimated as well, by calculating the annual average value of the meteorological factor at each pixel and linearly interpolating within the respective sensitivity table. Shadowing can influence shortwave radiation, particularly in the washes; however, since infiltration is relatively insensitive to shortwave radiation, shadowing effects are neglected here. The sensitivity to shortwave radiation for a semi-infinite column is calculated by interpolating the north/south and east/west rotation of each pixel within the shortwave radiation sensitivity table. This procedure captures effects due to cloudiness.

The nondimensional sensitivity of infiltration to all of the meteorological factors, assuming the region is uniformly covered with the high-permeability semi-infinite alluvium, is shown in Figure 5.

The nondimensional sensitivity is calculated by dividing the infiltration calculated using all meteorological information by the base-case infiltration. A corresponding distribution for the low-permeability alluvium is very similar, except the range in nondimensional infiltration is roughly half that for the high-permeability alluvium. In the vicinity of the potential repository footprint, the impact of meteorological variation on long-term infiltration is roughly a factor of two to four. It is straightforward to account for meteorological variation, but it is less significant at the Yucca Mountain scale than the hydraulic properties of the mountain, which may alter infiltration by orders of magnitude.

SENSITIVITY TO LAYERING

An example calculation demonstrates the sensitivity of infiltration to layering. In this example, the lower-permeability alluvium of the two considered previously overlies a fracture continuum. Fractures in the welded medium are characterized as an equivalent Darcy continuum, with average properties for Topopah Spring welded tuff used in the Sandia National Laboratories total-system performance assessment of Yucca Mountain (Sandia National Laboratories, 1994). The fracture continuum has a porosity of 0.001, bubbling pressure of 980 Pa, permeability of 0.01147 cm^2, and van Genuchten m of 0.7. The welded matrix is assumed not to interact with the fractures.

The long-term average flux obtained with various alluvial depths is shown in Figure 6. The depth of the alluvium cover has a profound effect on infiltration. When alluvium depths are less than 25 cm, fluxes through the fracture continuum are large but highly episodic, occurring only immediately after rainfall events. Increasingly larger events are required to initiate fracture flow for larger alluvial depths. If alluvium extends below 25 cm, no set of rainfall events are large enough to saturate the interface before evaporation overtakes moisture fronts held up by the capillary barrier at the interface. When the alluvium is deeper still, the interface is isolated from the atmosphere, some of the alluvium approaches semi-infinite behavior, and moisture can pond on the interface for longer periods. Once the alluvium is deep enough, between 5 and 10 m, the ponding depth above the interface is large enough that the capillary barrier of the interface is breached. In other words, the presence of a fracture continuum strongly influences long-term net infiltration fluxes when alluvial covers are shallow, but alluvial hydraulic properties control fluxes for deep alluvial covers.

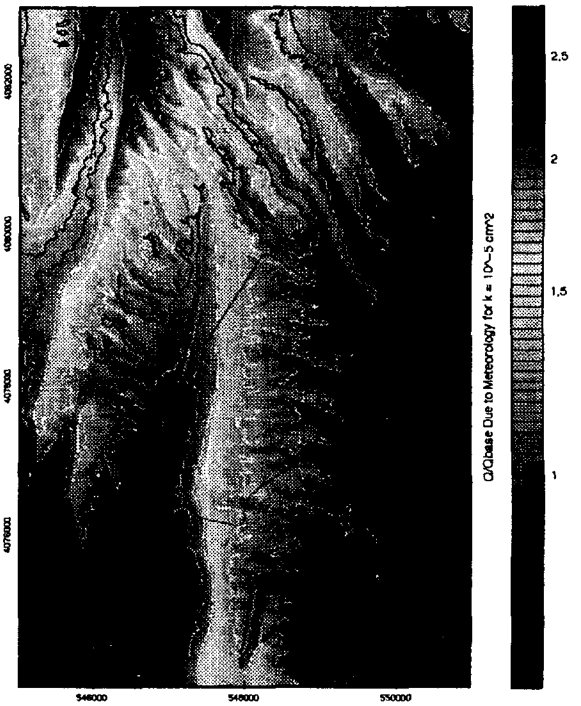

Figure 5: Ratio of infiltration to base-case infiltration due to variation of meteorological factors, assuming uniform coverage of semi-infinite low-permeability alluvium.

ESTIMATING ALLUVIAL DEPTH

Based on the numerical experiments with the porous medium parameters, it is apparent that an accurate assessment of the depth of alluvium over a fractured welded tuff is extremely important in estimating infiltration, at least for the 1D column model. Depth of alluvium is available at 59 boreholes scattered around Yucca Mountain, but is not available on a 30 m by 30 m grid. Accordingly, some method for assigning alluvial depth at this resolution is necessary until more data are collected.

For the purposes of demonstrating the methodology of estimating the spatial distribution of infiltration, a two-pronged approach was followed. In the regions where the Scott and Bonk (1984) survey indicates that alluvium exists, an empirical fitting function relating alluvium depth to surface slope was used. The fitting function is in the form of an exponential, so that depth of alluvium increases with decreasing slope. The two adjustable parameters in this fitting function were obtained using the slope and alluvium depth at 56 of the boreholes, with a correlation coefficient of 61 percent. This approach gave plausible results in the wash bottoms, but predicted implausiblely large alluvial depths at ridgetops. Attempts to identify ridgetops through curvature met with some success, but identifying a fitting formula yielding plausible ridgetop depths was not successful.

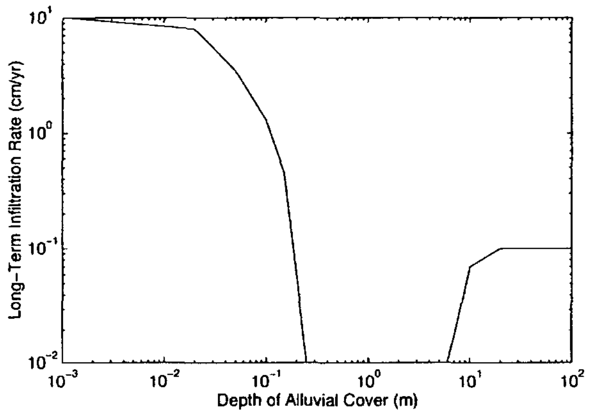

Figure 6: The effect of low-permeability alluvium depth on long-term infiltration flux.

The difficulties in estimating thin alluvial films led to the adoption of an alternative approach. A simple mass balance model was applied, balancing the steady-state divergence of downhill alluvial flux due to gravity (mass wasting) with a source term exponentially increasing with the slope. The nature of the source term is consistent with empirical formula relating ground slope and alluvial depth. Flux was assumed proportional to the thickness of alluvium and the slope. All coefficients were assumed to be lumped into the source term, and were assumed to be constant in space and time. The two resultant coefficients were manipulated by trial and error to obtain distributions such that the crest of Yucca Mountain could be interpreted to be bare in patches, and roughly a meter of alluvium existed midway up from the bottom of Solitario Canyon to Yucca Crest. The model was constrained to predict no more than 50 m and no less than 0.1 mm of alluvium for each grid, serving as rough-and-ready Dirichlet conditions. Starting from a uniform alluvial depth of 10 cm over the entire region, a few hundred iterations resulted in the final distribution shown in Figure 7. Note that within the Scott and Bonk (1984) alluvium outline, the empirical fitting function depth is plotted. The mass-wasting approach predicts a relatively thin alluvial film within the alluvium outline.

ESTIMATED INFILTRATION DISTRIBUTION

An inital estimate of the spatial distribution of infiltration is presented in Figure 8. Two categories of rock are considered, alluvium-covered fractured welded tuff and uncovered nonwelded tuff. Low-permeability (high-infiltration) alluvium is assumed. The fractured welded tuff is assumed to have the median fracture hydraulic properties reported in Sandia National Laboratories (1994), and the nonwelded tuff is assumed to have the median hydraulic properties for the high-permeability mode of the Paintbrush tuff (from the same report). It is arbitrarily assumed that unscaled infiltration is 0.05 mm/yr for alluvium depths between 25 cm and 5 m when overlying welded tuffs. Sensitivity to meteorological factors for all materials is assumed to be identical to the sensitivity for semi-infinite low-permeability alluvium. The nonwelded tuff is assumed to have no alluvial cover, as the depth-sensitivity calculations are not yet available for this case. According to this distribution, most of the infiltration comes from areas with very shallow alluvial cover, such as ridgetops. Areas with deep alluvium also show some infiltration. The peculiar checkerboard pattern of infiltration on some ridgetops, particularly those to the northwest of the repository, may be due to numerical instabilities in the alluvial depth calculations. Alluvial depth is the single most important determinant of the infiltration distribution for this example.

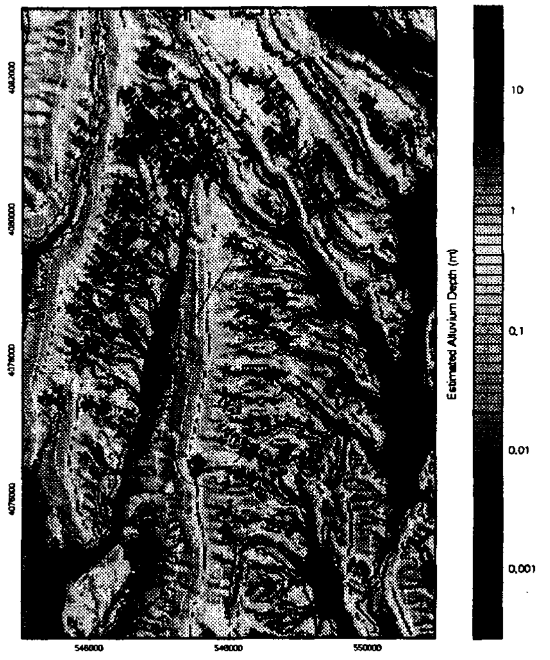

Figure 7: Estimated depth of alluvium using an empirical formula for deep alluvium and a mass-wasting calculation for shallow alluvium.

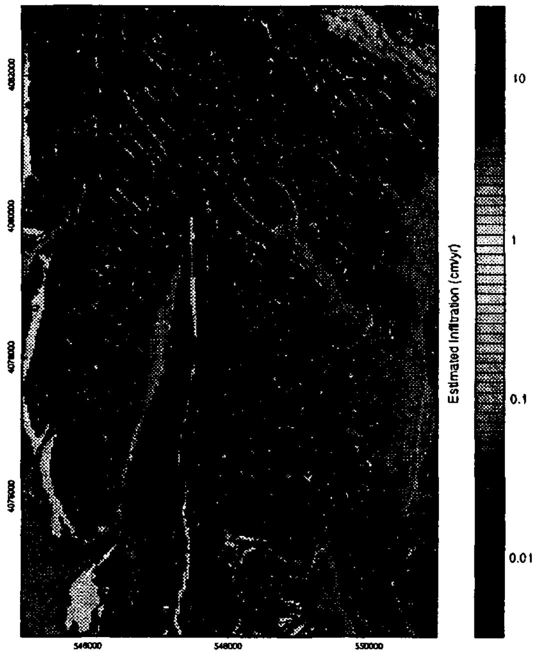

Figure 8: Sample distribution of long-term average infiltration, accounting for depth of alluvium, underlying bedrock, and meteorological effects.

There are a number of mechanisms, neglected here, that play a significant role in altering infiltration distributions. Vegetation is an important mechanism for limiting infiltration, and may greatly reduce infiltration where bare rock is not exposed. Vegetation would not affect infiltration estimates in moderately deep alluvium, as there is essentially no infiltration predicted for such cases anyway. Overland flow may also be a contributing factor to increasing infiltration at lower elevations. Also, lateral subsurface flow along hillslopes may be significant, which would alter infiltration patterns. And finally, intra-unit heterogeneity will presumably result in the development of fast infiltration pathways.

SUMMARY

Important highlights of this work include:

- A 1D finite-element column model is used to construct a sensitivity response surface for precipitation, temperature, vapor density, solar radiation, hydraulic properties, and alluvial depth.
- A cycled ten-year hourly meteorological record is used to estimate long-term average infiltration.
- A detailed digital elevation map, along with a geologic framework model integrating geologic data from various sources, is used to construct all of the factors required for interpolation in the built-up sensitivity table.
- Alluvium depths are estimated using a mixture of a data-derived empirical formula and a qualitatively reasonable mass-wasting calculation.
- Vegetation, overland flow, lateral subsurface flow, and geothermal-gradient flow are not considered. These processes are significant to various degrees.

- Of the meteorologic factors considered, precipitation and air temperature have the most impact on long-term infiltration. Meteorologic factors are relatively less important in affecting infiltration patterns compared to hydraulic factors at the Yucca Mountain subregional scale.
- For a two-layered bare-soil column in arid and semiarid environments, there is a tendency for the lower medium to dominate infiltration behavior for very shallow covers, the upper medium to dominate for very deep covers, and much reduced infiltration to occur for intermediate covers.
- As much of the alluvial cover over Yucca Mountain appears to be in the intermediate range, depth of alluvial cover over Yucca Mountain may be critical in estimating the spatial distribution of the long-term average infiltration rate.

ACKNOWLEDGEMENTS

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